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Relationships between physical, technical and competition measures in Australian golfers

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ABSTRACT

Informed testing and training of golfers is vital in supporting a multi-disciplinary approach to enhancing golf performance. However, the many identified physical and technical attributes (and methods to test them) that underpin competition performance are often given equivalence in the literature – creating uncertainty as to the scope and contents of an effective test combine for golf. To address this challenge, a new 5-stage Physical-Golf Performance Continuum (P-GPC) and comprehensive combine were developed to better inform the integrated testing and training of golfers of across all levels of ability. A large heterogenous sample (*N* = 122) of competitive Australian male golfers was investigated with a series of analyses conducted to improve the understanding of the relationships between physical and technical measures.

Study I defined four ability cohorts (Handicap = Elite: -6 – 0.4, Low-HCP: 0.5 – 7.4, Mid-HCP: 7.5 – 17.4, High-HCP:17.5 – 36) upon which to quantify the golf performance literature and assess the importance of physical and technical measures in subsequent studies. Research design elements as well as technical, physical and competition measures were aggregated by golf cohort (gender, age and ability) to highlight where evidence for the multi-disciplinary golf team is abundant or scarce. A checklist of parameters for each stage of the P-GPC was identified to inform combine formation and a heuristic for golf performance analysis.

Study II formed a comprehensive golf combine to cover parameters from each stage of the P-GPC. Twenty-five tests were presented with previously established reliability, validity and sensitivity. Study III employed the combine from Study II to determine the construct validity of each test to enable streamlined combines in golf. Benchmarks are provided for the physical and technical traits for golfers across ability levels. Many moderate to large effect size (*d*) differences were observed across the four ability levels for skill, technique and physical measures, such as Total Driver Distance (*d* = 0.96 – 1.53), 120 m Shot Distance to Target (*d* = -0.75 – -1.34), Driver Club Head Speed (CHS) (*d* = 0.89 – 1.08), 120 m Shot Spin Rate (*d* = 0.87 – 1.07) and 3 kg Lateral Medicine Ball Throw (*d* = 0.31 – 0.84).

Study IV produced 12 multiple linear regression models, from cross-sectional data, between stages of the P-GPC in two pathways, based on two skill tests used: 120 m Target Shot and Maximum Distance Driver Shot. Study V produced 12 linear mixed models using longitudinal repeated measure combine data as fixed effects and each individual golfer as a random effect. The linear mixed models typically had lower error than the regression models in Study IV and have greater utility for longitudinal applications such as quantifying training transfer and athlete profiling.

The results from the studies in this thesis allow for more efficient and effective testing and training of golfers relative to their ability cohort and have utility as benchmarks for athlete profiles and simplified, cohort-specific combines.

STUDENT DECLARATIONS

Doctor of Philosophy by Traditional Thesis Declaration

"I, Scott Balin Williams, declare that the PhD Traditional Thesis entitled 'Relationships between physical, technical and competition measures in Australian golfers' is no more than 80,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

"I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University's Higher Degree by Research Policy and Procedures". Ethics approval number – HRE17-105.

Signature: 

Date: 4th October 2021

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LIST OF ABBREVIATIONS

° – Degrees (angular range of motion)

°/s – Degrees per Second (angular velocity)

%BW – Percentage of Bodyweight

3D – Three-Dimensional

ABC – Activities-Specific Balance Confidence

Adj. R2 – Adjusted R2 (Coefficient of Determination)

ANOVA – Analysis of Variance

ARMSS – Applied Research Model for the Sport Sciences

B – Unstandardised beta coefficient

β – Standardised beta coefficient

BESS – The Balance Error Scoring System

bpm – Beats per Minute

cm – Centimetres

CHS – Club Head Speed

CI90 – 90% Confidence Interval Width

CI95 – 95% Confidence Interval Width

CMJ – Counter-Movement Jump

COG – Centre of Gravity

COM – Centre of Mass

COP – Centre of Pressure

CoV – Coefficient of Variation

d – Cohen's *d* (effect size)

EMG – Electromyography

ES – Effect Size

FMS – Functional Movement Screen

FSP – Functional Swing Plane

FTEM – Foundation, Talent, Elite, Mastery

Fx – Antero-Posterior Ground Reaction Force

Fy – Medio-Lateral Ground Reaction Force

Fz – Vertical Ground Reaction Force

GA – Golf Australia

GRF – Ground Reaction Forces

GMS – Golf Movement Screen

GPC – Golf Performance Continuum (may ditch this one)

GSFMS – Golf Specific Functional Movement Screen

HCP – Golf Handicap

HRR – Heart Rate Recovery

ICC – Intra Class Coefficient

IMTP – Isometric Mid-Thigh Pull

kg – Kilograms

kg/m – Kilograms per Meter of limb length (Torque)

kg/m/kg – Kilograms per Meter of limb length per Kilogram of body weight (Relative Torque)

L&T – Lead and Trail side of body

m – Meters

m/kg – Meters per Kilogram of body weight

m/m – Meters per Meter of leg length

m/s – Meters per Second

Max – Maximum

MB – Medicine Ball

MCIC – Minimal Clinically Important Change

MD – Mean Difference

MDC – Minimal Detectable Change

MDC^{95} – Minimal Detectable Change at 95% Confidence Interval Width

MET – Metabolic Equivalent of Task

MID – Minimum Important Difference

mph – Miles per Hour (club head speed)

mph/kg – Miles per Hour per Kilogram of body weight

mph/m – Miles per Hour per Meter of height or arm span

MSEBT – Modified Star Excursion Balance Test (truncated to SB)

MV – Movement Variability

MVIC – Maximal Voluntary Isometric Contraction

Mz – Moment of force about vertical axis

n – Sample Size

N – Aggregated Sample Size

N – Newtons of Force

OWGR – Official World Golf Ranking

p – statistical significance

PDS – Proximal to Distal Sequence

P-GPC – Physical-Golf Performance Continuum

PGA – Professional Golfers Association

Px – Pelvis

Q-Q – Quantile-Quantile Probability Plot

r – Pearson's Correlation Coefficient

R – Coefficient of Correlation

R^2 – Coefficient of Determination

RMSE – Root Mean Squared Error

ROFD – Rate of Force Development

ROM – Range of Motion

SB – Star Balance

S&C – Strength and Conditioning

Sig. – Statistical Significance

SD – Standard Deviation

SE – Standardised Error

SEM – Standard Error of Measurement

SEE – Standard Error of the Estimate

SMBT – Seated Medicine Ball throw (Chest Pass)

SWC – Smallest Worthwhile Change

TE – Typical Error

Tol. – Tolerance

TPI – Titliest Performance Institute

Tx – Thorax/Thoracic Spine

VIF – Variance Inflation Factor

W – Watts

YMCA – Young Man's Christian Association

Chapter 1: Introduction

1.1 Introduction

Golf is a universally inclusive sport played by an estimated 80 million people of all ages, gender and abilities across the globe (1) and a million Australians each year (2). Golf can be played professionally and socially throughout the lifespan (3, 4) and since 2016 has resumed as an Olympic sport, providing further relevance to the Australian talent development pathway. A growing body of literature has focused on golf performance enhancement to benefit both the aspiring elite golfer and the enjoyment of the club golfer, thereby enhancing participation, performance and the health benefits that golf provides the community (3, 4{Stenner, 2019 #2616).

The technical and physical elements that underpin golf skill execution need to be understood by the multi-disciplinary team that support the golfer (5-7). These physical-technical-performance interrelationships should inform the delivery of physical and technical training to golfers (8). Interventions also need to effectively target the individualised needs of the golfer (9, 10). These physical and technical needs are likely to vary across ability cohorts (11-13). Maximising the physical, technical and competition performance of golfers across the participation pathway can enhance enjoyment, participation and success for all levels of golfer (14-17).

A useful framework to guide this performance improvement is Smith's conceptual model (Figure 1.1), *A multi-disciplinary approach to golf performance enhancement* (15). The framework combines the various existing paradigms for golf enhancement, namely: physical, technical; tactical; mental; and life skills (15). Agreement exists between this holistic model and other published reviews of the golf performance (GP) literature that also suggest a holistic approach to golf performance and further investigation of the interplay between attributes such as physique and technique (14, 18-21). The outputs of reviews from Read et al (2018), Hellstrom (2009), Smith (2010) and others, the general guidelines for long term athlete development, combined with Smith's model, provide some evidence to guide the Australian golfing pathway (22-25).

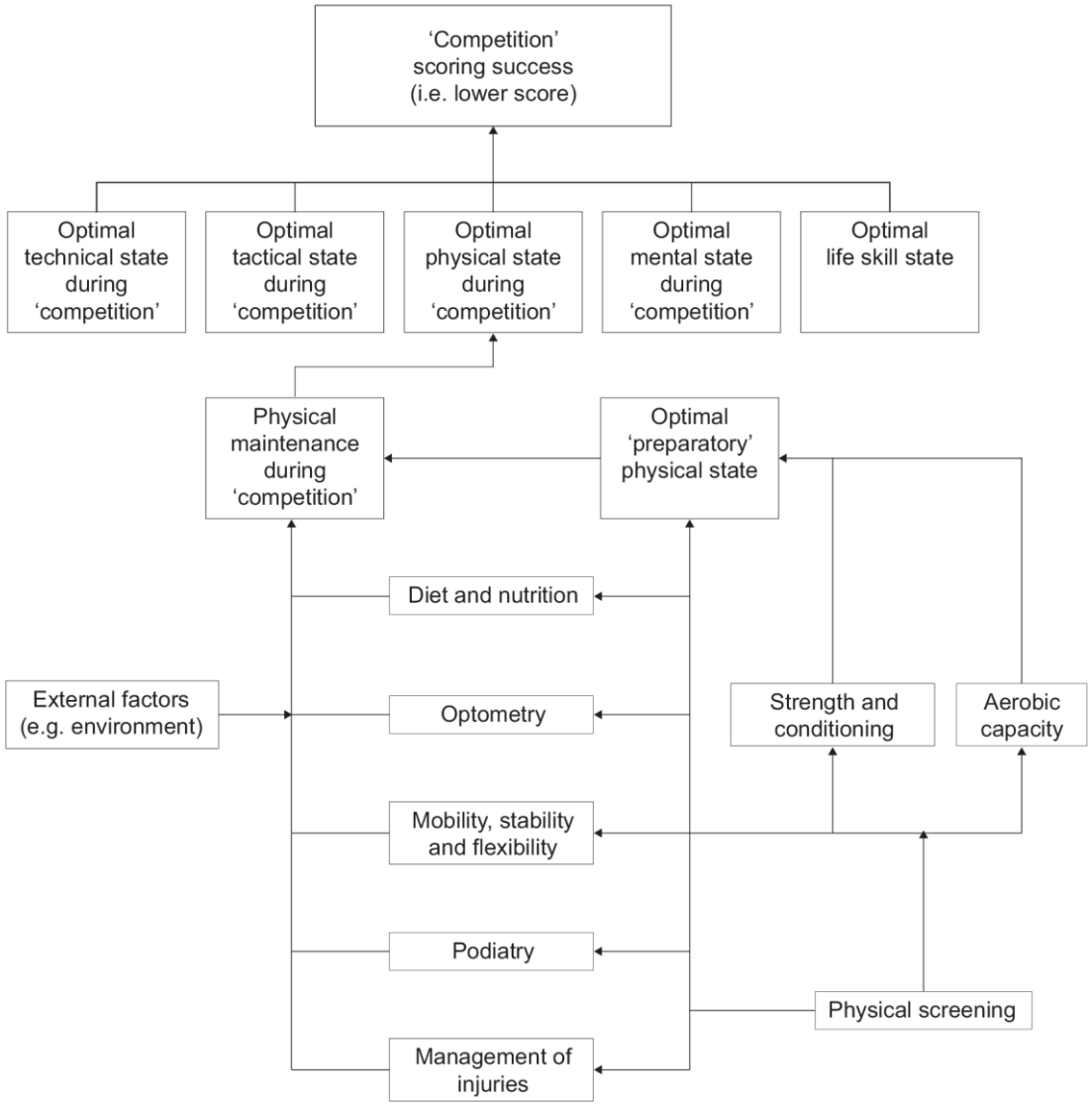


Figure 1.1 Adapted from Smith, M. A multidisciplinary approach to golf performance enhancement in 'The Role of Physiology in Golf', Sports Med 2010; 40 (8), p.640

However, more detail for these assessable and trainable parameters are required for research and applied golf settings. According to Smith's model, from a physical perspective, a competitive golfer who can effectively target their physical components would be represented as an improved 'preparatory' physical state, contributing to enhanced competition performance (15). However, the extent to which this 'optimal physical state' changes competition performance requires further investigation. Furthermore, practitioners training and treating golfers require greater detail than this model to guide their decision-making (26). This holistic approach to GP can be conceptualised in research and development programs as a staged continuum of physical-technical-competition performance contributors. A checklist at each stage of the

continuum can both guide the individuals of the multi-disciplinary team who act at the different intersects and highlight important interactions between GP mechanisms that explain the transfer of training (8, 27). For example, on-course statistics may determine that a golfer would benefit from increased distance in their 'long game'. In this case it would be worth the *strength and conditioning* (S&C) coach assessing and training physical aspects, such as power and flexibility. However, in this example, the S&C coach also must ensure that this benefit is transferring to increased distance on the golf course, and therefore needs to be privy to the effect of the physical improvements on technical and on-course measures over time (8, 28, 29). Additionally, the golf coach may formulate technical interventions to improve a player's golf swing to meet the player's GP goals. For this intervention to succeed, the coach needs to know a) the current physical underpinnings of the golfer's movement (i.e., whether the intended technical change is possible) (13, 30), and b) whether the technical improvement is transferring to on-course or competition improvement (8). Therefore, an evidence-based model that identifies all physical, technical and on-course parameters that underpin competition performance is needed to guide multi-disciplinary teams in golf research and in the field.

Understanding the relative importance of physical, technical and competition parameters can optimise the development of effective training approaches (31-33). Athlete profiling (Figure 1.2) individual golfers can allow tailored interventions, that prioritise individual needs, to maximise durability and transfer of training to performance (8, 34). For example, understanding the body *and* the biomechanics of a golfer may identify a golf swing the individual is capable of achieving (8, 35), using the individual's strengths and rather than inadvertently enforcing a swing technique that relies on a physical limitation (36, 37). The physical practitioner (i.e., S&C coach, physiotherapist, exercise physiologist etc,.) can then provide the player with a physical intervention aimed at minimising these physical limitations (10). Across sports, using athlete profiles to guide integrated interventions (32), appears the most likely approach to provide measurable performance differences that exceed the burden of time and resources of testing and profiling (38).

Key relationships between physical, technical, and competition parameters need to be determined to execute an integrated approach. Benchmarks for effective measures in each developmental area are also required (8, 39, 40). Identifying needs by understanding what is above or below average these parameters is a cornerstone for guiding athletic development and interventions (41). A collection of tests that span these disciplines, often referred to as a *combine* in a sports setting, can be used to assess the physical and technical priorities and effectiveness of interventions, at the level of individual golfer. Additionally, greater insights into mechanisms of GP using grouped

data with various analytical techniques. For example, analytical methods such as predictive modelling have been shown to improve performance and reduce talent costs in other sporting programs (42, 43). This test, intervene, re-test approach is inherent to individualising sport development in a holistic manner, whether on an individual basis or in squad-based settings (31, 32, 44).

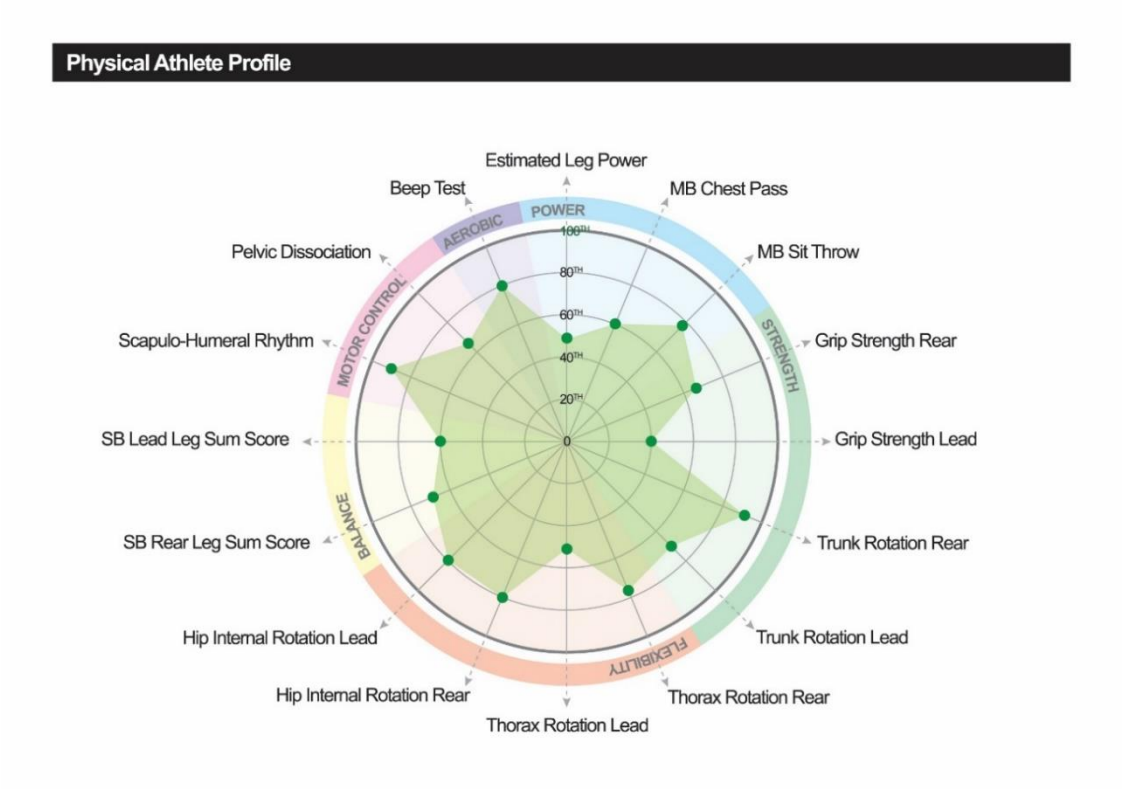


Figure 1.2 A sample physical profile of a golfer relative (by percentile rank) to a data set of male golfers (from the Author's work)

Since the 1980's there has been an exponential increase in peer-reviewed studies informing the multi-disciplinary approach to GP development, and therefore an increase in what should be considered when forming a combine to assess golfers. Associations have been established between multiple physical tests and related technical measures such as *Club Head Speed* (CHS) (12, 39, 45, 46), ball-speed (47) and shot carry distance (48). Several studies have formalised the assessment of isolated parameter sets such as mobility, balance, and movement quality (36, 49, 50). However, the validity of these *movement screens* for different cohorts is yet to be established. Furthermore, a definitive comprehensive combine that addresses the majority of physical, technical and competition parameters has not been published. Therefore, the content validity of a comprehensive combine requires a thorough analysis of the available peer-reviewed literature followed by extensive empirical testing of golfers.

Different research designs provide sports science with varying levels of translational outputs. According to Bishop's 2008 *Applied Research Model for the Sport Sciences*

(ARMSS) (Figure 1.3), the evidence-base for the first 2 stages is adequate for golf science to proceed to the subsequent stages – although gaps exist (51). For example, several systematic or narrative reviews have been published since 2009 that define and describe the define and describe GP (8, 14, 15, 52, 53). Stage 3 to 5 of the ARMSS have experienced increased attention in the golf sciences but have been hampered by sample size and methodological limitations. In golf, the remaining Stages 6 to 8 of the ARMSS have produced some interesting translational findings to performance, however, often without a sound mechanistic basis for why GP has improved (19, 54, 55). This thesis aims to identify gaps in the evidence base pertaining to the testing and training of golfers of all ages, ability and gender. From a research design perspective, these will address stages 3–5 of the ARMSS model. Subsequently, the studies in this thesis will identify the mechanistic predictors of performance to set the foundation for future experimental studies.

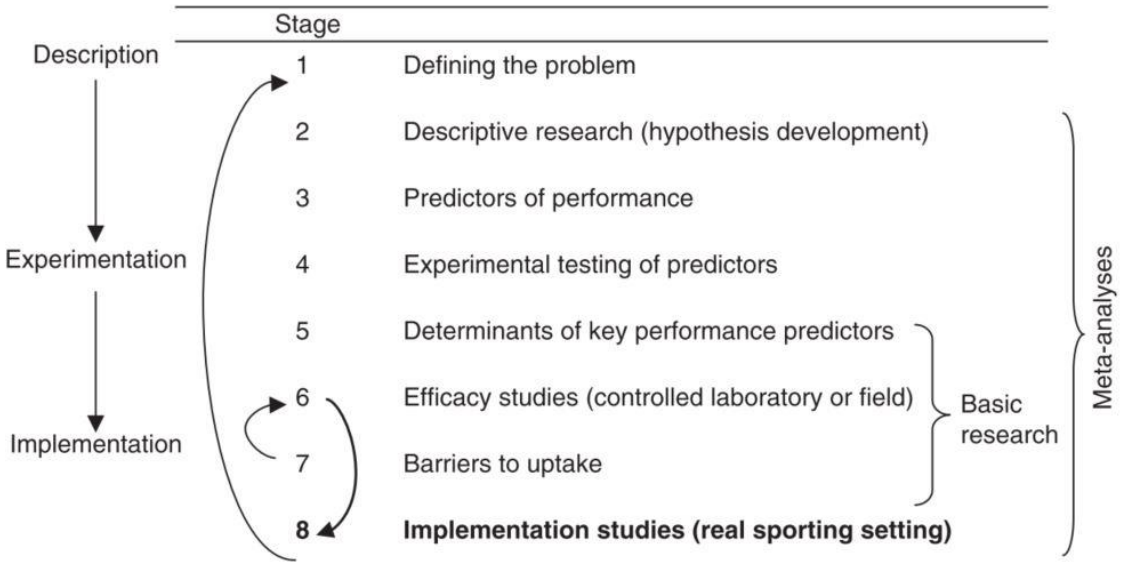


Figure 1.3 Applied Research Model for the Sport Sciences, from Bishop 2008 (51)

1.2 Objectives of the Thesis

The primary objective of this thesis is to determine the relationships between physical, technical and competition measures of performance in competitive Australian male golfers and how these vary with age and ability.

1.2.1 Aims

- To quantify the prevalence of peer-reviewed studies by golf performance parameter for various golfing cohorts (gender, age and ability).

- To form a Physical-Golf Performance Continuum (P-GPC) and comprehensive golf combine from the peer-reviewed literature for use in Study III and IV and V of the investigation.
- To quantify the differences across the P-GPC for different age and ability level cohorts of Australian male competitive golfers.
- To determine the relationships between physical, technical and competition performance measures across the continuum in different age and golf ability cohorts to inform the testing, athlete profiling and training of golfers.

1.3 Chapter Organisation

Chapter 1 introduces the rationale and specific aims for the dissertation, including the introduction of the P-GPC, which builds on earlier published frameworks.

Chapter 2 provides a narrative review of the published literature on the assessment of physical, technical, competition performance measures. The utility of this evidence-base to inform the multi-disciplinary approach in golf is discussed.

Chapter 3 (Study I) is a mapping review of the peer-reviewed literature for the assessment of physical, technical and competition performance. The prevalence of research on a cohort-parameter basis is presented gaps in knowledge. This analysis forms the basis for the construction of the P-GPC.

Chapter 4 (Study II) describes the formation of a comprehensive combine for golf to assess parameters from all stages of the P-GPC. A measurement property analysis for each test is provided. The utility of a combine for providing golf athlete profiles is also discussed.

Chapter 5 (Study III) The combine is then used to undertake a cross-sectional investigation of a large sample (n = 122) of male Australian golfers of varying ability. This study analyses the ability-group differences of physical and technical traits that span the P-GPC and provides benchmarks for these measures relative to ability. These findings can inform simplified combines to target specific golf cohorts.

Chapter 6 (Study IV) presents 12 multiple linear regression models that span the P-GPC, using the same cross-sectional data set from Study III. These models inform the multi-disciplinary team in golf, by identifying the physical and technical needs of a golfer and the integration of these measures to influence GP.

Chapter 7 (Study V) uses longitudinal repeat measures combine data to build 12 linear mixed models that span the P-GPC. These models extend on Study IV as they use a

larger data set and account for each individual golfer's repeat test scores as a random effect. These models improve the processes for talent identification and performance development across ability levels through improved statistical stability and representativeness of player traits. These models also have utility for the quantification of training transfer of interventions.

Chapter 8 contains a general discussion of the review and experimental studies, discusses the practical implications of this thesis, and provides recommendations for future research.

Chapter 2: Literature review

2.1 Introduction

A multi-disciplinary approach to optimise GP enhancement has long been recommended (14, 15). Undertaking an informed analysis of strengths and weaknesses is central to providing golfers with individualised interventions. The GP testing literature provides a plethora of tests across the domains of physical, technical and competition performance development. To situate the reader for subsequent review and original research studies contained in this thesis, background is provided on areas pertaining to the testing and utilisation of physical, technical and competition GP measures, in the form of a narrative literature review (56). This approach was selected from the various available review typologies to cater for the breadth of literature that required inspection across the various disciplines that ultimately contribute to GP. These included original research articles, review articles, book chapters, conference proceedings. This is not a systematic review, but rather aims to provide the reader with an understanding of the sport of golf and the context for investigating the relationships between physical, technical and competition performance in golf. Therefore, although important, the domains of the golf-health relationship, psychology, nutrition, and short game (e.g., putting) are not addressed in this review as they are outside the scope of this PhD thesis.

This review is divided into sub-sections based on the most highly tested parameters in the GP literature. Testing these parameters is the primary focus of this review, although some of the training interventions are also discussed to provide context for the testing. The combination of such research has informed the methodology for the original research in the chapters that follow. The strength and direction of correlations between GP measures are typically presented with *r* values or standardised differences between means using Cohen's *d* value. Supporting descriptive terms adapted for use in studies on sports medicine and exercise science are as follows: Trivial or negligible for *r* value = 0 – 2.1 or *d* < 0.2; Weak or small for *r* value = 0.1 – 0.3 or *d* = 0.2 – 0.5; Moderate for *r* value = 0.3 – 0.5 or *d* = 0.5 – 0.8; Strong or large for *r* value = 0.5 – 0.7 or *d* = 1.20; Very strong or very large for *r* value = 0.7 – 0.9 or *d* = 2.0; Extremely strong or extremely large for *r* value < 0.9 or *d* = 4.0 (57, 58).

2.2 The utility of golf performance testing

2.2.1 Talent identification in golf

Performance is different to potential, and identification is different to development (59). The conflation or misunderstanding of these factors can lead to potential errors in

decision-making across the GP pathway (60). To address these systematic deficiencies, there is a need to move away from a focus on early selection. The characteristics of successful elite and developing athletes highlight the need to take a long-term view to talent identification and development (59). For example, the characteristics of current effective performance are very different from those factors associated with the *potential to develop* and become successful (61-63). Therefore, the concept of talent must be defined as potential and not as current performance ability. Unfortunately, the majority of talent identification and development programs still use current performance measures as the main indicator of talent at all levels; an approach already shown to be highly problematic and a major barrier to athlete development (61, 62).

Research on the complex issues that underpin Talent Identification and Development can be divided into five key constructs: sport specialization and selection; practice; athlete development; junior and adult success; and the role of stakeholders in the sport system. Analysis suggests a gap exists between the theory and reality for each of these constructs. These gaps may indicate reasons for the lack of adult success in young athletes identified as 'talented' (60).

However, there are signs of a growing cohesion between research and practice in golf. These include:

1. The systematic creation of skills testing (64)
2. The assessment of mental coping strategies (65)
3. The uptake informed approaches to golfers' physical development (8, 12, 66)
4. The development of evidence-based coaching frameworks (67)
5. The development of technical benchmarks (40)
6. Research aiming to understand the mediators to the success of the development of talented golfers (68-70)

Many sports use superior physical test scores as a method for talent identification (71-73). However, in golf, whilst superior physical test scores may reflect effective development programs, from an identification perspective, these same scores could be interpreted inversely. That is, the young competitive golfers who display good GP with poor physical testing, provided they are indeed under-trained, may possess greater long-term potential than the average of their peers, as these physical traits are highly trainable with a large transfer to technical golf measures (74). Moreover, the rate of improvement in performance outcomes is arguably the most important identifier in terms of funding of potentially successful athletes – which plays a key role in success (64, 68). Given the modern aspiring elite golfer achieves professional success at a more rapid rate to their predecessors (75), it makes sense that relatively rapid process of training for physical

enhancement is a key element to golf success. In summary, golf has shown an appetite for using sport science to fast-track success. A combination of longitudinal analyses and bridging the gap between research and reality are needed to achieve this from a physical-technical-competition performance perspective.

2.2.2 Talent development in golf

Informing development with benchmarks

Other sports, such as Australian Rules Football, have produced evidence-based physical and technical benchmarks to inform athlete development in the high-performance pathway (76, 77). To that end, collaborative arrangements between research institutions and golfing bodies represent an opportunity to bridge the gap between science and the GP pathway (78). The national sporting organisation, *Golf Australia* (GA), regulated by *Sport Australia* (79) has operationalised a recently developed framework for such benchmarks. The *Foundation, Talent, Elite and Mastery* (FTEM) framework (24) illustrates the performance attributes that align with the 10 stages of talent development in golf (23). A unique feature of FTEM is the integration of its general and specialised phases with the active lifestyle, sport participation and sport excellence pathways. The additional phases in FTEM (relative to previous frameworks) allow a better understanding of the athlete transition between the participation and elite ends of the continuum. FTEM also has full inclusion of developmental support drivers at the sport and system level; but avoids chronological and training prescriptions (24). However, to date there are no physical or technical benchmarks to achieve within each stage.

The literature provides some technical and physical benchmarks that could be set as aspirational targets for development programs. From a technical perspective these include body-segment-relative rotational biomechanics, ground reaction forces and torques and club head presentation characteristics around impact (40, 80-82). From a physical perspective, balance, flexibility, strength, endurance and anthropometry benchmarks have been suggested (11, 12) These are typically based on data from elite golf samples and will be discussed in more detail in later sections of this review. To this end, many technical and physical measures have been shown to discriminate between sub-elite and elite ability levels, a trend seen across many sports (83).

However, until prospective, longitudinal research designs have been undertaken, benchmarks must be utilised with caution, as association does not equate to causation. Instead, the dynamic relationship between physical and technical measures and how these apply to an individual player over time needs to be understood. Furthermore, from a talent development perspective, individualisation of emergent technical aspects such

as swing style (84-86) and movement variability (87, 88) must be taken into account. Therefore, the need for individualised physical interventions based on athlete profiling is now apparent (10). As the evidence-base currently stands, a blended approach of utilising what is currently known and continuing to extend the knowledge base is recommended to inform performance interventions for golfers in the coming years (83).

Monitoring program effectiveness

One of the fundamental reasons for pre- and post-testing athletes is to gauge their progress in response to a training program (89, 90). For the golfer, this includes assessment of physical, technical and tactical measures to understand the athlete, and mechanisms of performance (8). A broad testing battery that includes these elements can efficiently address a breakdown in performance on both an individual and program level. This knowledge can allow physical and technical interventions to be optimised for the individual in a perpetual feedback loop (10, 91). This appears a worthy pursuit, as individualised, golf swing event specific, interventions have been shown to improve performance beyond general training (8, 20, 92). Read et al (2018) provide an exemplar of this approach in a case study of USPGA Tour player Justin Rose, using CHS, ball speed, carry distance and accuracy as competition performance measures to validate his S&C program between the years of 2013 and 2015 (8). Over this time frame, Rose achieved his over-arching goal to be able to carry his driver 300 yards on-course whenever needed, without losing his rank as the most accurate driver on tour. However, the prevalence of this approach on tour or in development programs is unclear. Furthermore, the body kinematic, ground reaction forces and physical improvements that underpinned Rose's success where not reported (although the S&C program is laid out in full detail). These additional mechanistic factors that allow the transference of newly developed physical capacities into technical capacity, and then competition performance, are of particular importance to the golfer aiming to make technical changes to their golf swing and need to be further investigated (27).

Monitoring for fatigue, injury and illness

Testing or monitoring the athlete is also used to ensure that, as a real-time feedback mechanism, the athlete is training in the so-called 'sweet spot' (93). This is typically defined where the athlete is training at a consistently moderately high training load (across physical and technical training) providing a protective effect against the likelihood of injury (94). The suggested biomechanical and training load causes of injury in golfers align well with prevalence and site of injury, see Figure 2.1 (52, 95, 96). Hence,

biomechanically relevant physical and technical tests can be a tool for early detection and injury prevention.

Monitoring individual sports requires different strategies to team sports (44) and items should be chosen systematically (97). Recent research has narrowed the scope of items and methods that are most appropriate for golf (98). Approaches to monitor the golfer can be divided into three main categories: pre-training readiness testing; daily data collection for monitoring; and periodic testing, either with surveys or direct testing of the athlete. Each has their own burden, benefits and appropriateness to each sport or athlete.

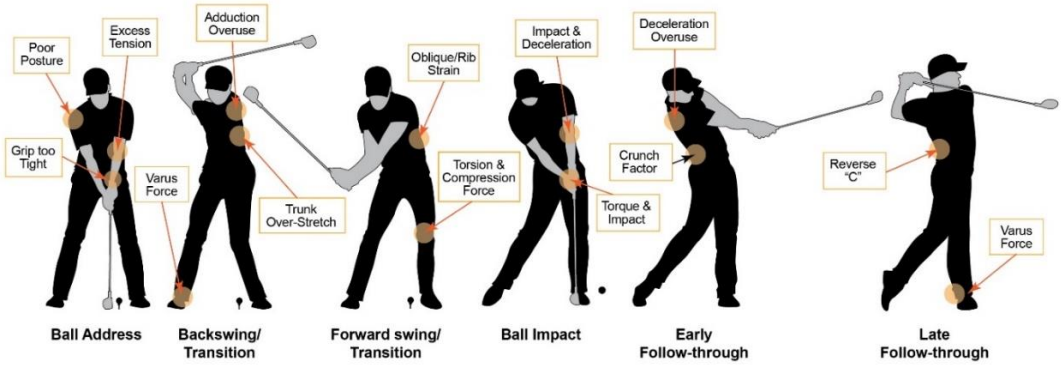


Figure 2.1 Site and typical cause of injury by swing phase, adapted from Cabri et al 2009 (52)

Across sports, pre-training readiness can be assessed using high-velocity movements such as vertical counter-movement jump (CMJ) (99) or drop jumps or high force movements such as a 1RM Mid-Thigh Iso Pull with force plates (89, 100). The practitioner establishes a baseline result from when the athlete is in peak condition and uses it as a benchmark for subsequent assessments. If, for example, an athlete falls 10% or more below the peak performance value (89). Whilst these tests have been used for the purpose of 'needs analysis' or to monitor program effectiveness in golf, training readiness is yet to be investigated in golfers. This gap should be addressed in future research as there is some evidence that fatigue and dehydration can reduce shot distance and accuracy by up to 10% (8, 101).

Daily data can be collected and used to determine the training dose-response relationship (102). These findings aim to educate the athlete and inform the practitioner to make regular individualised adaptations to the training regimen (89). Daily data can include subjective and objective internal and external training loads (94). Given retrospective recall for golf practice regimes have been validated, this can be done cheaply with low-technology options if needed (103). This data can be used to calculate the most effective training dose and potentially predict injury (104-106); although the

accuracy of these predictions is still being debated (107, 108). Self-report wellness items (109, 110) can also be used to ensure the athlete is responding optimally to training to avoid over-training or burnout (102). Importantly, the athlete burden and time commitment to monitoring must remain low to be viewed as sustainable for elite golfers (98). Equally, practitioners must view all athlete monitoring through a cost-benefit lens (111). Thus far, a Delphi-study by Williams et al (2018) to inform the development and feasibility of a golf-specific load monitoring tool provides a list of promising items for the daily athlete monitoring of golfer's (98). The total number of development hours across a month was predictive of official golf world ranking within a cohort of 14 tour players (112). Similarly, a study of 111 aspiring elite amateurs in the United Kingdom showed that the total number of shots during long game practice was predictive of HCP improvement over an 11-month period (R^2 = .041) (113). However, more evidence is needed to inform individualised practice and tournament volume thresholds with regards performance or injury for any golfers.

Periodic testing, can be undertaken from a physical and technical perspective but also can include surveying mood and recovery status via questionnaires (114), comprehensive wellness scales (109), although these are yet to be validated with golf performance. Movement screenings can be used for injury prevention and optimising physical and technical development of the golfer (15, 98), although prospective studies are needed to determine their efficacy for injury prevention (46). Movement screenings will be discussed in a later section of this chapter. Ultimately, a blended approach to the monitoring of golfers, combining pre-training, daily and periodic assessments, may be warranted – justifying further validation studies. Upon which, the feasibility for each monitoring option needs to be determined for any given golf development environment (98, 111).

2.3 Research design in golf performance research

2.3.1 What to measure?

A blend of physical, technical and competition measures are required to understand the underpinnings of a golfer's performance. Physical measures can quantify the traits of a golfer as well as the level adaptation (e.g., strength and power gains) stimulated by an S&C program. Studies that report the programming *and* physical and technical improvements gained after golf-specific interventions provide the multi-disciplinary team with more specific information that can be applied to the needs of individual golfers – as results vary somewhat across interventions in the golf literature (54). Therefore, a test battery, or *combine*, should endeavour to include a measure for all physical traits that

have shown a relationship to technical or competition performance, to create a physical profile of the golfer (15). Strength, power, flexibility, balance, motor control, anthropometry and aerobic capacity are all indicated as physical parameters worthy of assessment in golf (8, 14, 15).

Technical measures are required to determine the validity of physical measures or interventions. They are also important for understanding the mechanisms of performance for an individual golfer. Where gaps in the literature are present, group analysis is needed to determine the role in performance of both physical and technical measures. Group analysis is also useful for overall development program effectiveness (51). Body kinematics, *ground reaction forces* (GRF), club kinematics, ball kinematics, skill and competition performance are broad technical parameter categories that have been investigated in the golf literature. Greater detail will be provided on each of these physical and technical parameters later in this review.

2.3.2 Sampling & analysis

Findings from studies that use a homogenous sample of golfers (e.g., young elite males) cannot necessarily be generalised to other golfing cohorts (15). Many of the gaps in golf research exist on this basis. Indeed, the literature provides ample evidence to suggest that golfers of different gender (115), age (116, 117) and ability (11, 40) possess different physical and technical traits. Hence, the combining of age, gender or ability levels for analysis could conflate the differences between these groups. This can leave unintended gaps in understanding missing important details that may apply differently to each cohort within the overall sample. This approach, along with sparse participant characteristics is reasonably common in golf research (118-122). It is unclear whether authors take this approach for simplicity, increased sample size, or simply under-valuing the heterogeneity across golf cohorts.

In practice, end-user practitioners or programs are interested in either individual athletes or a squad of similar athletes, (e.g., sub-elite youth squad or clinic for older golfers). As such, the practitioner needs to understand which athlete published research findings apply to (51). Therefore, golf research needs to ensure that both internal and external validity is achieved via careful sampling, analysis and reporting of participant characteristics and results (123). Therefore, large heterogenous sample are advantageous to extend the evidence base on GP.

2.3.3 The influence of golf warm-ups

Given the importance of a standardised preparation for testing and the evidence of the variable effects of different golf warm-ups, the content and timing of the golf swing warm-up must be given due consideration by the tester. A warm-up up has been shown to increase clubhead speed (CHS) (124, 125), maximise drive distance (126), ball velocity (BV), centredness of strike and lead to straighter swings paths (127). For context, it has been reported that completing a warm-up regularly can increase CHS by 7–10 m/s (24.0 %) which equates to an estimated seven shot reduction in *handicap* (HCP) (124). Given this remarkable effect of warm-ups on GP, researchers must look to standardise warm-up procedures. Considerations include exercise selection, intensity of the warm-up, time point prior to measurement, and duration.

Exercise selection for warm-ups is important, given both positive and negative effects on performance have been found across different protocols. For example, a study on male college golfers determined that the addition of a total body passive static stretch routine, prior to a dynamic warm-up, should be avoided before practice or competition. The addition of passive stretching resulted in loss of distance (-5.62 %) accuracy (-31.04 %), CHS (-4.19 %), and consistent ball contact (-16.34 %) with driver, compared to active dynamic warm-ups with golf club protocol (128, 129). This was seen both acutely and over time, with the CHS, taking 30 minutes to recover, the only variable to adapt to this protocol and return to previous levels. Theoretical explanations for this acute decrease in performance include a more compliant muscle tendon unit, decreased neuromuscular reflex sensitivity, and neural inhibition attributable to the static stretch treatment (130). Conversely, an increase in CHS of 2.25 mph (1.01 m/s) (ES = 0.16) has been gained one minute after the use of just three CMJs (CMJ) intervention was recorded (131). This post-activation potentiation intervention is attractively efficient. The benefits were likely caused by post-activation potentiation, rather general dynamic warm-up effects, given an increase in temperature has the opposite effect of post-activation potentiation on muscle contractile function (132). The duration of the *warm-up effect* has also been investigated with 18 Low-HCP males in their 20's demonstrating superior enhancements from a dynamic stretch protocol, compared to both static stretch and no-stretch protocols. The dynamic stretch protocol showed improvements in five-iron CHS (4.2 mph, 1.9 m/s), ball speed (7.8 mph, 3.5 m/s), impact location and a straighter club path. Furthermore, these benefits held for at least 30 minutes after the dynamic stretch protocol (127). Warm-ups including resistance exercises produce similar effects to dynamic warm-ups (55, 133).

Given the potentially positive or negative effects on performance, testers must be clear on the outcomes they seek from the warm-up protocols selected. Testers may wish to

optimise results, observe the golfer in their natural state (i.e., allow the golfer to undertake their typical 'self-selected' warm-up protocol), or mitigate the negative effects of poor warm-up routines when standardising their pre-test protocols. Warm-up protocols can then be selected accordingly.

2.3.4 Selecting a representative shot for analysis

The definition of a golf shot that represents a golfer's current typical performance varies between studies. The participant is typically given between three and five attempts to produce their best shot, with four trials proven adequately reliable for group analysis (*Intra-class coefficient* (ICC) = 0.971) (36, 39, 134-136). A lower number of trials are more efficient for broader test combines and prevent fatigue effects. However, one study used 8 shots (47) and between 10 and 15 trials may be needed to determine what is typical of a player biomechanically due to inherent movement variability in the golf swing (84, 88, 137-139).

Representative shot selection is also determined by other factors such as test instructions, rules and expert opinion. For example, the instruction 'hit the ball with Driver as though they are in a competition where distance and accuracy are both important' influences the participant (140). Rules for accuracy of the driver shot in studies have required the ball to land within a 37 m-wide fairway (136) or 40 m margin (47), based on launch monitor feedback. The highest swing speed has also been used as the criteria for shot selection (134). Yet another study consulted an experienced Professional Golfers Association (PGA) Teaching Professional to ensure appropriate criteria for the participant's swing type, (i.e., modern swing versus classic swing) (135). Therefore, the greatest distance within a 40 m fairway, judged by a PGA Professional via launch monitor feedback will be used in this PhD study.

2.4 Assessing physical parameters in golf

2.4.1 Forming comprehensive combines for golf

The Australian Institute of Sport's key publication on the topic makes several recommendations for physiological tests for elite athletes in multiple sports (e.g., Australian Rules Football (AFL), Cricket, Tennis and several Olympic sports) (141). However, golf is not included, therefore recommendations from key reviews form the basis for current best practice. Recommendations include: investigation into how successful players' physique and technique are related and how these translate to distance and accuracy (14); combine these findings with detailed game statistics, shot

intention and environmental constraints to learn the processes leading to lower scores (14); an informed multi-disciplinary approach that individualises interventions for the golfer with a perpetual and systematic feedback loop (8, 10{Sheehan, 2019 #2682, 15). The benefits of anthropometrics, flexibility, strength and power on GP measures for adult male golfers have been demonstrated through multiple analytical techniques across studies (8, 11, 12, 66, 142). The extent to which these findings can be directly applied to female or junior populations is unknown (15). Furthermore, interpreting combine outputs requires awareness that results from group measures may not necessarily hold true for the individual (89). Ideally, subsequent to group-based studies, mechanistic relationships can be assessed with individual longitudinal repeat measures and/or A-B testing of interventions to add a further layer of individualisation (10, 58). There are also a limited number of studies that demonstrate temporal associations between changes in physical and technical measures with competition performance (28, 29, 143). However, these studies have methodological limitations and more longitudinal investigation is needed (54).

To ensure content validity of a testing protocol for golfers, an effort must be made to include an array of both physical, technical and competition measures. The totality of the golf literature covers many physical-technical-performance relationships that bear consideration when forming a comprehensive golf combine. Furthermore, a synthesis of the literature suggests a series of steps that can be taken when constructing a comprehensive combine for golf:

1. Form a collaborative group of clinicians, practitioners and researchers to develop the combine (98, 144).
2. Establish the reliability of each test within the combine (49, 145).
3. Create norms/benchmarks for different cohorts need to be established to determine what average, below average and above average thresholds are for specific cohorts of athletes (8, 15, 40, 146).
4. Establish the validity of the relationships between physical test score and their corresponding technical or competition performance measures, (e.g., quantify correlations or group differences) (14, 27, 50, 54).
5. Establish further measurement properties, such as sensitivity and feasibility for each test (81, 147).
6. Establish the concurrent validity (e.g., measurement error) of each test against previously established gold standard tests (148, 149).
7. Utilise the combine to assess a group of athletes and create individualised profiles to inform bespoke interventions for each athlete (8, 31, 34, 150).

The primary challenge when establishing an evidence-based combine is that most studies only assess between one and three parameters, (e.g., Power and CHS). Therefore, an aggregation of cohorts and parameters, filtered by research design, is required to determine a hierarchy for parameter-inclusion for a given cohort. This work is yet to be done. However, several studies have utilised somewhat comprehensive combines (i.e., investigating multiple physical and technical parameters). These exemplify the additional mechanistic findings that are derived from analysing a broader range of parameters. These broader studies mimic the needs of development programs to inform multi-disciplinary teams, and indeed many were undertaken in existing development programs (15).

Once parameters are selected, the most effective tests need to be determined for each parameter. This can be achieved with a hierarchical analysis of the measurement properties of all the available tests per parameter. Established measurement properties for a combine can better inform the end-user how to interpret results and the utility of tests for cross-sectional and longitudinal analysis. A summary of physical parameters and available tests from the golf literature is provided below.

2.4.2 Movement Screens

Movement screens are developed to test an individual's movement competency over a set of exercises that have a specific criterion (151). The aim of each exercise test is to identify functional movement deficits that may predict performance limitations or injury risk (152-155). Movement screens are typically conducted by physical therapists, fitness personnel or golf coaches (145, 156). Typically, these screens provide test-by-test scores and an overall composite score as a general indication of golf readiness. It is unlikely that a movement screen will describe the majority of variance in an athletic skill, with physical fitness qualities likely to dominate. For example, upper-body strength and power are known to explain a large portion of the variance in CHS during a golf shot (39). Movement screens that have been investigated in the golf literature are discussed below.

The Functional Movement Screen

The *Functional Movement Screen* (FMS) was designed by Gray Cook as a system for a simple and quantifiable method of evaluation basic movement abilities (153, 157). The aim of the FMS is to inform injury prevention and performance-improving interventions (158, 159). Whilst FMS has only been directly investigated in the sport of golf in one study, numerous studies have examined the relationship between the FMS and performance in other sports (160-163). It's also purported that the FMS has also provided

a conceptual foundation for the establishment of the golf specific functional movement screen (GSFMS) discussed later in this chapter (164).

The FMS uses seven movements to assess functional movement: Unloaded Deep Squat, Hurdle Step, In-Line Lunge, Shoulder Mobility, Active Straight Leg Raise, Trunk Stability Push-Up, Rotary Stability, and three clearing examinations, as described in previous studies (165, 166). Each of the seven movements is scored from zero to three. The greatest possible score is 21 (167). One study investigated whether FMS scores or 1 repetition maximum (1RM) squat – normalised to body mass – is related to athletic performance, specifically in 15 male and 10 female Division I golfers. Athletic performance was measured with: Sprint Times, Vertical Jump (VJ) Height, agility T-test times, and CHS. Trivial to small correlations existed between FMS and 10 m Sprint Time (r = -0.14), 20 m Sprint Time (r = -0.11), VJ Height (r = 0.25), agility T-test time (r = -0.15), and CHS (r = -0.06). Whereas the 1RM in the squat was very strongly positively correlated to 10 m Sprint Time (r = -0.81), 20 m Sprint Time (r = -0.87), VJ Height (r = 0.87), agility T-test time (r = -0.76), and CHS (r = 0.81). Similarly, only weak relationships existed between any of the individual tests and the athletic performance tests. The lack of relationship suggests that FMS is not an adequate field test and does not relate to any aspect of athletic performance, whereas normalised 1RM squat strength does (167). With only one study on the topic, complete dismissal of the utility of FMS in golf is not yet warranted. However, given movement screens have since been specifically designed for golf, future research effort should prioritise these golf-specific movement screens.

The Golf Specific Functional Movement Screening

In the mid-2000's the *Titleist Performance Institute* (TPI) formulated what is now titled, the *Golf Specific Functional Movement Screening* (GSFMS) (168). The GSFMS (also referred to in the literature as the Level 1 Physical TPI Screening) is central to a commercially available certification system. The GSFMS has been investigated in three peer-reviewed studies. The first of these investigated correlations between the GSFMS and 14 swing faults (which has since been reduced to 'The Big 12'). This study found some statistically significant correlations between several physical tests and swing faults (36), thereby establishing some validity to elements of the GSFMS. Two levels of independent variables (physical tests and golf swing faults) as described in TPI's Level 1 Certification. First, the variables were examined for significant relationships between the two levels using the Fisher's exact test. Then, an odds ratio was used to determine how likely the second level (golf swing faults) of independent variables might occur if the first level (physical limitations) were present (36). Some of the physical-test-swing-fault combinations showed higher odds ratios for those who cannot perform certain physical

tests and the likelihood they will present with a particular golf swing fault as compared to those who can. Findings included a golfer who is unable to perform: an Overhead Deep Squat is two times more likely to early hip extend in the golf swing; a Toe Touch is six times more likely to early hip extend; Balance on their left leg is three times more likely to early hip extend, lose posture, and slide during the golf swing; a Bridge on the right side is five times more likely to early hip extend, six times more likely to lose posture and two times more likely to slide during the golf swing (36). However, several major methodological limitations exist with this study and the protocols employed, which were not mentioned by the authors: 1) Reliability was not reported for any physical or technical test used in this study – which is problematic as, for example, the Single Leg Bridge Test and Pelvis Tilt Test have previously shown poor reliability in other settings (145); 2) The 14 swing faults are yet to be validated as detrimental golf swing features; and 3) Golf swings were assessed with limited criteria using 2D video analysis – which is far less accurate than most 3D systems. These limitations cast doubt across all findings in this study.

The second of these studies investigated the correlation between the GSFMS and the TPI Level-2 Power Screening (169). As with other movement screens, the overall or composite score of the GSFMS was not as informative as some of the isolated tests within it. This likely due to the specificity of individual tests to power tests with similar biomechanics. Nonetheless, Total Score had a moderate positive correlation with Vertical Jump (r = 0.34). The 90:90 Shoulder Test had moderate to strong positive correlations with Vertical Jump (r = 0.42), Sit Up and Throw (r = 0.43) and Seated Chest Pass (r = 0.57). The Single Leg Stance had moderate to strong correlations with Vertical Jump (r = 0.62) and Seated Chest Pass (r = 0.48). The Overhead Deep Squat had strong correlation with Vertical Jump (r = 0.54). The Bridge with Leg Extension had moderate positive correlation with Vertical Jump (r = 0.47). Finally, the Toe Touch test had strong correlation with Seated Chest Pass (r = 0.56) (169). However, many of these correlations display no biomechanical logic (e.g., shoulder flexibility and vertical jump share no logical relationship). Therefore, a sound mechanistic logic should be presented for findings from movement screens. These results are further confounded by the combining of genders for analysis and poorly described participant characteristics – creating confusion as to who the results apply to.

The most recently published study investigated the correlations between the GSFMS composite and individual element scores and variety of technical measures with a small heterogenous sample (37). The interrelationships between the physical measures were also investigated. Very strong relationships exist between the GSFMS composite score and: HCP (r = -0.78); CHS (r = 0.70); Ball Speed (r = 0.67); and Peak Pelvis Rotation

Speed (*r* = 0.69). Individual tests demonstrated strong to very strong bivariate relationships: 90 90 Golf Position and CHS (*r* = 0.72), Ball Speed (*r* = 0.78); Seated Trunk Rotation and Peak Pelvis Rotation Speed (*r* = 0.61). Other notable correlations included: Single Leg Balance and HCP (*r* = -0.72); Torso Rotation and HCP (*r* = -0.64); torso rotation with peak pelvis rotation speed (*r* = 0.74) (37). This study improved some of the limitations from Gulgin et al (2014), such as using a wireless 3D biomechanics (K-Vest) system, including validated Trackman measures, and attempting to establish intra-rater reliability for the physical measures (*r* = 0.97). However, this reliability measure is questionable as all measures used are rated as categorical measures and inter-rater reliability would be more informative for use in the field. The same yet-to-be-validated 'swing faults' were used as Gulgin et al (2014) as well as the omission of four GSFMS tests. The sampling of this study was also problematic – as the 11 golfers were not just heterogenous in ability level but also gender and age (18-70 years) – therefore age is a potentially confounding variable for results.

Despite its apparent feasibility and good utility in the field, higher quality, larger sampled studies are required to determine the veracity of the GSFMS. A strength of the GSFMS is its high correlation with HCP and alignment with test batteries that assess further important parameters, such as power. The primary limitations of the GSFMS to date are the lack of established reliability and adequate-quality validation studies to understand the relationship to technical measures. These methodological limitations can lead to a scenario where poor decisions are made for the golfer by the multi-disciplinary team. The prevalence of the GSFMS in the field deems that these weaknesses should be addressed in future research.

The Golf Movement Screen

The *Golf Movement Screen* (GMS) was designed specifically to examine the movement competency of golfers. The GMS consists of 10 exercises: Trunk Inclination, Seated Hamstring, Seated Thoracic Rotation, Rotation Over Fixed Foot, Lunge, Overhead Squat, Basic Balance, Mini Squat, Diamonds, and Side Plank (49). Each exercise is rated across a variety of the most important body segments that contribute to the movement. The body segments are rated and scored with a pass (1) or fail (0), which accumulate to give a total score for each exercise. All exercise scores are then totalled to provide an overall GMS composite score (0–93) (50).

The authors and expert contributors to the GMS purport it has the potential to be superior to the GSFMS screen, as it: has better established associations with pelvis, thorax, and spine during the golf swing; possesses a more sophisticated rating system (50). A further advantage is that the GMS protocol has been assessed for reliability (49). For the inter-

rater analysis, one experienced and three novice raters examined the videos of ten golfers of varying ability preforming the GMS and were asked to rate their movement competency. The composite score had good intra- and inter-rater reliability with ICC = 0.94 in both cases. The total score of each test included in the GMS achieved good intra-rater reliability (ICC = 0.76–.94), with nine out of the ten tests achieving good inter-rater reliability (ICC > 0.75). Average kappa values for the intra-rater analysis for each body segment demonstrated moderate to very good reliability across the GMS (k = 0.4 – 0.84); however, the inter-rater reliability reported for most of the segments was only fair (k = 0.20 – 0.37) (49). The GMS has good levels of total score and total exercise score reliability when examined by both experienced and novice raters. An experienced rater can reliably use total score, total exercise score and body segment scores; whereas, novice raters should use body segment scoring with caution (49).

The GMS has also been assessed for validity against wide range of technical measures both cross-sectionally and longitudinally with 62 high-level adolescent (male and female) golfers. Trunk inclination, basic balance, squat and side plank exercises had a small to moderate positive correlations with X-factor at impact (r = 0.25 – 0.33). Spine side bend at the top of backswing had a small to strong correlation with nine of the 10 exercises and total GMS score (r = 0.26 – 0.53). As a comparative reference, when examining the validity of the Resistance Skills Training Battery in adolescents, it was concluded that a relationship of r = 0.40 between movement competency and muscle fitness indicated acceptable construct validity (170). With valid relationships established with these biomechanical factors, it is intended that the GMS will have the ability to specifically direct training and coaching interventions. However, given the established differences in physical (171) and technical (137, 138, 172, 173) attributes between male and female golfers, the strength of the relationships presented in this study are not clear for male or female cohorts, as the genders were combined for statistical analysis. Furthermore, it is not clear how all of the body kinematic measures selected influence golf swing performance, given the inter-individual differences in sequencing between golfers (86).

Longitudinally, temporal associations were shown between the improvement of GMS scores and HCP. Twenty-four male and 12 female golfers (14.38 ± 2.88 years) were included in the study. The golfers completed the GMS on three testing occasions over a two-year period. Total GMS scores improved year-on-year from 41 ± 13 on entry, to 52 ± 13 in year one, and 63 ± 14 in year two. HCP also improved from 6 ± 5 on entry to 2 ± 4 in year 2. The findings suggest that golfers in a talent development program are able to improve their movement competency, and that the GMS has the sensitivity to detect these changes (143). The factors that lead to these changes are unknown as training interventions were not reported and given the young age of the group of golfers,

biological maturation was likely a strong influencer (174). The mechanistic influence of the improved GMS scores on the previously identified biomechanical markers were also not reported.

Future research should determine the overall contribution of the GMS to golf proficiency. Ascertaining whether the GMS can predict swing mechanics and GP when combined with additional measures such as strength and power would be a worthy approach. The appropriateness of the GMS for different cohorts such as older golfers must also be established. Nevertheless, the GMS can explain some of the variance in swing mechanics and its practicality and feasibility suggest it will have reliable utility in the field.

2.4.3 Anthropometry

Typically, studies that investigate the relationship between physical capacities and GP will take basic anthropometric measurements of participants and then use this information for three main purposes: To determine whether anthropometry itself has any correlation or predictive power for the outcome measures; to ensure that groups are evenly matched in experimental studies; to create derived metrics such as torque or relative power which uses limb lengths or body weight respectively to potentially discover more highly correlated variables to the outcome measures. Although some anthropometric measurements (e.g., height) are not trainable, some of these fixed measures have shown potential for talent identification for the sport of golf. For example, sit height and arm length were strongly correlated ($r > 0.7$) with CHS and CD for five-iron and driver in Canadian National Team golfers (66), although genders were combined for this analysis – which is likely to inflate the importance of limb length due to the typically longer-limbed male golfers. Conversely, some measurements can potentially inform training and dietary regimes if an advantage can be gained, such as body weight or composition. The most analysed anthropometric measures are in Table 2.1. Whereas the anthropometric measures collected for participant characteristics are provided in Table 2.2. The data in these tables are drawn from the analyses in Chapter 3 and, to the authors knowledge, include all available peer-reviewed journal articles at the time of publication.

Table 2.1 Prevalence of anthropometry measurements for GP

Anthropometric Measurements for Performance	# Studies Present
Height/Limb Length	13
Body Composition	5
Somatotype	1
Muscle CSA/Symmetry	1
Weight	1
BMI	1

Table 2.2 Prevalence of anthropometry measurements for sampling purposes

Anthropometric Measurements for Sampling	# Studies Present
Weight	118
Height	114
BMI	14
Body Composition/Lean Body Mass	9
Arm-Span/Length	6
Seated/Sitting-Height	2
Biacromial-Width	1
Girths	1
Upper-Body Mass	1
Upper-Body Length	1

Across studies, small positive correlations and coefficients of determination are commonly found between anthropometry and technical measures. A study of 40 Low-HCP golfers showed that height (R^2 = 0.257) and arm length (R^2 = 0.204) were significantly related to CHS; weight (R^2 = 0.048) and shoulder width (R^2 = 0.041) were not (175). Conversely, a study with 33 male elite golfers showed body mass was related to CHS (*r* = 0.51) (176). A study of somatotype of 100 male Japanese golfers across six different playing abilities showed a tendency toward increased mesomorphy for higher skill levels (177). However, typically most anthropometric measurements are less correlated to GP than measures of power and strength. For example, a study comparing 10 low- and 10 high-HCP golfers demonstrated that anthropometry had little influence on CHS and was similar between ability levels (12). This suggests golf is likely to be suited to many different anthropometric statures. Therefore, in this PhD study, with a large heterogenous sample that includes adolescent golfers, anthropometric measures will only be collected to describe participant characteristics.

2.4.4 Flexibility

Flexibility and mobility measures vary widely in their relationship to technical measures across studies. CHS and HCP have shown no or negative relationships with hip internal (12, 142) and external rotation mobility, measured at 90° supine (142). A small, combined genders, study of Low-HCP golfers showed trivial or inverse correlation between *X-factor* (defined as the relative or differential rotation of the golfer's upper body to hips (178, 179)) and thoracolumbar rotation (*r* = 0.01) and hamstring flexibility (*r* = -0.73), whilst maximum pelvis rotation *range of motion* (ROM) in the back swing and hamstring flexibility was moderate (*r* = 0.53) (180). Rotational trunk flexibility, measured on a trunk rotator machine, had a negative correlation with CHS (*r* = -0.27) (45). Furthermore, the commonly-used sit and reach test has produced trivial to small non-significant positive

or even negative correlations and driver CHS (*r* = .04 – -.74) and carry distance (*r* = .09 – -.72) with driver and five-iron (48, 66, 181).

Although relevance of X-factor, purported to be a key power source in the swing (182), has come under question in the most recent decade (which is discussed on page 64) – the lack of meaningful relationships between these flexibility measurements and X-factor is surprising. This suggests that either the influence of flexibility on performance is more nuanced than that of strength and power, or, that many flexibility assessment methods lack criterion validity. For example, one small-sampled study found that passive hip rotation ROM assessments lacked convergent and predictive validity of the dynamic kinematic hip rotation during a golf swing, when captured with a high-speed opto-electric *three-dimensional* (3D) motion capture system (183). Furthermore, it has been found that improvements in mobility do not automatically or instantly transfer into functional movement patterns unless additional time is devoted to 'grooving' new motor patterns (184).

There is now some evidence that other factors such as neuro-muscular organisation of the agonist-antagonist relationship that occurs around a given relevant joint, allows optimised rate of force development and intersegment sequencing (140). This may have a greater influence than increased ROM *per se*, and therefore require different assessment techniques and interventions to obtain. This could explain why the inclusion stretch-based programs, especially if golf-specific and/or part of a broader S&C program still typically have a positive impact on GP (185). Whereas the assessment methods prevalent in the scientific literature only measure end ROM, which may not actually change. Instead, neuromotor control parameters (i.e., muscle recruitment onset time, amplitude, and intersegment latency) are important elements of lumbopelvic-hip movement and coordination during the golf swing but are often not measured in studies on flexibility (186). This neuro-muscular perspective could also explain why in studies where significant flexibility gains are made concurrently with improved swing performance, increased swing ranges of motion are not seen (187). Conversely, the overactivation of the hip external rotators (i.e., piriformis, gluteus maximus in the lead leg) which can be measured with surface *electromyography* (EMG) (188), can limit for hip internal rotation (186). Therefore, the improved pliability of muscles and functioning of the kinematic muscle pair, can allow for greater rate of force development in the prime movers and potentially avoid the inefficiencies that accompany undesirable swing characteristics (36).

The neuro-muscular view of flexibility for golfers was demonstrated in the treatment of 100 elite golfers with shortened hip flexors (140). A combination of trigger point therapy with a practitioner-assisted 60 s stretch, followed up with one week of dynamic *medicine*

ball (MB) exercises was more effective than following up with home-based stretching of this muscle group (140). The benefits of this neural reorganisation of the lumbo-pelvic region transferred into improved hip rotation in the downswing (140). Positive effects have been shown with PNF training demonstrating CHS increased (7.3%) from baseline to post-test (185). Similar improvements to driver distance and accuracy were found following an individualised special composite stretching program (92).

Given the importance of measurement method, flexibility scores could provide greater inference to GP via highly golf-specific flexibility tests that utilise thresholds. One study demonstrated that below the threshold of 20° internal hip rotation, professional golfers exhibit increased lumbo-pelvic movement during the downswing swing (186). This is likely to be less efficient and more injurious. Furthermore, it has been shown in male tour players with decreased lumbar spine extension, lead hip internal rotation, and lead hip FABERE's distance positively correlated to a history of low back pain (189). Comparatively, lumbar spine flexion and measurements in the rear hip did not (189). The authors posited that loss of ROM in these joints could be multi-factorial, with possibilities including: capsular tightening; hypertonicity in the lead hip external rotators that inhibit internal rotation; or lumbar extension being limited by a multitude of factors (189). Another study found a group of sixteen Mid-HCP (Age = 48.6 ± 7.4 years, HCP = 9.1 ± 4.6) male golfers with a history of lumbar pain demonstrated significantly less trunk extension strength (at 60 °/s), left hip adduction strength and trunk rotation toward the nonlead side when compared to an age and ability matched non-symptomatic group (190). These studies provide evidence for quantitative and qualitative functional thresholds with utility for enhancing GP.

Addressing joint restrictions often requires a multi-faceted approach. The multiple tissues involved may require different techniques and therapies to regain or retain healthy ROM. The suggestion that hip and lumbar spine stretching may reduce episodes of low back pain in golfers is speculative, as the ability of stretching to regain lost ROM is unclear (189). Therefore, a segment-specific threshold approach with direct application to resolving the cause of pain, restriction and poor biomechanics is superior to global measurements of flexibility. This notion is therefore in support of the 'joint-by joint' approach suggested by Boyle (2012), where joint-specific issues of ROM and stability need to be addressed to optimise performance and reduce likelihood of injury (7).

In addition to considering joint ROM and stability, the neuro-structural perspective of flexibility suggests the golfer's priority is to maintain dynamic ROM under force, amplitude and directions comparable to the golf swing. When trunk flexibility, X-factor and CHS were analysed in 15 Low-HCP male golfers, three flexibility variables were associated with faster CHS. Trunk and lower trunk left and right axial rotation assists with

shoulder girdle movement at maximising CHS through segment summation (40, 191, 192) and may allow for an effective X-factor stretch in the downswing (136).

Despite the uncertainty of how improving or maintaining flexibility assists swing mechanics, one study outlined an effective periodised regime for 48 adolescent boys and girls between 14 and 18 years across a competitive season (119). The program progressed from five days per week of static stretching to three days per week of PNF stretching, resulting in consequential improvements in shoulder horizontal flexion and extension, lumbar spine flexion, and ankle dorsiflexion and plantar flexion over the control group who did not stretch (119). Details of the program were sparse, but the study did at least show some feasibility to adolescents undertaking regular stretching in-season.

In conclusion, the specificity of the flexibility measurement appears paramount to further understanding the effect of this physical parameter on technical performance. Dynamic force, body segment, swing event positions, and individual diagnostics influence the validity of flexibility measurements and therefore need to be considered when selecting ROM tests. Identifying and establishing thresholds, or reductions in baseline flexibility due to dysfunction, appear more important than examining flexibility as a continuous variable. Continuous measures of flexibility exhibited lower or no correlation to performance. These factors, in part explain the wide variation in results in flexibility measures in the literature to date. Future prospective studies should look to validate flexibility measures (including active ROM) against decreased pain or biomechanics.

2.4.5 Balance & postural control

Although there is yet to be consensus on the best quality method for assessing balance for golfers, there are many valid and reliable options available to the researcher or practitioner. Test methods can be low or high-technology and may be selected based on the strength of relationships with technical measures reported for specific age and ability cohorts in the literature. For instance, moderate negative-correlation have been demonstrated between balance and average score in competitive high school aged golfers using single leg stork stand test (r = -0.31) (193). Whereas the Balance Error Scoring System Test (BESS test) score and average distance for five male college subjects showed a very strong relationship (r = -0.85) (48). Similar results were found in 18 club golfers in their 30's and 40's, using a modified stork test and found that average balance duration of both legs (r = 0.56), left leg (r = 0.62) and right leg (r = 0.49) were all correlated to drive distance (194). These results show that low or high-tech options have the ability to discriminate ability and performance in this younger age group and are therefore worthy of test selection.

Older golfers demonstrate different physical and technical traits to their younger counterparts and may therefore require different balance assessments. Being a target based sport, golf requires good balance and precise control of posture for the swing and walking the uneven terrain of the course (195). Therefore, in the older golfer, the golf-balance relationship may well be bi-directional. Repeated golf practice and play may enhance balance control confidence in its older participants (195) and balance training may also improve GP (134, 196). I appears that golfers in their mid-sixties have better balance than their age-matched counterparts (197), similar to that of tai Chi instructors or 20-year-old students. These benefits were empirically measured with: Static and Perturbed Single-Leg-Stance and Forward-Lunge tests; improvement in knee-joint proprioception; faster reaction times; and the ability to lean further with better control without losing stability (197, 198). However, in the latter of these studies, the difference in age between the two cohorts was approaching statistical significance with the golfers mean age 66.2 years (± 6.8 *standard deviation* (SD)) and the control group mean age 71.3 years (± 6.8 SD) (197). Therefore, a longitudinal prospective controlled study would be needed to quantify effects of golf participation on balance in older golfers. Other tests such as the Functional Reach Test, Sensory Organisation Test and Modified Activities-Specific Balance Confidence (ABC) Scale have been used to assess the balance of golfers aged over 60. Positive correlations between these measures reveal the importance of balance control under reduced or conflicting sensory conditions in older adults. Balance confidence in daily activities and sensitivity to differences between golf and non-golf cohorts show utility of these tests for older golf populations (195).

Recently, researchers have gone further to understand the mechanism of good balance in expert golfers, utilising otoneurological testing with video head impulse posturography, and rod and disk tests. These tests were employed alongside a swing session procedure, in which performance was measured by means of the Flightscope X2^{TM} doppler-radar launch monitor system. The study found that relative to non-experts, expert golfers demonstrated a high-level of visual-independency – which may be functionally related to an effective motor strategy preferentially not referring to an inappropriate reliance on visual input (199). Investigating the visuo-spatial nature underpinnings of skill execution can potentially lead to more specific skill training for golfers. Further evidence that tests of postural integrity have their place in competitive golf is demonstrated with measurable shrinkage (height-loss) during golf round simulations (200). Mean shrinkage after playing nine holes was 2.53 mm compared to 1.78 mm for those who merely walked the same distance. Shrinkage was even greater when the golfer carried their clubs bag, at 4.76 mm over nine holes (200). Therefore, balance tests with higher sensitivity, specificity and addition of a postural component may be employed to make new discoveries, particularly with elite golfers.

However, technology-based balance tests do not always provide better information to the practitioner. The highly accurate Biodex Balance System (*Shirley, New York, USA*) (201) found only trivial correlations between balance and CHS & CD with driver and five iron in 101 recreational golfers (181). Conversely, the Modified Stork and Single Leg Balance Test, for maximum time (capped at 37 s) correlates with both scoring average and drive distance in 56 high-school aged golfers (193, 194), has established test-retest reliability (ICC = 0.81) (66) and has good utility in the field due to its simplicity. Single leg balance tests, eyes open and closed, when undertaken on 3D force plates for assessment of vertical, anterior/posterior and medial/lateral ground reaction forces have shown only statistical significance for discriminating proficiency levels for right leg eyes open anterior/posterior & medial lateral GRF (11). These results seem to suggest that simple field tests of balance do not possess inferior measurement properties.

Given the reliability and convergent validity of other low-technology field tests of balance, the highly investigated Modified Star Balance Excursion Test (MSEBT, later truncated to SB) appears to be a worthy candidate for golfers. The MSEBT was recommended for golfers in a recent narrative review, is employed in the field of elite level golf (8) and displayed robust measurement properties as reported in a recent systematic review (202). Mechanistically, the MSEBT combines single leg balance with body rotation and a flexibility challenge of maximal reach. This combination provides initial face validity by mimicking features of the golf swing. This test will involve a participant assuming a unilateral stance and performing the posteromedial, medial, and anteromedial excursions on a commercially available purpose-built mat (although measured tape lines on the ground will suffice). Reach distances can also be considered relative to leg length and expressed as a percentage according to the formula: *relative reach distance = reach distance/leg length x 100* (203, 204).

In summary, balance and postural integrity is important for golfers of all ages, gender and ability. Good balance in the golf swing is underpinned by the integration of physiological abilities and technical prowess, both of which are potentially trainable. There are multiple methods available for the assessment of golfers' balance and posture both in swing and on-course. Any test of balance and posture should be selected for its feasibility, validity, accuracy and appropriateness for the specific golfing cohort. The validation of physical balance tests concurrently against in-swing balance performance is needed. Prospective longitudinal studies are also needed to better understand the influence of balance on GP and how this may vary across cohorts. Although many technology-heavy options for balance testing are available, the field tests appear superior due to their discriminant and convergent validity to GP and excellent reliability.

Therefore, it appears that technology-based balance tests are only necessary when specific balance or postural indices are sought after.

2.4.6 Motor control

In golf, investigations into motor control are either *in-situ* biomechanical analyses of the golf swing, which are discussed in a later section, or an analysis of how the body moves segmentally outside of the golf swing. The latter is often arranged into a battery of orthopaedic and movement-based assessments that are expected to converge with relevant movements in the golf swing (36, 37, 49, 50). The joint or movement task-related assessments utilised are often qualitative or threshold-based, rather than quantifiable as a continuous measure. Beyond orthopaedic tests, golf-related motor control research has also gained benefit from EMG and other novel empirical tests.

A facet of motor control is synonymous with correct 'neuro-muscular activation' or 'muscle firing sequence'. This is also a common focus amongst strength conditioning coaches (205) and physio/physical therapists (206) when working with golf athletes. Training for optimal motor control patterning is hoped to transfer into the golf swing. Whilst there has been extensive investigation utilising in-dwelling or surface-based EMG on golfers during the golf swing, only one study has investigated the EMG activation of golf specific exercise (207). This study found that the use of golf-specific training aid, elastic resistive bands and MB Lateral Throw, in a pivoting motion towards the target, all showed 25-50% of *maximal voluntary isometric contraction* (MVIC) in lead and trail gluteus medius and 15-32 % of MVIC in lead gluteus maximus and 27-53% of MVIC in trail gluteus maximus, with the MB Lateral Throw as hard as possible being the best way to increase the activation of the trail leg gluteals in the downswing (208). These values are lower than the EMG activation for the same muscle groups seen in the golf swing with lead side glute medius and maximus reaching over 35% (209) and 50% (210) respectively, right glute medius and maximus over 70% (209) and 80% (210) respectively (211). Therefore, making an appearance in some of the golf S&C literature, the use of MB Lateral Throw (91, 120), and possibly plyometric versions (212) to increase MVIC% become important strength and conditioning exercise selection.

In addition to EMG findings, inter-segment coordination also appears to be measurable, trainable and of importance to performance. However, valid methods for assessment are still being determined for golfers. For example, in a heterogenous group of club golfers, hand-eye coordination was assessed using a timed 3D maze designed to challenge hand-eye dexterity. Faster maze times showed strong negative correlation to total drive distance (r = -0.60, p = 0.008). Although, the mechanistic link to performance is not clear as there was no association with the centre of hit between the clubface and ball (194).

Additionally, a recent novel study demonstrated that a combined Interactive Metronome and golf swing mechanics training protocol improves motor timing and golf technique. Interactive metronome is a sensor-based software program that measures the improvement of an individual's motor timing (196). Participants progressed through a variety of timing-based activities including clapping, tapping and club-free golf swings (to the timing of 54 *beats per minute* (bpm) metronome with visual feedback of accuracy within 0.15 s) twice per week for 6 weeks. The intervention resulted in improvements ($p < .05$) in CHS, club path variability, and smash factor, with professional golfers maintaining superiority in each measure over amateur golfers (196). In summary, motor control is commonly assessed in-swing with, biomechanical or EMG analysis, or out of the swing using either orthopaedic or novel tests.

2.4.7 The cardio-respiratory system

Despite cardiorespiratory endurance being touted as fundamental physiological capability required in GP (14, 15), golfers typically perform at low to moderate heart rates (average ~ 108 bpm) (213). However, during a round of golf maximal heart rate percentage can momentarily spike higher (95 - 137 bpm) and has shown to be 17% higher in competition rounds, possibly reflecting a psycho-physiological response (15). Couple this with rigors of travel, practice, life demands and the importance of freshness to effective skill execution and a well-trained cardio-respiratory system begins to look a more important asset to the competitive golfer (214). The aerobic and muscular endurance demands of golf are well characterised in Smith's (2010) review of 7 studies on the topic (15). However direct relationships to performance are less clear. Resting heart rate has shown a non-significant relationship with driver distance in a small heterogenous sample (194). The One Mile Walking Test (maximum heart rates are recorded relative walking speed) was used to assess the cardiovascular endurance of 56 competitive high school golfers (193). This test was selected due to is perceived specificity to golf but showed trivial correlation ($r < .01$) to golf scores. With established test-retest reliability (215) this method could still be considered for older populations. Similarly, the three minute step test was utilised with 101 male recreational golf players (age: 38.23 ± 16.55 years) yielding no correlation to Carry Distance or Club Head Speed (CHS) with driver or iron (181). Given these weak findings, more sophisticated techniques may be required, particularly for young or elite cohorts. Until that point cardio-respiratory measures appear typically less important than the previously presented physical parameters.

Anaerobic capacity was established for the Polish National Junior squad (15-17 years) using the 30 s Wingate test on a foot-operated cyclo-ergometer. On average, the output

measures from this test (e.g., Total work kJ, power W, these relative to body mass time to and the ability to hold maximum power) were similar to or lower than and more varied most other national-level sports in this country (216). The author suggested the need for structured S&C programs for young competitive golfers in Poland. The Leger Multistage Run Test was used to measure the cardiovascular performance of the Canadian National Team (66). Participants were required to run at gradually increasing speeds between lines separated by 20 m, with the failure level of the athlete used to predict absolute maximum oxygen consumption (VO2max) (217-219). Although it was found that the 15 male golfers were aerobically fitter than the nine females, no meaningful correlations with technical measures were reported (66). Similarly, the effectiveness of a conditioning program in 38 male golfers (aged 16 – 19 years) was determined using a cycle ergometer. The graded YMCA Cycle Ergometry Protocol was used to determine VO2max (220). The test was sensitive to changes elicited by the training program with a post-test improvement of 35% with a concurrent HCP (HCP) drop of 6.96 to 4.70 across the group (29).

Therefore, cohort-appropriate field tests that can predict VO2max are indicated for the assessment of the aerobic system with golfers. More novel techniques that assess recovery state, such as heart rate variability, may also be warranted, although they measure a different construct (221). Older golfers are arguably more likely to experience performance benefits from general training programs that likely increase aerobic fitness (134, 222), along with important health benefits such as reduced blood pressure and other measures of well-being (118, 223). More work is needed to understand the mechanistic links to GP, and whether aerobic testing is indeed warranted, via multi-factorial and longitudinal studies.

2.4.8 Power, rate of force development and stiffness

Power diagnostics provide multiple benefits to athletes. These include the assessment of readiness to train or compete; chronic response to training interventions; strengths and weaknesses; comparison to normative data; allow greater individualisation training prescription (31). The power attributes of golfers have been quantified several ways in the literature: maximum/peak power; average power; rate of force development (ROFD); or field tests. Equipment required to collect this data includes force plates, contact mats, linear position transducers, vertical jump height sticks, MB throws, and CHS.

The ability to produce power is correlated with established important in-swing technical process measures such as pelvic angular velocity and hip torque (122, 224), increased CHS (39, 45, 46, 66, 100, 176, 225) and ball speed (47). The validity of these findings across studies, is further strengthened by the replicated findings of the strong

relationship between CHS and HCP (225, 226). The mechanism for this transfer of power to GP is partly explained by the EMG activity for key muscle groups of highly proficient golfers in more than a dozen studies (192). EMG studies also support the use of various MB throws for testing and training, due to the specificity of muscle activation and intensity (208, 211). However, when selecting tests of power for golfers, additional power indices need to be considered in order to test *specificity*. For the capacity to produce power to transfer into the golf swing the following factors should be considered in testing:

- unilateral versus bilateral limb use (227)
- use of a stretch-shorten cycle or countermovement (227)
- similar range or amplitude of movement to the golf swing (207)
- similar posture and joint positions to the golf swing (207, 228, 229).

Multiple cross-sectional correlational studies have shown strong relationships between basic field test of power and GP measures in Low-HCP young male golfers. Medicine ball throws (lateral or seated chest pass) and vertical jumps (static squat and countermovement (CMJ), for height or flight time) have shown good reliability (ICC = 0.85 – 0.95) (39) and moderate to strong correlation with CHS (39, 45, 46, 66, 176), driver distance and greens in regulation (66). The validity of these tests are further strengthened by their ability to discriminate proficiency level (46). The MB Sit Up Throw, has had less investigation (169), yet is highly utilised in the golf industry (230). Sayers et al (1999) leg power estimation equation derived from vertical jumps has stronger correlation to CHS and factor in bodyweight of the athlete (176, 231). Power estimates also avoid the confounding effects of maturation or hypertrophy over time and allow athletes of different bodyweight to be compared (74, 176). However, it is not yet clear whether leg power, the ability to apply force through the ground or jump ability have different effects on swing biomechanics.

Studies have used a combination of similar cross-sectional power measures in regression models to explain variance in HCP. Trunk power, hand grip strength, normalized leg and hip power, measured from 40 Low-HCP and professional golfers, were combined with stepwise multiple regression analysis to explain 76.2% of swing speed variance (175). Another study combined a variety of measures from 44 young male Low-HCP golfers. Height, Driver Ball Speed and MB throw speed explained 68.7% of variance in HCP across the sample (47). These models also suggest the need for comprehensive combines to understand the mechanisms of performance.

The past 25 years have seen an accumulation of experimental S&C that have shown the benefits of increasing power over 6 to 12 weeks (54). The majority of these studies demonstrate a significant temporal association with various technical improvements,

such as increased: Pelvic Angular Velocity and Hip Torque (232, 233); Thoracic & Lead Arm Angular Velocity (233); CHS (74, 91, 131, 234); Carry Distance (233-235); Total Distance (234-236); and Ball Speed (74, 234, 235, 237). Recent golf S&C studies have included force plate derived metrics of jumps such as positive impulse which can be calculated from the area underneath the force time curve. The CMJ *positive impulse* (PI) appears particularly useful as it directly measures the golfers vertical GRF. PI from CMJ appears the most valid of vertical force metrics, with strong correlation to Driver CHS (r = 0.79) in 27 elite male golfers (age: 19 ± 1.45 years, HCP: −2.7 ± 1.9) (238) and predicting 37.9 % of the driver CHS thirty one tier two Challenge Tour professionals (age: 26.9 ± 5.4 years)(239). Other vertical metrics used in golf studies include Isometric Mid-Thigh Pull (IMTP) peak force and rate of force development, 20cm Drop Jump PI, Squat Jump PI, and Single Leg Jump Force Symmetry (100, 238-240).

Given that golf involves change of direction and rotation, the strong relationship of vertical force production and CHS may be somewhat surprising. One of the mechanisms for the transfer of this capacity to GP appears to be lower limb stiffness (Kvert). A recent study demonstrated positive relationships with Kvert an increased rate of force development in young male adult low to Mid-HCP golfers (142). A stiffer system may reduce the time needed to remove the ‘slack’ from the series elastic component therefore, reducing electromechanical delay and enhancing rate of force development (142, 241). This likely benefits CHS production due to the short duration of the downswing (142). Interestingly, the same relationships were not found in the upper body. Therefore lower-body plyometric-based training should be considered once the golf athlete is appropriately prepared.

In summary, most findings from studies into power and golf suggest that all three body segments: the legs/hips, trunk/core, and arms/hand, require power to convert ground reaction forces into increased CHS. This is a worthy pursuit for the golfer, given the repeated findings of the relationship between CHS and HCP (100, 226). The field tests used in the peer-reviewed literature typically cover the whole body with four basic tests: MB Chest Pass; MB Sit Throw; MB Lateral Throw; and a vertical jump measurement (power estimate or raw score), either Squat Jump or CMJ, with or without reach component. The vertical jump gives greater indication of power improvement if a power estimation equation is used to factor in body weight. Force plates show the promise of a unique contribution too by assessing force-time attributes that may allow improved rate of force development through the ground. S&C coaches may use a combination of power tests in combination with other parameter measures to understand assess and inform program effectiveness (39).

2.4.9 Strength & muscular endurance

Over the last two decades or so, the requirement of strength for golf has become clear (118, 242), although it was not always a priority among golf professionals (243). The work experienced around joints in the golf swing (244, 245) and the high shear forces experienced at the lumbar spine are also now understood (246). Summary reviews of EMG studies provide a valuable guide for which muscles are most utilised at different phases of the golf swing (192, 211). *Maximal voluntary isometric muscle contraction* (MVIC) values are over 100 % for several muscle groups (211), during the average .23 s of the downswing (247, 248). In addition to training, strength analysis, is a vital to understand the physical needs of an athlete (31), and can monitor the effectiveness of golf conditioning programs (12). Additionally, in the golf literature, strength measures have been presented as, maximal strength (high-intensity, low repetitions), strength endurance (low intensity, high repetitions/time), isotonic (same force), isometric (same position) or iso-kinetic (same speed) (31). It is suggested that strength test results for the golfer should be presented in absolute values (kg), not as relative strength and body mass should be considered in body mass strength tests, but not in 1RM strength tests with external resistance (176). Ideally, each body segment used in the golf swing requires specific assessment of strength.

The musculature of the abdomen (249) and lower back play a fundamental role both guarding against large asymmetrical force vectors (250) and producing power in the swing (251). However, professional golfers' core musculature undergoes asymmetrical adaptation to these loads when compared to healthy controls. They become stronger when rotating towards the aiming side (252) and more hypertrophied in the lead side muscles responsible for this movement: psoas major; rectus abdominus; erector spinae and multifidus (253). Therefore, these asymmetrical adaptations appear to be largely functional. EMG studies show that the contralateral external obliques, ipsilateral internal obliques shorten and lengthen during the swing. Whereas the erector spinae, rectus abdominis, quadratus lumborum, transverse abdominis, and multifidus provide stability in a more isometric fashion (192, 211, 251). Improving back extension and flexion strength and ROM through a S&C program in young adult elite females elicited improvement in driver CHS and Carry Distance compared to the control (254). Hence, golf seems well aligned with other sports where core training is understood to be worthy of its own assessment and training in athletes for both performance and injury prevention (255).

The golf testing literature provides testers with several options for core and lumbar spine strength assessment. Trunk Rotation Iso-Kinetic Strength at 60 °/s strength aligns with proficiency across all three levels, increasing with ability (11). Similarly, golf-specific

woodchop strength, was greater in Low-HCP golfers than High-HCP golfers and positively correlated to CHS (12). Vertical Sit-Ups (repetitions × body mass) have moderate positive correlation to CHS (r = 0.29) in elite golfers (176). Trunk Flexor and Side Bridge endurance and asymmetry tend to discriminate ability level and predict low back pain in high-level golfers (256, 257) respectively but exhibit trivial correlation to CHS in recreational golfers (181). Interestingly, low back strength has stronger relationships with GP than back pain in high-level golfers (256). This is possibly due to the most common cause of back pain in this cohort being overuse, which logically may lead to higher levels of both pain and performance at times (i.e., due to higher volumes of practice and play). Recreational golfers show positive correlation between lower back strength and Driver Carry Distance (r = 0.47), Driver CHS (r = 0.56), Iron Carry Distance (r = 0.44) and Iron CHS (r = 0.60) (181). The lack of sensitivity of the Biering-Sorensen Test or the back extensor MVIC with dynamometry in long sitting suggests strength testing must be specific to the golf swing.

Hip strength is also of key importance to golfers (18). Sell et al's 2007 study found that golfers in the highest proficiency group had greater hip abduction and adduction iso kinetic strength at 60 °/s strength (11). Mechanistically, the strength of key hip muscles such as left and right gluteus medius and maximus is also moderately correlated (r = 0.42 – 0.49) with peak pelvis rotational speed and were notably different with the average peak pelvis rotation speed of the Low-HCP group being 123.15 °/s faster than the High-HCP, although ESs were not provided and participant characteristics were poorly defined (122).

Upper body strength provides a variety of benefits to the golfer. Grip strength is a commonly utilised strength test in golf research (54). In a variety of studies and cohorts grip strength has been shown moderate to strong positive correlation with CHS (175, 176), Ball Speed (258), Driver Distance (258), as well as discriminating ability. S&C programs in the literature have typically shown temporal association between improved grip strength improvement and improved driving performance (29, 91, 237, 259), without necessarily reporting the correlation between the two. Chest strength is also important to golfers, given the pectoralis major muscle experiences the most forceful contraction of any muscle group at impact with driver (192). Sell et al's 2007 multi-cohort study found that golfers in the highest proficiency group had greater shoulder right internal and external rotation and left external rotation iso kinetic strength at 60°/s strength (11). Upper body strength, as measured by Bench Press bar speed, has moderate to strong positive correlations with Driver ball speed and HCP in competitive high school golfers (47) CHS in recreational golfers (181) and discriminates ability levels in another study (12). Bar Dips (repetitions × body mass) also have moderate positive correlation with

CHS in elite golfers (176). An 8RM on a pec deck machine had strong correlation with CHS (r = 0.69) in Low-HCP golfers (45). Given the many options available, feasibility and appropriateness of the test to the cohort may determine the best tests for upper body strength.

Lower body strength is another important physical capacity for golfers. Measured with 1RM back squat is strongly associated with HCP and CHS in high school and elite male and female golfers respectively (47, 176, 254). Maximum wall-squats in a minute with recreational golfers as well as overall strengthening of older golfers have also shown positive correlation and increases in driver CHS (181, 222). Isometric Mid-Thigh Pull Peak Force showed very strong correlation to multiple technical measures in elite youth golfers: Six-Iron Carry Distance (r = 0.91), Driver carry (r = 0.91), Six-Iron CHS (r = 0.89) and Driver CHS (r = 0.88) (260), although genders were combined for analyses. These relationships of leg strength bear close relationships to the ability of the golfer to produce vertical force and are likely to underpin power production (235).

Although yet to be discussed in golf literature, S&C coaches across sports are often reported to desire an answer to the question, 'How strong is strong enough? (261, 262). Studies have shown that the improvement of overall strength can improve CHS and other technical measures in older (134, 222) and young elite males (258) and female golfers (254). Strength benefits the golfer via preventing injury and providing a foundation for power and efficient biomechanics. Identifying a minimum requirement for each of these strength measurements with safe, reliable and valid tests may streamline the physical development of all golfers. Competitive golfing cohorts may even benefit from knowing the point of diminishing returns for performance for each strength test. A greater breadth of longitudinal studies across cohorts, is required to answer these questions.

2.5 Golf technique

2.5.1 Golf biomechanics

A proficient golf swing is composed of a sequence of highly complex biomechanical movements and requires precisely timed and coordinated body movements to achieve great distance and accuracy (194). While numerous studies have been published on the technical assessment of golfers, a wide gap between science and practice still exists (263). Golf is a highly individualized sport and golf skill development is largely driven by instructors' experiences and preferences than scientifically validated facts and evidences (263). Thus, there is ample room for improvement in terms of evidence-based practice (263). Empirically gathered inputs from high-level golf coaches regarding their technical

analysis of the golf swing have led to the formation of two prevailing research questions. First, are existing biomechanical data collection and analysis methods appropriate for measuring posture and body rotation of the golf swing? Second, how can we biomechanically analyse posture and body rotation for individual golfers and throughout the swing to further understand their relationship with performance (264)?

Current technical analysis studies reveal that skilled players exhibit increased force production, efficiency and consistency relative to less skilled players (265). Assessing technical parameters requires the understanding of three key concepts or models: a) the *functional swing plane* (FSP) (266); b) foot-ground interaction; and c) the functional double-pendulum and kinematic sequence (263). Two measurable key biomechanics concepts in the golf swing that can be used to measure the golfers' performance within the above models are: a) angular momentum generation by utilizing external forces and moments; and b) angular momentum transfer within the body and from the body to the club. The foot-ground interaction is the key aspect in terms of angular momentum generation, allowing for work to be generated by the lower extremities. The total work performed by the lower extremities is measured by integrating the powers of the lead and trail ankle, knee and hip joints during the downswing (267). Although it varies from player to player, primary contributions from the trail leg come from the knee joint, while the lead leg uses more of a combined effort of the hip, knee, and ankle joints to generate energy (267). Whilst the FSP-based angular motion measurement and the kinematic sequence are related to the aspect of angular momentum transfer. In addition to the foot-ground interaction and kinematic sequence mentioned here, new areas of interest are currently emerging, such as the hand-club kinetics, net joint moments generated at various body joints, and kinetic sequence (263).

With these biomechanical principles in mind, it is accepted that the fundamental purpose of the golf swing is to do work to generate club head kinetic energy to be transferred to the ball at impact (244). This phenomenon is explained by Nesbit & Serrano 2005 (p. 520), "The golfer winds up during the backswing to create a distance over which positive forces and torques can be applied to the club thus creating a potential to do work. During the downswing, these forces and torques function to both control the club trajectory, and increase the velocity, or kinetic energy of the club by doing work. This work is done at an ever-increasing rate of speed which is a measure of power. During the downswing, the club shaft flexes a great deal, storing and releasing strain energy. All the complex body segment motions and motion timings are intended to produce the maximum amount of useful work that can be transferred from the golfer to the golf club." (268).

2.5.2 Consideration of swing styles & movement variability

Recently, the concept of movement variability (MV) has gathered increasing interest from golf researchers. The scientific discussion in this area can be divided into two definitive categories, *inter-golfer movement differences* and *intra-golfer MV*. The first category deals with the proposition that there is likely to be many different optimal ways to swing the golf club, largely driven by the individual's anatomical, physiological and psychological make-up. These differences between golfers could also be described as *swing styles* or *preferences (84, 86)*. Whereas the second category refers to inherent variation in skill execution. Some of this variation is 'noise' and undesirable (e.g., the classic definition of movement variability) (6). Some is functional adaptation for strategic shot selection, which is thought to be desirable and increase the stability of skill execution (87).

As the understanding grows around the complex relationships of ground, body and golf club, so too can the reciprocal relationships between these factors and physical characteristics and therefore give rise to more effective training interventions (6). Although the body of evidence in the golf biomechanics literature points to several key parameters that discriminate between level of golf ability, the variability in assorted measures even amongst skilled players, raises the question of whether there is only one ideal swing method for all individuals (265, 269). Different swing styles have been noted as far back as the 1960's when the 'modern' swing began to supersede the 'classic' golf swing (270). Indeed, to date multiple golf studies have effectively structured data collection and analysis around different, yet all effective, swing styles (Table 2.3). It has been noted that different swing styles have inherently different body kinematics (86, 271), weight transfer patterns (84) and distribution of work around the joints on the lead and trail sides of the body (267). Kwon (2016) has also identified three additional effective swing styles in elite golfers based on the deviation of clubhead trajectory from the FSP, noting that the club head moves consistently on the FSP in through the 'impact zone' for all three:

- *planar* – the club head moves slightly above the FSP late in the back swing and again during follow-through;
- *spiral* – the club head moves slightly above the FSP in the back swing and then below the FSP during follow-through;
- *reverse spiral* – the club head remains on the FSP in the back swing and then moves above the FSP in the follow-through (263).

Table 2.3 Swing styles based on kinematic and GRF at three swing events (PSTSS, pelvis shoulder torsional separation style)

Swing Style (Reference)	Address and Backswing	Transition	Downswing, Impact & Follow-Through
Modern Swing (136, 192, 270-274)	Large shoulder turn with a restricted hip turn. Reduced hip turn is accomplished by keeping the front foot flat on the ground throughout swing.	Aim to create a large X-factor.	Shoulders open to pelvis at impact. Reverse “C” position is common in the follow through.
Classic Swing (192, 270-273)	Allows a large hip turn and lead heel lifts off the ground.	Reduces X-factor.	Shoulders and pelvis parallel ai impact. Erect “I” position in the follow through with the trunk leaning further towards target than the modern swing.
Minimalist Golf Swing (16)	Pre-swing rotation of the torso, positioned away from target. Maintain the lead shoulder higher and body weight closer to target than typically seen, from set-up to the top of the backswing.	Requires less vertical and lateral body-movement during the downswing	
Front Foot Style (84, 85, 275, 276)	COPy % starts even at address then moves to rear foot in backswing.	COPy % moves towards lead foot.	COPy % continues to move towards front foot through to impact.
Reverse Style (84, 85, 275, 276)	COPy % starts even at address then moves to rear foot in backswing.	COPy % moves towards lead foot.	COPy % moves towards back foot through to impact and follow through
PSTSS: Late Shoulder Acceleration (86)	N/A	N/A	Elongated early downswing phases. Delayed onsets of peak angular velocities in downswing result in smaller peak-impact angular velocity decreases. Relatively earlier wrist releases (uncocking) in downswing
PSTSS: Large Downswing Stretch (86)	N/A	Lacked shoulders-arm-club separations in transition Short transition phase	Relatively earlier wrist releases (uncocking) in downswing Partial proximal-to-distal sequence ‘pelvis → thorax/shoulders/arms → club’
PSTSS: Large Backswing Stretch (86)	Relatively larger backswing Most consistent proximal-to-distal sequences throughout the entire swing with well-spaced transitions of the body parts/club in particular	Larger total XF stretches. More elongated transition phases.	Shorter early downswing phases. Earlier onsets of peak downward angular velocities of the body parts. Larger peak-to-ball impact angular velocity decreases.
PSTSS: Medium Total Stretch (86)	N/A		Partial proximal-to-distal sequence ‘pelvis → thorax/shoulders/arms → club’
PSTSS: Small Total Stretch (86)	N/A	Lacked thorax-shoulder separation in transition Short transition phase	N/A

The emergence of technological analytical tools that have overcome earlier measurement barriers (277), have allowed golf scientists to more accurately infer the meaning of variation in the golf swing. Subsequently, in golf, MV has been quantified with various objectives in mind including:

- Intra-individual MV, using the coefficient of variation (CoV) across five to 10 golf shots for different biomechanical markers at discrete swing events to determine similarities (138) for specific golf cohorts
- comparison between high and Low-HCP golfers (278)
- the relationship between MV and outcome of full swing (269)
- the relationship between MV and putting stroke (279)
- evidence that MV can be influenced by conscious control (280)

Thus far, the emergent research suggests that better performances are more likely if some swing-related variables exhibit lower MV – particularly closer to impact and more distal in the body (88, 281). Conversely, a higher MV for other swing measures does not diminish golf performance and may even be desirable (Table 2.4). For example, multiple studies show that a consistent (low MV) weight transfer velocity in the back swing for a player is not important, yet it is for the down swing (85, 276, 282). Understanding the influence of MV of different swing measures on GP, separate to the issue of swing styles, is important knowledge for researchers and coaches.

Table 2.4 Optimal golf swing traits and variability

Golf Swing Trait	References
Low Variability Desirable	
Alignment of shoulders to feet at address (open or closed)	(281)
Progressively minimize variability towards distal segments address	(281)
Peak X-factor precedes peak GRF free moment	(40)
Downswing initiated by reversal of pelvic rotation	(40)
Weight transfer velocity in downswing	(85, 276, 282)
Pelvic-thorax coupling in downswing	(283)
Shoulder and pelvic angular velocities	(284)
Timing between body segment peak angular speed	(285, 286)
Progressively minimize variability towards distal segments at impact	(88)
Higher, pelvic rotational velocity at impact	(284)
Progressively minimize clubhead trajectory variability toward impact	(88, 138)
Grip pressure at impact, with greater force in the lead hand	(287)
Clubhead speed, efficiency of strike, centeredness of strike, angle of attack, club path, and face angle at impact	(288)
Fluctuation Neutral or Desirable	
Weight transfer velocity in backswing	(85, 276, 282)
X-factor stretch	(289)
Dynamic balance measured by GRF and centre of pressure patterns	(290)
Thorax-head coupling in downswing	(283)

A cohesive scientific approach that incorporates the MV concept is an important step toward moving golf swing technique coaching towards a holistic, individualised and

evidence-based approach (87). The impact of variability on the complex motor skill of the golf swing is yet to be fully investigated. For example, it is not clear where the trade-off between functional and detrimental variability lies when in pursuit of enhanced performance outcomes (87). In golf research, if swing styles and movement variability are not analysed separately in group analyses, authors must at least give due consideration to the potential confounding variation from these sources.

2.6 Assessing technical parameters in golf

Simply persisting with the game of golf over the long term or playing more regularly does not necessarily lead to greater performance (194). To better understand the relationships between the body and GP we must first understand which technical aspects are most important to measure and how best to measure them. Determining the most important technical aspects of GP has primarily been addressed by determining the differences between skilled and unskilled players. Computer-based 3D swing models have also been used to measure and determine the most efficient and effective way to swing a golf club. The common assessment methods for technical parameters provided in Table 2.5.

Table 2.5 Golf Technical Parameters

Technical measure	Method and equipment
Body kinematics & centre of mass	3D motion (wired, wireless, sensor or high-speed camera systems), Computer models
Ground reaction forces & centre of pressure	Force plates (X, Y, Z axes and moments)
Neuro-muscular system in golf swing	EMG (surface or in-dwelling electrodes)
Club kinematics	Doppler radar, high-speed camera systems
Ball kinematics	Doppler radar, high-speed camera systems
Movement variability & swing styles	Any method above

The peer-reviewed literature presents differences in many technical parameters across ability levels, often unidirectionally with HCP. However, the understanding of the interplay between these technical measures is less well known. The bulk of the technical parameter studies are laboratory-based. The ecological validity of these studies would be enhanced by the inclusion of competition performance measures. Furthermore, many studies compare group means without reporting confidence intervals. This approach misses the large inter-subject variation in technique, shown in several studies (91, 121, 291, 292). These challenges can be somewhat overcome by data mining techniques and predictive models to better understanding non-linear relationships of technical measures (291, 293-295).

To synthesize the golf technical literature, a sequential approach to categorising measures is useful. That is, organising the measures into groups as they relate to the

timing of the golf swing is logical from both a data capture and end-user perspective. Therefore, a review of the literature for technical measures is presented in four main sections:

1. **Technical process measures – body**: X-factor variables; proximal to distal sequence; temporal body kinematics; other body kinematics.
2. **Technical process measures – ground**: ground reaction forces; centre of pressure; centre of mass; kinetics.
3. **Technical process measures – club, ball and launch**: CHS, ball speed; club path and plane; impact variables.
4. **Technical outcome measures**: carry and total distance; skills tests.

2.6.1 Technical process measures: Body kinematics in the golf swing

X-factor and related variables

The inception of 3D analysis for golf swing kinematics combined with the guidance from expert coaches (179) led researchers to some promising early findings on *X-factor*. Higher X-factor seemed to discriminate between playing ability and improve golf swing efficiency. X-factor is the relative or differential rotation of the golfer's upper body to hips (178, 179). This measurement is referred to as 'the top of the backswing'. High-HCP golfers tend to demonstrate greater hip rotation at the top of the backswing and reduced maximum X-factor values relative to Low-HCP golfers (182), which has been attributed to physical factors and/or different swing concepts (271). *X-factor stretch* is the elastic stretch that momentarily increases this differential rotation at the beginning of the downswing as the pelvis reverses its rotation. It is posited that the interplay between the pelvis and shoulder girdle allows highly skilled golfers to create greater X-factor stretch (19%) than their less skilled counterparts (296, 297). This X-factor stretch is subsequently followed by progressively faster angular velocities from the more distal segments (i.e. trunk, upper limbs and club) ultimately leading to greater CHS (265). In combination more effective rotational biomechanics, tour players also utilise reduced side bending and resulted in reduced time to impact from initiation of backswing (296).

Technological advancements in 3D biomechanics (e.g., vector coding techniques developed from gait analysis (298)) and specific swing event (e.g., top of back swing, impact) analysis have allowed exploration of further variables such as *X-factor stretch rate* (212, 233), *rate of recoil* (212, 264). X-factor at impact, peak X-factor, and peak upper-torso rotation are highly correlated to CHS at impact (median r = 0.94, .90, and .90, respectively) (40). X-factor stretch varies with different club and swing effort – suggesting it may also be a strategy for distance control and therefore prone to functional

variability (289). Therefore, investigating X-factor variables requires a considered approach to test design and instruction (299). Although beneficial to elite performance, X-factor stretch is purported to increase injury risk. The basis for this is an excessive reliance on the elastic structures of the body that not all golfers are conditioned for (249, 274).

More recently, divergent findings on X-factor variables have raised questions on the uniformity of measurement techniques (182, 300), suggesting measurement error in some of the earlier research (300). Newer X-factor computation methods utilising the FSP and *cardan* rotation-based methods has found X-factor values are diminished and are not directly correlated with CHS (300). Instead, a 'lateral-bending/flexion-extension/axial' rotation order of rotation was deemed to be the most suitable cardanic sequence to assess X-factor and lower trunk movement in the golf swing. Therefore, bio-mechanists are encouraged to 'model the golfer's body (trunk/arms/club) as an inclined axle-chain system so that the rotations of its parts observed on the FSP can represent the actual angular motions closely' (86). This model for analysis allows for more accurate research examining the X-factor and its relationship to CHS and lower trunk movement and low back pain in golf (301). Despite these challenges, the measurement of pelvis-thorax coupling have shown good reliability for inter and intra-tester, between-day and between-location scenarios (302). In summary, the dynamics and interplay between previously defined body kinematics, including X-factor variables, are making new discoveries that increase the potential for an individualised approach to optimising a GP.

The proximal to distal kinematic sequence

As important as X-factor variables may be, it is important to contextualise that they exist within the whole-body golf swing motion known as the *proximal to distal sequencing* (PDS) of the kinematic chain (303) (Figure 2.2). The peak angular speeds of the segments appear in time order from proximal to distal end. In other words, the pelvis reaches its peak first, followed by the upper thoracic, then the lead arm and lastly the hands and club (304). The peak angular speed of the most distal segment, the club (within its plane of motion), appears at or just prior to impact (304). Indeed, most assessments of segmental sequencing in throwing, striking or kicking have indicated a PDS of body segment kinematics (305).

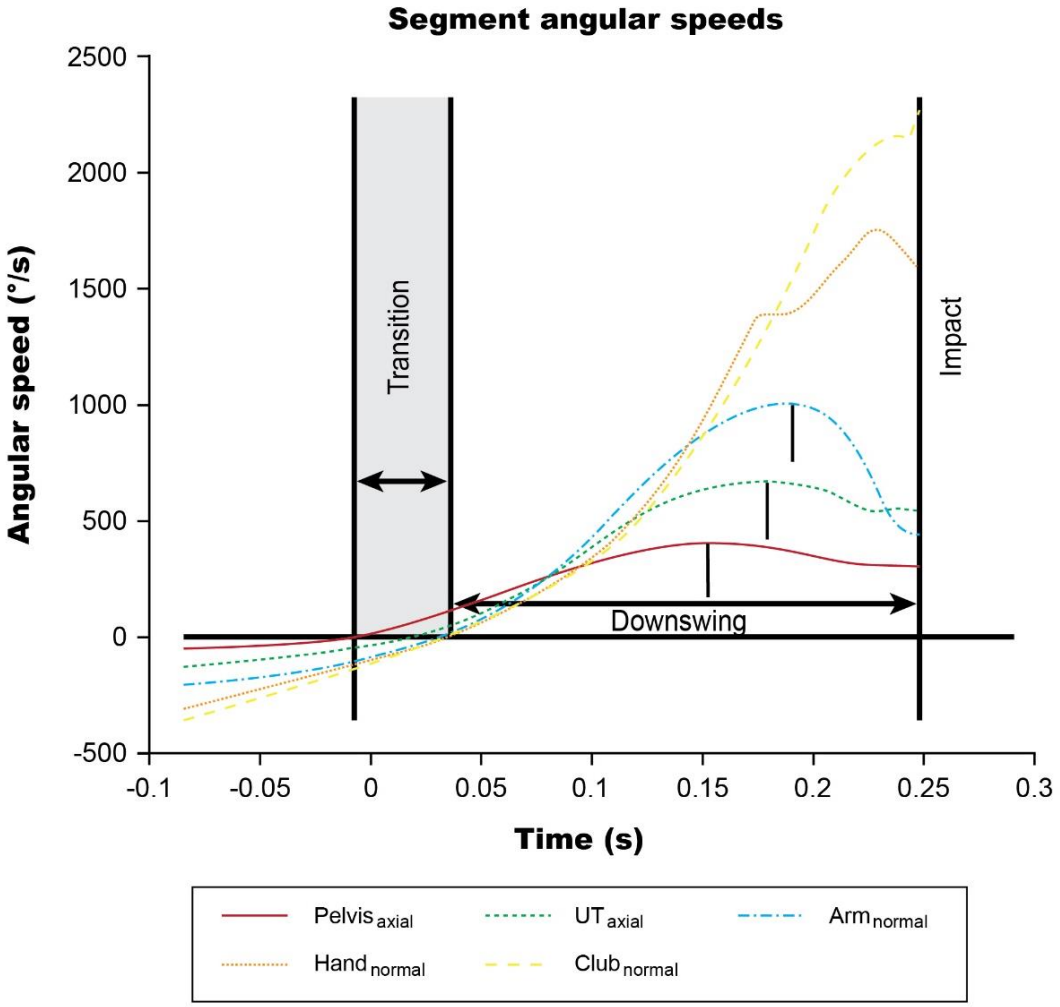


Figure 2.2 The kinematic sequence of a professional golfer with six-iron. Adapted from Neal 2018 (304)

By virtue of the PDS, the golf swing conforms to the summation of speed principle (306). That is, each succeeding segment reaching a higher maximum angular speed than the preceding one (307). This requires both a deceleration of the proximal segment which creates the momentary stability needed for an eccentric-concentric sequence of the spinal rotators (308). This coordination sequence creates a stretch-shorten cycle in the musculo-tendinous structures; allowing for an increased acceleration of the more distal segment (191, 297). This movement pattern is specifically referred to in golf as `leading with the hips' (Enoka, 1994). Thereby, dynamically the hips and shoulders rotate in opposite directions before both rotate back towards the target. This stretch-shortening cycle would increase the acceleration of the shoulders. This allows a greater amount of work can be done by the muscles than if they had simply performed a concentric contraction without the preceding rapid eccentric contraction (191, 308). After impact, eccentric muscle actions decelerate the body and club to enable the golfer to finish the swing in a balanced position facing the target (247). However, further research that

combines the principles of kinetic energy and EMG is needed to fully understand the mechanical phenomena of stretch-shorten cycles in the golf swing (304).

In the elite golfer's swing, the PDS achieves optimal efficiency when the time lags between the peaks are of similar magnitudes (~0.3 s) (309). The peak speed of each successive distal segment is higher than the contiguous proximal one, and these speed 'jumps' are of the order of 250 °/s. Professionals with higher swing speeds exhibit a peaking order of the body segment speeds, determined from the mean timing variables: pelvis, thorax, then arm. Whereas the amateurs with lower swing speeds, exhibit: pelvis, arm, then thorax (13). Skilled players that utilise PDS, employ this movement characteristic for partial and full-swing shots (307) and possess both higher segment accelerations and decelerations (except the pelvis) (13). PDS has also been shown to improve golf shot accuracy (310). Interestingly, even highly skilled golfers cannot subjectively detect when they have made kinematically efficient swings; rather they are sensitive to the centeredness of club-face strike (309). However, despite the importance of an efficiently sequenced golf swing, it has been estimated that only 42% of tour players utilise an optimal sequence; therefore there are several other factors that allow elite performance to occur (311).

Sequential measurements of body kinematics

Further to the kinematic PDS, most positive phenomena in the golf swing are compounded with optimal timing. Advancements in technology have allowed temporal measurements, rather than just absolute values, to be increasingly investigated. These include measurements such as: phase times between *swing events* (stages of the golf swing); times of peak backward and downward angular velocities for each segment, relative to ball impact; transition times for each segment, relative to ball impact; peak backward and downward angular velocities for each segment; and peak-to-ball impact angular velocity decreases for each segment °/s (86). Skilled golfers have greater pelvic accelerations and a larger time between peak pelvic velocity and ball contact (peak to impact time). Moderate correlations exist between average pelvic acceleration and shot distance (r = 0.37) and smash factor (r = 0.39); also between peak pelvis angular velocity and impact time (r = 0.40) and smash factor (r = 0.40) (286). The net effect of these measures would seem to give the skilled golfer greater time to generate a powerful and accurate strike on the ball. Another study showed that club kinematics and CHS varied with club selection, but the movement time and proportion for each phase of the swing remained identical (285).

A heterogenous sample of 100 golfers were matched for height and weight and then stratified by ball velocity. Group differences and moderate relationships ($r \geq .50$) were

observed between an increase in ball velocity and the following variables: increased torso–pelvic separation at the top of the swing; maximum torso–pelvic separation; maximum upper torso rotation velocity; upper torso rotational velocity at lead arm parallel, and last 0.4 s before impact; maximum torso–pelvic separation velocity; torso–pelvic separation velocity at both lead arm parallel, and at the last 0.4 s before impact (312). The timing of these measures make an important contribution to ball velocity (312).

In summary, although body segment angular speeds and accelerations are important to CHS and performance, a compounding effect is created when consistent, well-coordinated, larger time frames between body segment peaks are utilised. Therefore, a temporal element to body kinematic analysis of the golfer is advantageous.

Other golf swing body kinematics

In addition to the exploration of X-factor, the PDS and temporal phenomena of some discrete variables also discriminate player ability. Elite players demonstrate: a larger amount of trunk rotation ROM (ROM) at the end of the backswing; increased trunk rotation velocity during the downswing; accelerate their torso through and past impact – relative to High-HCP golfers (265). Lateral tilt velocity has also demonstrated a large contribution to total segment angular speed in professional golfers, therefore analyses of trunk dynamics should not be merely restricted to the axial rotation direction (283). Furthermore, it is evident that different clubs produce different trunk motion characteristics. For example, right handed golfer use greater left side bending ROM and right side bend velocity with seven-iron (relative to driver) – due to a more vertical plane of the shorter club; driver exhibited greater left rotation ROM (313). Hence, 3D analysis should consider the many variables on offer within the various software programs.

In addition to force summation from the pelvis, thorax and shoulder girdle, the rotations of the hands and arms, along their longitudinal axis, are used for both power production and club-head presentation (305). The mechanics of these movements are vital for developing coaching emphases, strength training schedules and injury prevention programmes (305). Although often assessed separately from the entirety of the kinematic sequence, multiple studies have investigated the role of this hand-club force couple relationship in golf (14, 314-318). Findings suggest this force couple (‘loading the shaft’) adds additional CHS, but also an additional challenge to accuracy (14, 319). Therefore, reducing the variability of this distal end of the PDS can improve performance (88). To maximise distance and accuracy, elite players appear to set the golf club at the top of the backswing with a greater stretch of the shoulder joints as well as more radial deviation of the wrists. Furthermore, the release of this increased wrist angle was delayed much later on the downswing among skilled golfers resulting in increased CHS at impact of

between 5 and 10 % (14, 265, 319, 320). It appears that dynamic 3D wrist actions late in the downswing are a hallmark of male professional golfers, serving to increase CHS and square the clubface, that separates them from female professionals and amateurs (172, 173, 307). These discrete, more distal, biomechanical measurements, assessed under differing conditions, can further inform coaching and training interventions.

2.6.2 Technical process measures: Using the ground

Ground reaction force and centre of pressure patterns

The golf swing is often considered a 'ground-up' phenomenon (267). Therefore, 3D golf ground reaction forces (GRF) provide important context to the highly investigated body kinematics of the golf swing. GRF profiles are waveforms representing the change in these forces throughout the golf swing (321). 3D single or dual force plates are used to capture GRF during the golf swing. Typically, an X-axis (toe-heel force vector), Y-axis (rear to lead foot force vector) and Z-axis (vertical force vector) are captured for both the rear and lead foot (Figure 2.3). These measures are often integrated to produce metrics such as centre of pressure (COP) via a software interface (322). These outputs can provide insight into weight transfer (84) and dynamic balance patterns via COP patterns in each axis during the golf swing (i.e., COPx, COPy and COPz). Rotational moments of ground reaction force about a vertical axis (Mz), a vertical axis for each foot or the COPz. Peak free moment (Mz about COPz) per kg is highly correlated to CHS at impact (median r = 0.94) (40).

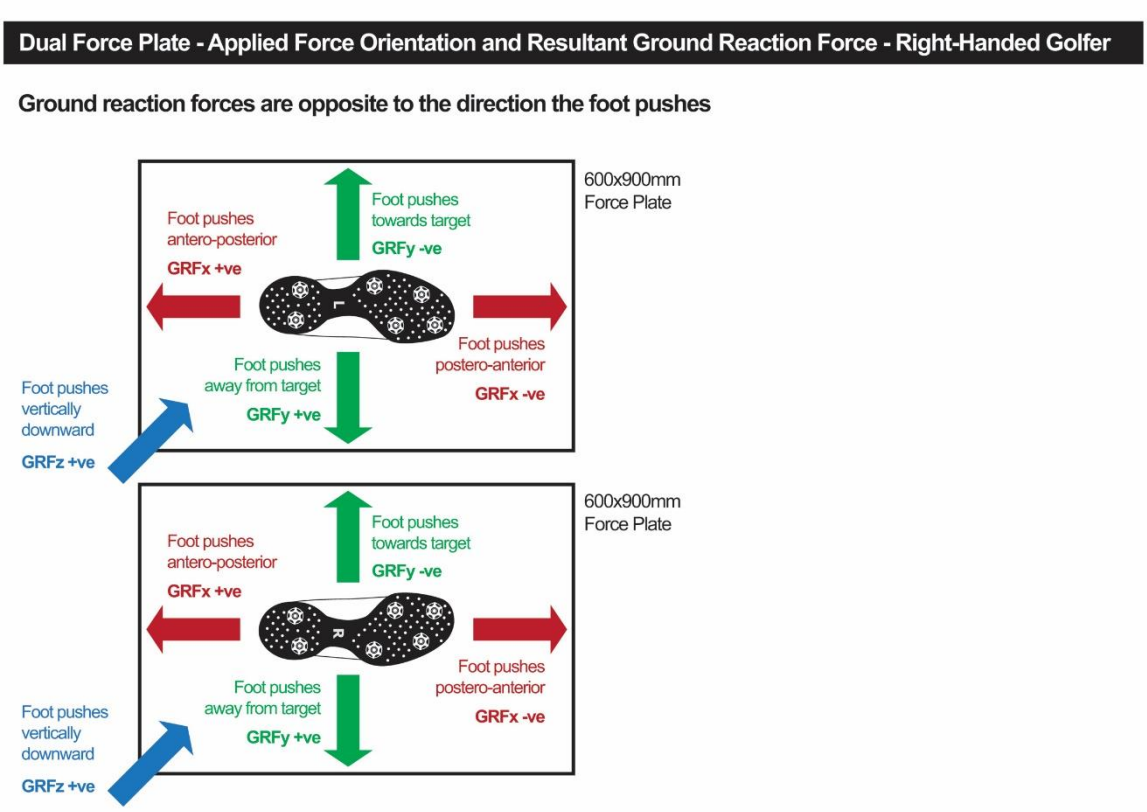


Figure 2.3 3D force plate vectors for the right-handed golfer. +ve, positive GRF value (derived from plates). -ve, negative GRF value. Antero-posterior, Fx. Medio-lateral, Fy. Vertical force, Fz.

GRF and COP patterns in isolation have shown relationships to technical measures and ability level. The most consistent relationship being a larger weight transfer range, from rear foot to lead foot in the downswing, associated with a larger CHS (275) and lower HCP golfers (290). Low-HCP golfers (relative to High-HCP) exhibit greater downswing forces and torques at the feet, including more pressure (66% compared to 49%) and lateral force in the lead foot and more to the heels at impact (80). This is thought to occur due to more rotation of the body and Mz GRF in the downswing (265, 290, 323). However, GRF results are also individual-specific, with golfers returning different combinations of significant factors (275, 290).

Centre of mass patterns (*COM) & dynamic balance*

Further insights are gained when GRF is captured simultaneously with body kinematics (324). In particular, centre of mass (COM) has been used in conjunction with COP to assess the dynamic balance of golfers at different *swing events* (stages of the golf swing) (324). Different methods have been used to estimate and dynamically assess COM. COM can either be estimated with motion capture systems or calculated more accurately by constructing biomechanical models. Model construction involves dividing the body into differing numbers of segments and then factoring in: the joint angles; mass and COM

position for each segment (322, 325); kinematic descriptions such as the trajectories of each joint rotation centre (324). Typically, this information is obtained and measured from a combination of anthropometric tables (which account for different somatotypes and ages (325, 326)), electro-goniometers, wireless or high-speed camera motion capture systems. COM typically resides within the pelvis of most people, but can vary with somatotype and limb length etc. In biomechanical motion capture the sacrum is often utilised as the surrogate for COM, however this has been shown to introduce unacceptable levels of measurement error in some settings (327). Nonetheless, this digitised estimation point is then monitored throughout the golf swing with the use of either sensor-based wired or wireless systems, or a collection of high-speed cameras calibrated to that digital point and communicating back to a software.

The combined analysis of COM and COP demonstrates that professional golfers have superior dynamic balance ability, achieved by controlling the COP excursion to compensate for the increased variation of COM. This is thought to produce a more stable swing mechanism (328, 329). Furthermore, in-swing balance is influenced by club length/mass and wrist elbow control in the swing (329), providing one technical mechanism for how expert golfers achieve better balance in their sport. Refinement of this combined analysis technique has led to the investigation of COM–COP inclination trajectories between professionals and two lower ability levels (324, 328). The professional golfer group showed a lower value of normalised COM–COP inclination angular jerk than the other two groups in all directions. Put simply, professional golfers tend to move more ‘smoothly’ during the downswing. This is attributed to the neuromusculoskeletal system that maintains balance with superior postural control (324). A similar study showed that experienced golfers (HCP = 11.7 ± 10.5) golfers showed high variation in the separation between the centre of GRF and centre of gravity (COG) – the point on the ground directly below COM – throughout the swing in all directions. Furthermore, this separation was larger with driver than 7-iron (329). Although extensive equipment and expertise may be required, the addition of COM-related measurements to other assessments adds further insight to the both the common and individualised movement strategies employed by elite golfers. Understanding how a golfer needs to move in the swing – as well as the resultant forces and perturbations they experience – can guide the testing and training of golfers to support GP.

Golf swing kinetics

Typical kinetic investigations of the golfer have focused on determining the forces and torques generated around the joints during the downswing (330). Joint segment positions are often captured simultaneously with GRF with force plates (329). Unlike kinematics

that measure velocity and positional displacements, kinetics information provides insight to instantaneous accelerations, forces and torques about joints. This yields a snapshot image of swing dynamics (245).

An investigation of kinetics for both six-iron and Driver in 10 highly skilled (HCP < 5) male and female golfers was undertaken. Joint kinetics were calculated using GRF and segment kinematics to determine net joint moments. These measurements targeted the 0.1 s surrounding the time when the peak 2D moments about the COM in the transverse plane were being created; prior to ball impact in the golf swing. The multi-joint control during the golf swing highlight the need to design interventions that are player, and leg specific for performance improvement (331). Specifically, the anterior muscles (uni and bi-articular) of the lead hip and knee joint, and posterior muscles of the rear hip and knee joint are heavily used (331). Another study investigated trunk rotational and weight transfer patterns between age, height, weight and gender matched skilled (n = 13, HCP = .8 ± 2.6) and unskilled (n = 17, HCP = 30.8 ± 5.5) golfers. Group findings suggest the better players had: earlier trunk horizontal rotation and rapid weight transfer to the rear foot (and larger relative Fz to bodyweight) during the backswing; earlier pelvic horizontal rotation and earlier weight transfer to the lead foot (and larger relative Fz to bodyweight) during the downswing; less upper trunk horizontal rotation and more posterior pelvic rotation at follow through (332).

A further study used the data of 84 golfers to create a golf swing computer model. The model was used to perform detailed analysis of four deliberately diverse players in terms of age, HCP, experience and rounds per year (245). Many biomechanical differences were seen between the four players, highlighting that golf swings differ with proficiency. Quantities related to skill level included: hand trajectory, work ratio, work, club head and grip velocity, alpha torque and angular velocity, and power (245). Other quantities seemed to reflect swing style and not skill level (245). The study discovered little correlation between body type and swing characteristics or skill level (245). An energy (work) based approach was employed with the same full body model and a club model to investigate the work, power, kinetic energy, strain energy, energy conversions, and efficiencies of the body joints and the club This approach proved that forces and ROM are equally important in developing CHS. Differences in swing style and skill level were revealed in the motion, force, and energy characteristics of the swing (244).

In summary, kinetic analyses through direct and calculated measurements provides researchers and practitioners an in-depth understanding of the forces that act on the body during the golf swing. Understanding the forces experienced by each joint in the golf swing provides specific guidance to the S&C coach for the isolation and compound strength testing and training of golfers.

2.6.3 Technical process measures: Club and ball kinematics

With club and ball tracking systems now commonplace in golf environments, kinematics analysis is routinely undertaken for individualised coaching. Understanding the impacts of club and ball measures can guide successful interventions to enhance skill execution (technical outcome measures). Strategic shot selection (e.g., hitting a fade versus a draw) is a functional source of movement variability that needs to be controlled for a technical assessment (i.e., the shot intention must be known and environment consistent) (87). However, there are consistent differences across ability levels exhibited by club and ball measures that have strong correlation or are predictive of HCP or align with ability levels (288, 293, 295). Many of these measures directly influence shot outcomes (82).

Club head speed

The most highly utilised club kinematic measure is CHS (8, 14). CHS provides a valuable insight to GP as it is both a valid assessment of power and has moderate to extremely strong inverse correlation with HCP (r = -0.45 – 0.95) and very large ESs between ability levels (d = -3.21) across all skill-levels (12, 100, 226). CHS has also been used for sampling purposes, due to its strong discriminant validity (13). CHS is the most representative available measure for transference of gains in physical power to performance for the golfer. For example, CHS has a lower skill requirement than ball speed or distance measurements (which also require an efficient ball impact and launch parameters respectively). Conversely, CHS may be less representative of competition performance than the latter two measurements.

The specificity of CHS as a power measurement has led to its utility to quantify the effectiveness physical interventions in studies for all cohorts of golfer: Junior male (74), older male (118, 134, 222), elite male (91), junior female (133), older female (236) and elite female (254). However, when synthesizing this research, the variation in the accuracy and reliability of equipment used across studies to capture CHS needs to be considered (147, 333). Equipment used to assess CHS includes: doppler radar launch monitors – which typically sit a few meters behind the golf ball (333), infra-red system, multiple highspeed camera arrangements or optical systems (82). Each system captures the club head slightly differently, and thereby may produce different numbers. However, provided reliability is high, any system is suitable for experimental analysis within a given study.

Published interventions for generating superior CHS have targeted multiple technical mechanisms: optimising the proximal to distal kinematic sequence order and timing of

peak segment velocities (304); reducing the radius path of the hands during the downswing (334); increasing wrist torque and/or ROM and utilising this force couple later in the downswing (13, 172, 320, 334); increasing downswing amplitude and utilising X-factor stretch (335); maximising the use of ground reaction forces (336); weight transfer (84). Even greater increases in CHS have been shown in physical interventions that have targeted: strength, power, flexibility and other physical characteristics that enhance the neuro-muscular capacities of the golfer (54).

Ball speed

Similar to CHS, ball speed has shown strong correlations with HCP (47) and group differences align with ability level (288). Ball speed is the result of CHS and the centeredness of impact (resulting in the output measure of impact efficiency – also reported as *smash factor* in some commercially available launch monitors) (288, 337, 338). A 'centred or squaring' strike avoids generation of additional angular motion in both the clubhead and that occurs with ball shots struck away from a projection of the club head centre of gravity (COG), resulting in increased dispersion and decreased speed (288, 338, 339). Ball speed, in turn, creates total driving distance once launch and environmental conditions are also factored in (82, 288, 340). Ball speed has been utilised as an outcome measure to quantify the effectiveness of (typically physical) interventions across multiple cohorts: Junior males (74), male club golfers (187), elite males (233), and elite females (233) – but is yet to be utilised for older or junior females. The mechanisms for increasing ball speed include all those mentioned for CHS, plus some additional skill elements that allow for optimised club head presentation and impact location. These impact measures are influenced by coaching, concepts, practice and effective club fitting (e.g., a longer driver can increase ball speed) (341). Therefore, relative to CHS, ball speed has both additional confounding variables if measuring physical interventions and greater ecological validity to GP. Hence, drive ball speed should be considered a primary training outcome from both a physical and technical perspective (47).

Club path and plane

Computer modelling suggests that a further 3.3 m/s in driver CHS can be gained by the right-handed golfer 'pulling' the club left just prior to impact (Figure 2.4). This increased centripetal force applied by the player on the club, inward towards the centre, outmatches the high centrifugal force of the club head, which is fleeing the centre of the golf swing. This results in parametric acceleration of the club head (342), resembling the velocity-curve of a hammer throw (343). This also results in a decreased or 'shallowed' driver

swing path. This model agrees with another genetic algorithm computer simulation. The simulation found that positioning the club below the golfer's swing plane, early in the downswing, facilitates the squaring of the clubface for impact; while positioning the club above the plane has the opposite effect, leaving the clubface open relative to the target line (344). A further investigation of driver club head path analysed the 'swing hub' of four golfers of different ability-level. Results showed that swing radius was increasingly non-circular the better the standard of player. This efficient, ellipse-shaped, club head path is important for: reducing the kinetic loading on the body; maximising transfer of the body's kinematic energy to the club head, an increasing the chances of a an accurate ball strike (314). This flatter swing is most likely is created by a well rotated pelvis, thorax and cleared left shoulder at impact, as displayed by better golfers (247, 342).

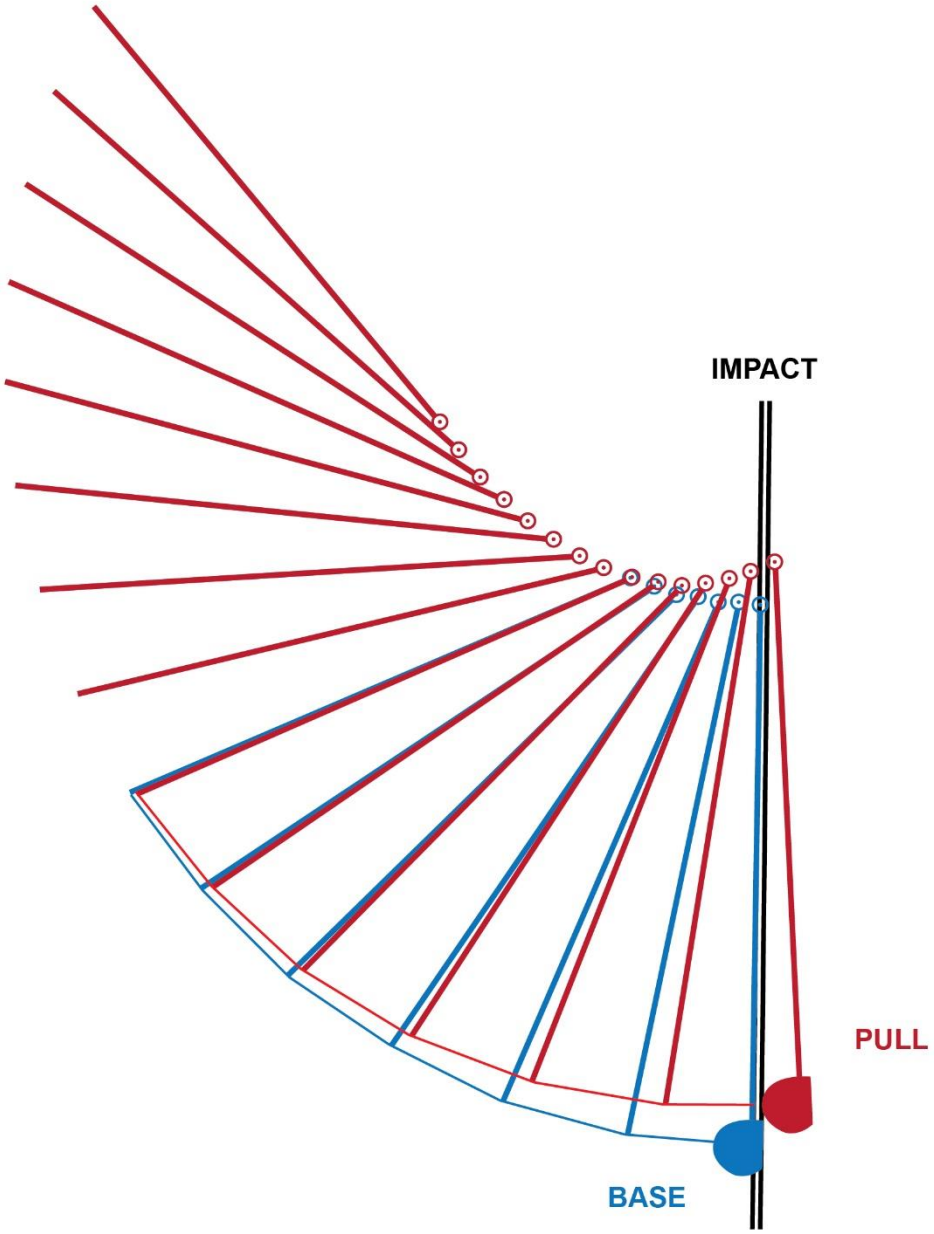


Figure 2.4 Driver trajectory with and without pull motion. Adapted from Miura et al 2001 (336)

Changing the steepness of the driver swing plane by 10° has little effect on the delivery of the clubhead to the ball (344). Conversely, a more recent study has created rule of thumb values created to better understand the relationship between club path and angle of attack for different vertical plane angles (345) (Figure 2.5).

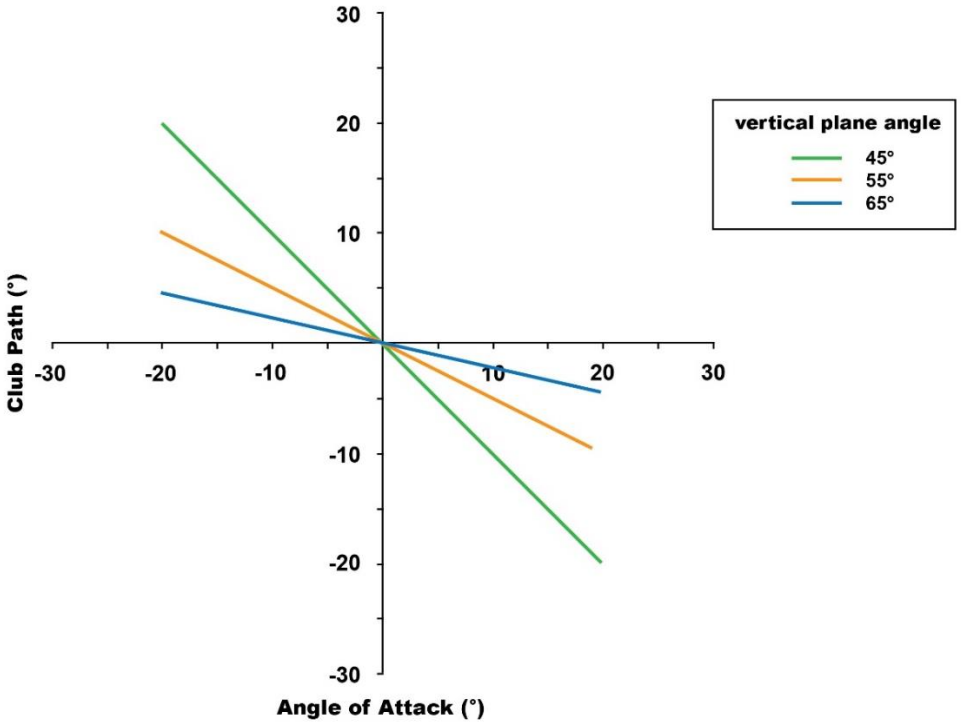


Figure 2.5 Relationships between club path and angle of attack relative to vertical plane angle when horizontal plane angle is zero. Adapted from Morrison et al 2017 (345)

Assuming a horizontal swing plane of zero, the more vertical the swing plane, the greater the change in angle of attack when club path moves away from zero (i.e., starting the ball to the left or right of the target line) (Figure 2.6) (345). Therefore, if it is desirable for the player to reduce variance in club path at impact, a more vertical swing plane could be adopted. Conversely, if reduced variance in angle of attack is desired, a less vertical swing plane may assist. Additionally, this study found that the club path towards impact of better players formed more of a 'sweeping' ellipse (rather than more circular for the lesser player), which supports previous findings (245, 314).

Table 2.6 'Rule of thumb' figures for the relationship between path, angle of attack and vertical and horizontal plane angle. Adapted from Morrison et al 2017 (345).

Vertical plane°	Horizontal plane°	Club path°	Angle of attack°
45	0	1.0	-1.0
55	0	1.0	-2.0
65	0	1.0	-4.5

Other club and plane considerations include:

- club kinematics vary between club used, but the movement time and proportion for each phase of the swing does not (285)
- skilled golfers exhibited well-defined and consistent FSP, for the golf club and motion planes for the arms (266)

- the arms and club head do not move on the same plane (266)
- skilled golfers typically exhibit semi-planar downswings with two distinct phases: a transition phase and a planar execution phase (266)

In summary, optimal club head path and plane can optimise CHS and efficient and accurate ball striking. Therefore, these are worthy of testing to assess the effect of physical or technical interventions.

Impact variables

Given the prevalence of launch monitors in golf settings, device accuracy needs to be known for correct interpretation of findings. A recent study determined the concurrent validity of club and ball measurements for two commercially available launch monitors, *Trackman™* and *Foresight™*. The level of agreement was determined between the monitors and a benchmark system, an optical 3D dynamic displacement measurement system with multiple high speed cameras, previously used in golf research (346). The objective was to determine which measurements possess accuracy appropriate for use in coaching or research (333). Overall, ball parameters had better agreement than clubhead parameters. Both launch monitors demonstrated broad applicability within the coaching domain and demonstrated research applicability for some (mainly ball) parameters (333) (Table 2.7).

Table 2.7 The % of data points within the research and coaching grade reference ranges by parameter and launch monitor. Adapted from Leach et al 2017 (333)

	Parameter	Reference range	Trackman™ %	Foresight™ %
Research grade	Ball Velocity	±1 mph	98	84
	Launch Angle	±1°	87	97
	Launch Direction	±1°	76	71
	Spin Rate	±50 rpm	83	54
	CHS	±1 mph	54	29
	Attack Angle	±1°	38	67
	Club Direction	±1°	45	58
	Face Angle	±1°	66	26
	Dynamic Loft	±1°	65	33
Coaching grade	Ball Velocity	±1 mph	100	99
	Launch Angle	±1°	97	98
	Launch Direction	±1°	98	95
	Spin Rate	±50 rpm	97	91
	CHS	±1 mph	87	67
	Attack Angle	±1°	65	83
	Club Direction	±1°	82	86
	Face Angle	±1°	89	46
	Dynamic Loft	±1°	83	59

Given the inherent inaccuracies of some club head measures in commercially available monitors, some studies have developed bespoke accurate impact measurement

systems. This ensured any inter-relationships could be evaluated without recourse to any preconceived models inherent within commercially available devices (288). This system was then used in a multi-cohort investigation of 285 male and female golfers across all abilities. The study established links between variability in clubhead presentation and variability in shot outcome. Impact location variability heavily influenced launch angle and total distance variability (82) (see Figure 6). Driver ball speed, maximum height and total distance all increased for male and female groups as HCP categories decreased. The variability in horizontal impact position was shown to be the largest factor in determining variability in launch angle and total distance. The most important factor in determining the variability in launch angle was the variability in effective (dynamic) loft (82). Therefore, impact parameters may need specific measurement techniques.

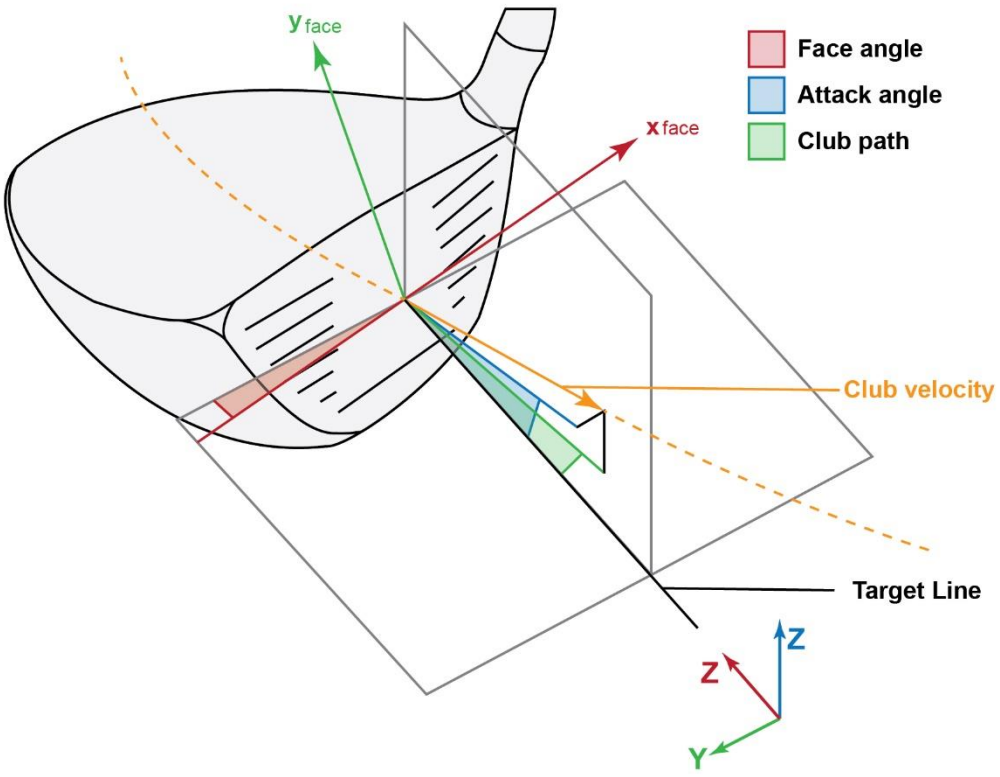


Figure 2.6 Schematic of a shot outcome predictors based on clubhead presentation variables. Adapted from Betzler et al 2014 (82)

Other studies have used measures of ball-striking efficiency such as impact point (127) and smash factor (126, 196) as a GP variable. This approach acknowledges that skill and accuracy must be maintained or improved in equal proportion to power improvement through training interventions. Smash factor is calculated by simply dividing ball speed

by club speed to indicate the efficiency of energy transfer and, therefore, the quality of the golf shot (126). However, only in one study (127) was the launch monitor validated and calibrated against gold standard measurement. Another study used a low-technology method to measure centredness of strike: The centre of the clubface was identified by measuring the width and height. A piece of contact sensitive paper (70 x 35 mm) was placed over this position, so that the centres of the contact sheet and clubface overlapped and was used to quantify the centeredness of hit for every shot. Given the limitations and difficulties of gaining detailed analyses of impact and club head presentation measures from launch monitors, the more time-consuming and expensive research-grade technologies are warranted for additional findings, until technological advancements in launch monitors can overcome this limitation.

Therefore, the study by Sweeney et al (2013) in addition to the aforementioned work of Betzler et al (2012) and (2014), based on accurate, research grade systems, have provided important additional findings on a broader array of impact measures (82, 288, 338). All three studies used regression analyses to quantify the explanatory power of club-head kinematics and ball contact measures at impact on multiple outcome measures. Sweeney et al (2013) used velocity, orientation, path, and *centeredness* (distance from club-face centre) to explain the variability in five dependent variables of early ball flight characteristics (resultant velocity, launch angle, side angle, back spin, side spin). The results of the study indicated that club-head kinematics at impact explained a significant proportion of early ball flight characteristics (adjusted R^2 = 0.71–0.82), even when generalized across individual clubs (338). Additionally, 82% (F = 90.2) of the variance in side angle (direction of velocity vector in the transverse plane) was explained by the club-head rotation in the transverse plane (338). These are additional measures should be considered for their influence in GP, even when devices such as launch monitors in GP environments are unable to capture them.

The ability to consistently produce efficient ball-striking with optimal club head presentation is a worthy pursuit for the competitive golfer. Commercially available launch monitors have allowed for these diagnostics to routinely inform coaches and players in the field. However, both coaches and researchers need to be aware of when research-grade measures and methods are required to be used.

2.6.4 Technical outcome measures

Driver carry & total distance

Driving performance is typically considered as a combination of distance and accuracy from the tee and has become increasingly important to tour golfers. Driving distance on

the PGA Tour has increased by 20-30 yards (18-27 m) over the past three decades (347, 348). This is probably due to advances in technology, training and coaching (347, 348). Since 2011, driving distance is the most important golf statistic in terms of earnings on the USPGA tour (348). The increased dispersion that is coupled with greater distance, and a strategic narrowing of fairways by course designers, has perpetuated a corresponding driving accuracy decrease of 6 – 8% during that time (347, 348) and therefore also explains greater variance in tour earnings (348).

Commensurate benefit from driver distance is experienced by club golfers. Broadie's strokes gained driving statistics applied to the golfer who averages 90 strokes for an 18-hole round of golf reveals that a 26.4 m driving distance advantage converts to a saving of 2.1 strokes for every round played (349). An increase of 14.8 m driving distance represents a saving of 1.2 strokes per round (349). This is similar to professional tournament estimates from the 1960's (248), showing good temporal stability in an evolving game. Therefore, it is not surprising that driver distance has been utilised as an outcome measure for samples of male elite (235, 258), junior (234) and club golfers as well as female club golfers from a broad age range (187, 349, 350). To optimise distance, the physical and technical mechanisms for increasing CHS and ball speed must be present. Additionally, launch parameters need to be optimised, such as angle, spin and direction, and finally roll out once the ball has landed (82). Therefore, both elite and club golfers benefit from the testing of distance as an outcome measure to both tactically informing their game on-course (by knowing how far they hit the ball) and assessing the effectiveness of physical and technical interventions.

There are multiple methods available to test distance. Although often tested indoors with launch monitors and virtual targets, drive distance and accuracy have also been assessed outdoors with real targets (194, 351). Most studies determine driver distance within pre-determined accuracy limits. These tend to be roughly reflective of a typical fairway landing zone. Acceptable landing widths employed in the literature include: a 37 m-wide fairway (136) or 40 m margin (47). The obvious benefit of using driving distance as an outcome measure, over CHS and Ball Speed, as the technical outcome measure is its ecological validity. Unlike club or ball measures, it directly represents a key competition skill that has shown to discriminate ability levels from club golfers to tour players (82, 348). However, driving distance is a composite of other measurements, such as CHS and launch parameters at impact combined with the roll of the ball following carry distance, to explain how it occurred. Therefore, distance should be used as a measure of overall program effectiveness or specific technical interventions, rather than for physical interventions.

Golf skills & shot accuracy testing

Skills testing can provide a convenient surrogate for the capture and analysis of competition performance. Hence golf, like many other sports (352, 353), has created some standardized skills tests to fulfil this same need in a short space of time (354). Skills tests for approach shots have been developed and shown discriminant validity and reliability. Both the Approach Iron Skill Test and the Adapted Nine-Ball Skills Test have shown reliability and an ability to discriminate between elite and high-level amateur golfers (354, 355). These protocols can be used by players and coaches as a practical tool, for talent identification or by researchers as an outcome measure (354). Across all shot-making required for golf competition, the development of valid and reliable skills testing is allowing for efficient assessment of skill. However, tests still need to be validated against competition performance and with females and club golfers.

2.7 Assessing competition performance

2.7.1 HCP

HCP is the most common measurement of on-course competition performance in golf research. It has the advantage of being applicable across all ability levels and is representative of longitudinal competition performance. The purpose of a handicapping system is to enable golf players of differing abilities, men and women alike, to compete on a fair and equitable basis. HCP also enables golfers to monitor their own golfing development over time. HCP is expressed as the number of strokes that the player is entitled to use to adjust their gross score. The player's round-by-round scores returned over time are used to adjust their HCP (356). Most systems determine a golfer's HCP by the average number of stokes over or under par (with a small adjustment to golf course difficulty and field performance) from the most recent 20 complete rounds of 18 holes played. A percentage of the best of these rounds is used, factoring in different competition formats (e.g., stableford, par) and an equation is applied (356-358). A lower HCP is an indicator of a more skilled player. However, until recently, subtly different HCP systems were in operation around the world. The GA HCP System (359), European Golf HCP System (356), USGA system (358) are the most prevalent systems utilised in the golf literature.

The GA HCP System formula takes the best eight scores from the 20 most recent 18 hole rounds and allows 93% of these strokes over par, factoring in course difficulty via a slope rating (357). The United States Golf Association (USGA) formula only differs slightly as it takes the 10 best scores from the 20 most recent 18 holes rounds and allows

96 % of these strokes over par while also factoring in the course difficulty (128, 358). Whereas the European Golf HCP System bears striking differences, despite the use of the USGA course (slope) rating system, utilising five HCP categories, computed buffer adjustments for seasonal conditions along with other variations (356).

To date, this means that the combining of international golf research using HCP as an outcome or categorical measure would possess a small amount of internal error (i.e., a given player may have a slightly different HCP dependent upon the system employed). For the purposes of this literature review and subsequent analysis, this error will be ignored. However, although not pertinent to any of the studies included in this review, for a number of years now the world's leading golf organisations including Royal & Ancient and the USGA, have been working with golf's major handicapping authorities to create a world HCP system (360). On a global level, the world HCP system took effect as of January 2020 which will negate many of the abovementioned differences between HCP systems (360). Thus, HCP will become a more accurate research tool when international comparisons are needed.

2.7.2 Traditional on-course statistics

For many decades *traditional* golf statistics were the most common method of longitudinally tracking GP (354), analysing of different classes of shots hit on-course (347, 361). These competition measures are named 'traditional' due to being supplanted by the modern statistical modelling technique of *strokes gained* (362, 363). Traditional statistics that have been analysed in the literature include fairways hit %, driving distance, greens in regulation, putts per round and stroke/scoring average. Prior to new statistical models, it was purported that scoring average, total scoring, and competitive earnings were the most appropriate means to measure overall performance of elite golfers (14). Other measurements of competition performance exist and can give more granular information to the golfer about where their strengths and weaknesses lay. In the early 2000's, these traditional statistics were refined with the addition of metrics such as total/average distance of putts hole, scrambling % and bounce-back % (scoring a birdie immediately after a bogey) to give a more detailed snapshot of competition performance (364).

However, it had long been suspected that traditional golf statistics needed improvement. Composite measures such as *greens in regulation* (i.e., reaching the green in the expected number of strokes, 2 for a par four) could not distinguish whether a player was good, bad or indifferent on each individual aspect of GP (347, 363). Researchers began utilising PGA Tour Cast web site data to create models that more accurately reflected GP, initially for isolated aspects of the game such as approach shot accuracy, and

validating these models performance against world ranking (347). Regardless of these refinements, traditional statistics have at least two drawbacks: a) Most statistics measure the effect of a combination of shots and do not isolate the quality of individual shots e.g. if a golfer misses a green and then chips in, the number of putts recorded will be smaller not because of good putting, but because of an exceptional chip shot; and b) Most traditional statistics do not distinguish between large and small errors, e.g. whether a fairway is missed by one m or 30 m (363).

2.7.3 Strokes gained

To address the statistical drawbacks with traditional statistics a new *relative shot value* model was formed. Modelling using all shot, relative to the hole, data was formalized to create a complete system where each shot played could be evaluated in reference to a large database. Hence, more insightful information as to where a player's strengths and weaknesses lie became available (363). This modelling was then applied to the largest tour in the world, utilising the strokes of 299 PGA Tour players with at least 120 rounds between 2003 and 2010. Strokes gained has since become the primary method for assessment of performance in golf and is now central to the media broadcasting of the game (362). Shot value, also known as *strokes gained* is a quantitative measure of the quality of each shot in comparison to a data base of shots (e.g., of scratch golfers, the PGA Tour season field. Longitudinal shot value analysis for an individual golfer is a useful way to measure consistency; indicating where practice and improvement are most needed. Models from the rounds of many different players now allow this analysis to be undertaken for amateurs (363) and professionals (362), using their respective data sets.

2.7.4 Official world golf ranking

Official World Golf Ranking (OWGR) is established across a 2-year time frame for professional golfers playing in tournaments eligible for world ranking points. The number of points available is dependent on the level of the golf tour and the strength of the field. Therefore, OWGR is suited as an outcome metric for this duration or longer for samples of tour players. OWGR has some established validity in relation to on-course statistics. OWGR demonstrated small to strong positive correlations with 2006 PGA tour approach shot statistics for 14 randomly selected players from three different world ranking bands. This analysis showed that OGWR had a high correlation with approach shot accuracy from 50-99 yards, (r = 0.56), 100-149yards (r = 0.49), 150-199 yards (r = 0.71), 200+ yards (r = 0.64); the percentage of shots that finished within 5 yards (r = -0.62) and outside 12 yards (r = 0.66) (347). Another study also found a link between official golf world ranking and average monthly time spent on practice, training activities with the

predictive model: 225.901 hours of training x (-0.092 x OWGR) = Total training hours in a 28 day period (112). OWGR has also been used for participant selection to denote an active tour player as they need to have made a cut in at least a tier two event within the past two years to maintain a ranking (98). However, to date, no other study has used OWGR as an outcome performance measure. In summary, OWGR has utility for sampling and as a predictor, but is limited to specific cohorts and durations as an outcome measure.

2.8 Variation across golfing cohorts

2.8.1 Junior golfers

There is a growing body of literature on the engagement of young people in golf (17). As it relates to physical, technical and competition performance, the following parameters have been investigated:

- technical assessment for the golf swing (365)
- effects of tapering on on-course performance (366)
- physiological load of competition under different conditions, e.g. carrying bag, pulling cart or driving cart (367)
- duration and effect on heart rate of pre-shot routine (368)
- stress response during competition (369)
- effect of different warm-ups on performance (133, 370)
- assessment of anerobic and motor capacity (216)
- predictors of low back pain (256)
- flexibility (180)
- balance and movement quality and X-factor in the swing (50)
- physical characteristics and correlation with driver CHS (225) and other GP measures (47, 371)

The breadth of the current body of junior golf literature exhibits gaps relative to Smith's 2010 *'Multidisciplinary approach to golf performance enhancement'* (see Figure 1.1, page 22). To date, the determinants of movement skills, strength and power need to be generalised from other junior sport research (116, 174). However, many of the relationships between physical-technical-competition measures bear similarity to adult populations. For example, CHS has a strong relationship with HCP (226) and can discriminate ability levels in young golfers (288). A correlational study into 36 male (age: 15.1 ± .8 years, HCP: 1.8 ± 2.4) and 33 female (15.1 ± 1.1 years, HCP: 4.0 ± 3.9) elite

amateurs demonstrated strong inverse relationships between CHS and HCP for male (*r* = -0.50) and female (*r* = -0.52) golfers (225).

Predicting score based on physical measures in adolescent golfers can be problematic. Typically study cohorts from development programs possess heterogenous abilities, physical attributes and maturation stage (116). One such study, with 56 15–18-year-old golfers from American high school golf programs, found only small to moderate correlations between a comprehensive range of physical tests and stroke average. Age (*r* = 0.41), Standing Long Jump (*r* = 0.36) and Balance (Stork Test) (*r* = 0.32) were the strongest of these, with the latter only explaining 17% of the variance in score (193). The fact that age was most highly correlated with stroke average shows the challenge of sampling a homogenous cohort in this age range due to maturation effects (372, 373). More recently, studies have utilised simple but effective field tests of power and more homogenous ability levels to discover stronger relationships. 36 male (age: 15.1 ± .8 years, HCP: 1.8 ± 2.4) elite amateurs showed the following strong positive relationships: left Seated Medicine Ball (MB) Throw (*r* = 0.67), and right Seated MB Throw (*r* = 0.61), MB Lateral Throw to the left (*r* = 0 .71), and MB Lateral Throw to the right (*r* = 0.62) (225) and 33 female (15.1 ± 1.1 years, HCP: 4.0 ± 3.9) elite amateurs showed strong inverse relationships between CHS and HCP (*r* = -0.52), mass (*r* = 0.72), CMJ power (*r* = 0.60), MB Lateral Throw to left (*r* = 0.57), MB Lateral Throw to right (*r* = 0.56) (225). Multiple stepwise linear regression analysis identified 77% of the variance in CHS could be explained through Seated MB Throw to left and MB Lateral Throw to left in males, whereas, 84% of the variance in CHS could be explained through Mass, MB Lateral Throw to right and Height in females (225). Further full body strength indices have proven valid in 13 national squad golfers (males: 7, females: 6; age: 15.6 ± 1.5 years; HCP: 2.7 ± 3.0, range: +0.5 – 8).

This youth cohort had also engaged in S&C for an average of two and a half years (range: 0 – 5) prior to having their IMTP assessed on a force plate and golf swing tested using a Trackman launch monitor. Very strong positive correlations were found between IMPT Peak Force and Six-Iron Carry (*r* = 0.91), Driver Carry (*r* = 0.91), Six-Iron CHS (*r* = 0.89) and Driver CHS (*r* = 0.88) (260). This relationship between IMTP Peak Force in these well-trained elite youth golfers was remarkably higher than in a previous study of twelve male recreational golfers (age = 20.4 ± 1.0 years, HCP = 14.5 ± 7.3) who demonstrated a weak (*r* = 0.20) relationship with IMTP Peak Force (100). The difference in study findings could be that the well-trained youth cohort were not limited by physical function or technique, thereby strength measures discriminate ability level more effectively in this cohort. However, a limitation of this study was combining genders for analysis – especially when there was no assessment of maturation status (which varies greatly

between genders in adolescents (174, 372)), which could theoretically artificially inflate the importance of strength.

There is strong evidence that adolescent golfers, like all youth (374), gain important benefit from structured S&C programs. For example, a controlled (age and HCP matched) experimental study with 16 male adolescent golfers (17.3 years, SD = 1.5), showed 3% improvements in CHS and Carry Distance compared to the control group. The intervention group completed an eight-week plyometric training program in addition to their golf-specific practice (28). Indeed, for the junior golf population there are benefits to just once weekly supervised S&C sessions on physical and GP over 12 weeks. 39 male golfers aged 11-17 years (age: 13.54 ± 1.10 years, HCP: 10.26 ± 4.67 strokes) were assigned to either an intervention or control group. Using magnitude-based inferences and confidence intervals, the intervention demonstrated (relative to control): likely increases in CMJ predicted power (308.35W; CI90: 176.97 to 439.73); likely increases in CHS (4.25 mph, 1.90 m/s; CI90: 1.79 to 6.71); possible increases in ball speed (4.09 mph, 1.83 m/s; CI90: 0.78 to 7.40). These benefits of physical training once per week offer a practical introductory step for youth golfers towards structured S&C (74). It would, however, be of interest to assess the benefits of a more frequent comprehensive S&C program on youth golfers over an extended period, to better reflect the elite training environment.

Future research should factor in the established clear differentiations between children and adolescents, which are mediated by growth and maturation (116, 373). This approach can determine the relative importance of performance parameters to the young golfer without the confounding factor of maturation status (375). This knowledge can maximise talent development through improved talent identification and appropriate training (375).

2.8.2 Female golfers

Global golf participation by females is much lower than males, ranging from as low as 15% of members in England (376), 22% in the United States (377) to as high as 35% in Germany and Austria (378). In Australia, females comprise 21% of golf members (379, 380) and 19% of the adult participation (381). The numbers of golf professionals (teaching/coach) are lower still, with only 5% of American teaching professionals being female (377). Conversely, women represent golf's greatest potential growth market, to combat the global decline in golf participation (378). Yet women experience a higher attrition rate than males (381, 382). Given that poor health or injury is the number one reason for attrition, and gaining physical fitness being the third most important reason for joining the sport in Australian golfers (381), female-specific physical requirements of the

sport must be defined. Lack of playing ability and enjoyment are also important factors for females being lost to the sport (377, 381).

Currently, the bulk of studies and assessment protocols are skewed towards investigation of male golfers. A starting point to bridge this gap is understanding the technical differences between genders. To date, studies that relate to physical, technical and competition performance measures that have investigated female cohorts have focussed on:

- traditional and golf specific programs on older female club golfers physical and performance gains (236)
- stress response during practice and competition in female juniors (369)
- swing technique (383)
- thorax-pelvic kinematics (137),
- GRF and GP in Low-HCP golfers (384)
- GRF, kinematic and kinetic differences between male and female professionals (385)
- bone mineral density and body composition in elite golfers (386)
- understanding junior athlete wellness (387)
- muscle strength functional ability and anterior thigh tissue thickness of older recreational golfers compared to sedentary controls (388, 389)
- the physiological demands and physiological support for elite amateurs (390)
- the deterioration of physical characteristics and health across a professional season (391).

An investigation by Zheng et al (2008) into the swing kinematics of 25 female LPGA and 25 male USPGA Tour golfers found a lack of differences in temporal values and most postural values. This indicates similar body kinematic timing and styles between male and female golfers at the professional level (172). However, key differences were found between the LPGA group and the PGA group in shoulder and pelvic orientation, trunk rotation velocity, wrist and elbow joint angular velocity. At the peak of back swing, important differences were found in trunk forward tilt (LPGA: 25 ± 48 and PGA: 31 ± 48), and in pelvis orientation (LPGA: 49 ± 88 and PGA: 42 ± 78). Furthermore, different pelvis rotation at the ball impact was found (LPGA: – 52 ± 118 and PGA: – 42 ± 128) (172). These findings were supported by a more recent study by Bae et al (2018) that found male professionals showed a statistically significantly higher peak joint angle and maximum range of angle in sagittal and frontal axis of the pelvis, hip, and knee than female professionals (385). Due to the these greater ranges and swing speed, male golfers conducted driver swing using stronger force of the lower body and GRF based

on strength of hip and thigh than female golfers (385). The other key difference between genders is wrist angular velocity, where the LPGA group had 29% less wrist cocking than the PGA group (172). Interestingly, this matches injury prevalence data where injury to the wrist was most influenced by gender difference (52, 270). Therefore, golf coaches should expect to see different segment positions at the top of the back swing and strengthening the forearms and wrists should be a high priority for competitive female golfers.

Coaches working with all skill levels have also noted differences when coaching female golfers. A survey of LPGA teaching professionals has established some important physical-technical differences for female golfers (relative to men), that tended to diminish with higher ability (377). A summary of the themes that were presented are:

- Breasts can affect what is considered optimal set-up posture, arm hang and distance from the ball for the individual.
- Women tend to possess less upper body strength but greater flexibility and a wider pelvis.
- Women must rely on alternative sources of power (than men) such as:
    - more rotational movement in both their hips and shoulders
    - a wider stance if lower body stability is needed
    - less reliance on club lag and more reliance on 'turning in posture' (377)

These findings are supported by biomechanical studies where females exhibit higher thorax and pelvis variability for axial rotation at the midpoint of the downswing and ball contact (138). Another, small sampled, kinematic analysis concluded that: women produce a wide swing with larger hip and shoulder joint rotation angles at the top of the backswing, whilst men flexed their left knee more during the backswing – the authors posited that this was possibly to promote a greater weight transfer to the rear leg to compensate for less suppleness (392).

Across ability levels, female golfers have lower CHS, ball speed and driving distance than their male counterparts. The top and median ranked female player of the 158 golfers who competed in LPGA tournaments in 2019 had a season average driving distance of 283.8 yards (259 m) and 257.5 yards (235.4m) respectively (393), which is approximately 13% less than that of the top and median ranked of the 188 golfers PGA Tour male players at 317.9 yards (290.6 m) and 294.1 yards (268.8 m) (394). These differences in driver distance and ball speeds become more pronounced between genders at lower ability levels. For example, in a large sampled study that divided 246 golfers into four ability levels and gender, Low-HCP (HCP = 6-12) male golfers were found to have driver distance and ball speeds 23.1% and 21.0% higher than females, whereas the High-HCP

golfer (HCP > 21) differences were 62.3% and 43.2% respectively (82). In terms of accuracy, multiple linear regression modelling has shown that for seven-irons collegiate female golfers wrist-lagging angle is a predictor for the accuracy, but not for the distance (315). Other variables such as CHS, smash effect, sidespin and backspin were also found to be significant in the model (315). However, absolute invariance of the swing biomechanics is not the goal of highly-skilled female golfers (88). Similarly, assuming there is a common technique that produces optimal performance appears to be invalid for Low-HCP female golfers (383). Indeed, the variations in female GP are not easily explained by differences in swing style or technique alone (172). Therefore, studies that aim to assess the impact of swing performance characteristics may benefit from defining swing style body kinematics (as male studies have) or consider the individual rather than group data (86, 383).

Given the divergent findings as ability levels drop between male and females, S&C interventions may be especially pertinent to High-HCP female golfers. Not surprisingly, female golfers respond in a positive fashion to S&C programs. 12 weeks of combined traditional and golf-specific resistance and flexibility training improved the back flexion ROM, back extension and squat strength of nine Korean female golf professionals. CHS and Carry Distance also increased in the training group compared to control (254). Golf-specific S&C programs for female golfers can increase driver performance without increasing X-factor stretch – aligning with male cohort studies. This suggests increased strength can provide options for the female golfer to utilise contractile elements of the muscular system, and less reliance on the elastic components, possibly reducing the likelihood of back pain (395).

This body of evidence sets the platform for more detailed longitudinal analyses of how some these identified technical and physical measures vary with ability and may influence female GP over time. Golf-specific S&C programs appear to have even greater potential to improve female GP compared to their male counterparts, due to their typically lower levels of strength and power. Therefore, identifying technical and physical measures to monitor is important.

2.8.3 Older golfers

Golf is a sport that can be enjoyed throughout the whole lifespan. Studies on ageing professional golfers and nonagenarians maintaining very high standards of play, demonstrate that golf can be enjoyed and help maintain an active lifestyle into old age (396-398). The population bulge of the ‘baby-boomer’ cohort, who have now reached retirement age, provides an opportunity to grow the game of golf (399). Encouraging

older golfers to begin, resume or remain regular participants in golf also provides health benefits through physical exercise and social interaction (4, 400).

The age-related neuro-muscular and musculoskeletal changes that affect the older golfer have been summarised in a recent review of the literature (117):

- Connective tissue and cartilage have altered proportions and components including increased stability of cross-links & resistance to lengthening in collagen.
- The muscular system has a decrease in the number of motor units and muscle fibers and size of type two fibers.
- Some lean muscle is replaced with fat and connective tissue.
- Muscular strength can begin to decline in the fifth decade of life and at a rate of 1.5% per year from age 60.
- The nervous system loses both structure and function, including:
    - reflex responsiveness
    - one third of spinal cord axons
    - 10% nerve conduction velocity
    - sensory, visual and proprioceptive function.
- The skeletal system experiences bone loss of 0.3 – 0.5% per year after 30, resulting in 35% cortical and 50% trabecular bone loss over a lifetime with women being particularly susceptible after menopause.

Understanding the influence of these changes, combined with findings from age-related interventional studies, provides important considerations for age-appropriate testing and training:

- Despite age-related decline, the muscular system retains plasticity for training effects throughout the lifespan (401), hence the benefit of physical training for the older golfer (134, 222, 402).
- Golf may provide bone mineral density protection in the lumbar spine for female golfers due to the loading characteristics of the golf swing (386).
- Understanding both the unique physical requirements and benefits to older golfers allow for risk reduction strategies for illness and injury and augmentation of training programs for older golfers enjoy quality and longevity in golf (3, 402).

From the golf swing perspective, biomechanical analyses demonstrate unique characteristics for older golfers. When compared to younger golfers, older golfers tend to:

- reach their peak downswing force earlier in the shot (403)
- exhibit a trend toward a faster overall speed or tempo of the shot (403)

- exhibit greater changes in applied force and greater variability (403)
- show a pattern of divergence among the force-time histories from multiple shots suggesting greater (dysfunctional) variation in shot dynamics (403)
- be slower in controlling dysfunctional variation suggesting that as age increases, so may neuro-musculo-skeletal noise (403)
- have lower trail hip external rotator torques during the golf swing (404)

Young and senior healthy male amateur golfers generated comparable (CHS-adjusted) hip torques during a golf swing (except rear hip external rotator torque). This suggests that hip rotational strength and power could be a primary generator of CHS for older male golfers – worthy of testing and conditioning (404). Interestingly, a comparison of older and younger females varied differently to men. CHS showed strong positive correlation with hip internal rotator torques for lead and rear leg (r = 0.70 and .56, respectively). However, when separated by group, these correlations were only significant for young females (r = 0.80) (171). These findings align with previous studies that showed pelvic strength and speeds in the swing discriminate ability level, with a particular importance of lead hip internal rotation speed (122, 224). Therefore, hip rotation power is important to the older golfer and worthy of testing and training.

In terms of navigating an 18-hole round of golf, the physiological requirements for the older golfer to enjoy the game of golf with optimal performance and reduced injury likelihood can be summarised as:

- an ability to undertake low to moderate intensity, measured at 4 Metabolic Equivalent of Task (METs) (405) – although the intensity is relative to the overall fitness capacity of the player, topography of the course, climate and mode of transport for the golfer and clubs (406)
- walking over a five hour period (200)
- an ability to achieve a mechanically sound athletic address posture to enhance ball striking and reduce injury risk (399)
- an ability for each joint to express the necessary mobility and stability under the dynamic forces of the golf swing (399)

There is encouraging evidence from the literature that many of the age-related changes affecting older players and the injuries they experience. A cohesive team-based approach for prevention and rehabilitation is suggested, including:

- professional teaching and coaching to prevent reoccurrence of injuries resulting from poor swing mechanics
- education concerning adequate warm-up practices and back care

- the utilization of a targeted conditioning program for golf, emphasizing the key body structures involved, helps to prevent further injury (399).

Training programs that effectively target these golf-swing and on-course physical needs of older golfers can indeed improve GP. In the late 1990's a study was able to demonstrated that the traditionally held-belief that strength training and golf were incompatible was false (118). This study included basic strength and flexibility program three 40-minute supervised sessions per week for eight weeks with older club golfers, improving CHS and anecdotal driving distance on course (118). Body composition and blood pressure improvements were also reported. Although genders were combined and participants characteristics sparse, these findings suggest potential long-term health benefits for older golfers who also undertake gym training (118).

Furthermore, improved GP can increase motivation and decrease amotivation to play golf (16). One suggestion to improve performance was investigated with a coach-based biomechanical intervention. The intervention included 11 coaching sessions of the Minimalist Golf Swing (MGS), designed specifically with the older golfer in mind. The ''magic move'' of the MGS is maintaining the trail side's (especially the head's) lateral flexion throughout the backswing, resulting in less unwanted movement and a greater likelihood of an accurate ball-strike (16). However, more research is required before this becomes a guideline for the older golfer. Fortunately, for the ageing golfer, both the cross-sectional and longitudinal data over a 20-year period of tour players at The US Masters golf event, support the notion that skilled performance in golf is more resistant to age-related decline than other sports. The quadratic profile of accelerated decline that is commonly seen in performance research is not as evident in golf, notionally because it is a skill-based, not physically-limited sport (407).

Although there are still gaps in the evidence-base for older golfers, it is the conclusion of most authors who have synthesized the literature to date, that conditioning programmes should be highly recommended for all older players irrespective of their level of participation (402). These programmes prevent injury and can improve performance. They should incorporate flexibility, strength, endurance, speed and balance exercises, specifically tailored to the demands of golf in order to be effective (402). This will enable a greater number of older golfers to continue to enjoy the golf -health benefits for a greater length of time.

2.9 Practical applications & limitations

A large and growing body of literature has investigated physical, technical and competition measures in golfers. However, unless measuring the effect of a specific

intervention, most researchers investigating GP have utilised cross-sectional data (i.e., captured at one time point). There is little evidence concerning the longitudinal relationship these physical tests exhibit with technical and competition performance. Even the bulk of interventional studies are less than three months in duration (54), which does not accurately reflect typical long term athlete development process in a sport like golf (22, 143). Furthermore, there is evidence that the performance-related physical and technical characteristics, and therefore training priorities, may differ across gender (66, 172, 173), ability levels (11-13) and age (400, 408, 409). Therefore, poorly described participant characteristics, lack of consensus when describing ability levels cohorts, and combining genders for analysis further limit the interpretability of many GP studies. To extend on this literature, cohort specific analysis within a large heterogenous sample is warranted. Overall, there appears to be less research for female and junior cohorts, however, specific parameter-cohort gaps still need to be quantified.

Throughout the process of this literature review, additional golf performance mediators (i.e., beyond the physical, technical and competition measures investigated in this thesis) were frequently encountered within publications. These are also identified in Smith's (2010) model (Figure 1.1 page 22), and can be summarised as:

- Psychology
    - mental routine
    - shot routine
    - mental toughness
    - life skill
- Recover & fuel
    - environmental acclimation
    - hydration
    - nutrition
    - training and recovery
- Health management
    - injury management
    - podiatry
    - optometry

Although these parameters are not within the scope of this thesis, they warrant inclusion within the continuum to be developed as an output of this narrative review and the mapping review in Chapter 3.

Chapter 3: Study I – A mapping review of the golf performance testing literature

3.1 Abstract

Assessing the physical, technical and competition characteristics of golfers is vital to informing the multi-disciplinary approach to golf performance. However, the implications of these test results cannot be assumed to be generalisable across different gender, age and ability cohorts. This chapter provides a mapping review of the peer-reviewed literature with respect to testing golf performance-related measures. A 3-stage process yielded 192 peer-reviewed from between 1982 to the end of 2019. Data was extracted for analysis in the areas of research design, golfing cohorts, as well as technical and physical capacities that were tested. Each article was assigned to one or several of the 24 cohort categories delineated by a) gender b) three age groups: < 18 years, 18 – 49 years, > 50 years and 3) 4 ability levels: *Elite* where golf handicap index (HCP) was < 0.5; *Low-HCP*, 0.5 – 7.4; *Mid-HCP*, 7.5 – 17.4; and *High-HCP*, ≥ 17.5. The outputs of this study include a) a tabulated, quantitative summary of the literature, b) identified gaps in knowledge by parameter and cohort, and c) the *Physical-Golf Performance Continuum* with a checklist for golf performance testing. 116 of the 192 studies were descriptive or exploratory with and increasing incidence of experimental designs employed in recent years. Male 18 – 49-year-old golfers and technical parameters were more highly investigated than juniors, females, older golfers and physical parameters golfers. This study provides a resource to understand the gaps in evidence for golfers, and an extensive checklist by which to investigate them.

3.2 Introduction

The objective of this mapping review was to quantify the prevalence of the peer-reviewed GP testing literature, relative to each performance parameter (e.g., flexibility, golf swing kinematics etc.) and golf cohort. *Cohort* is defined as a sample of golfers of the same gender, age and ability range. A *mapping review* categorises and 'maps out' the existing literature to inform further reviews and/or primary research by identifying and quantifying gaps in the research undertaken on a topic (56). This approach differs from a scoping review protocol (3) as it is confined to only peer-reviewed publications. Further, it is different to systematic reviews that, in golf, have synthesised the findings of a selection of intervention-based studies (19, 54, 55). Instead, this mapping review can include other forms of exploratory research such as cross-sectional studies that have included GP testing; an important distinction when seeking to identify all available tests and measures available to the golfer.

GP testing can inform various aspects of a golfer's development. Performance testing provides vital information on the overall technical and physical needs analysis of an athlete (31). This analysis can be used to individualise interventions and subsequently monitor the effectiveness of the golfer's physical and technical programs (8, 12). The time-efficient, standardised approach to information gathering provides an accurate gauge for the multi-disciplinary team supporting the athlete (354). Test data can provide a feedback loop for developing individualised interventions to maximise athlete performance (10, 89).

Golf is a sport with many technical, tactical, physical and mental parameters that form complex relationships that influence performance (14, 15). Therefore, it has been recommended that both researchers and practitioners assess the physique and technique of golfers to inform training interventions (8, 10, 14, 20, 176). Many physical and technical tests indicate golf ability in the literature. Studies typically either investigate golfers using physical assessments (e.g., leg power test), technical assessments (e.g., measurement of ball speed), competition assessments (e.g., course statistics or handicap) or a blend of these assessments.

Given the delineated roles of the practitioners that utilise the evidence-base provided by the golf literature, the physical and technical studies need to be quantified separately. For example, a key application of physical assessments is the development of physical training programs for golfers that address: remaining injury-free, ball-striking accuracy, and hitting it further (34). To achieve this, physical practitioners (e.g., S&C coaches, physical/physiotherapists) use physical measures to create physical profiles. These profiles highlight the potential for performance improvement or injury prevention and can

be individualised to their golfing client (10-12, 39, 410). A physical profile of a golfer typically assesses swing-specific movements, including lower limb and glute strength, lower limb rate of force development, rotational power, rotational force control and trunk endurance, dynamic balance and frontal plane control, upper body power, and mobility (8, 34).

The most common application of a technical profile is to act as a 'needs analysis', to assist the golf coach's decision making for technical change for a golfer (8, 35). Coaching interventions informed by this profile may be golf-swing related, such as increasing efficiency of the kinematic sequence (304), which could be defined as a technical process parameter. A coach may opt for a broader strategic on-course goal, such as increasing ball speed with Driver, which could be defined as a technical outcome parameter. This in turn could create more eagle opportunities on par-5's, which would be defined as a competition performance parameter. From a technical perspective, numerous studies have investigated the technical process and outcome parameters that discriminate GP and ability levels (82, 247). For example, Low-HCP golfers exhibit lower variability from shot to shot in clubhead speed and impact location than High-HCP golfers (288).

The interdependency of the four broad performance categories: physical; technical-process; technical-outcome; and competition performance; has driven integrated research to understand better the cause and effect of these variables (8, 36, 50, 143). The perpetual challenge for practitioners is to do this individually with golfers in the field (411). Further, technical-process change with the golfer needs to be undertaken with several other aspects in mind: age, stage and readiness of the golfer for technique changes (35, 410); the influence of the physical profile; Individual swing styles (84, 86, 270); movement variability (6, 87); and the scientific principles of coaching technique change, especially with elite golfers (35). Each aspect could enable or prevent the success of the change in technique. For example, golf coaches may first consider the players physical structure and performance, before addressing technical process short-comings of their game (34). Ultimately, if a technical-process change has been successful, technical outcome improvements, such as increased ball speed should follow (47). Thus, the latter can be used as trail-indicators of the effectiveness of physical and technical interventions (8). Indeed, there may be the assumption that the golfer will naturally implement these technical outcome improvements (e.g., increased ball speed) in the on-course competitive environment. Other than a small-sampled study that suggests a lag of 12 weeks to transfer physical gains to competition performance gains (237) – the literature on the translation of technical outcome measures to competition performance is sparse (14).

The literature that informs golf combines (i.e., a collection of golf-related tests) appears to represent adult male golfers with low handicaps very well. Conversely, a decade ago it was purported that there is limited understanding of the physical profiles of both junior and female golfers in the peer-reviewed literature (15), despite golf's broad participation across gender, ability and age (2, 376, 412). Whilst each golfer should ultimately be treated as an individual, the current body of evidence has uncovered key physical and technical commonalities within golf cohorts. The findings from these studies suggest the need for different testing and training approaches based on gender (137, 138, 172, 173, 377, 413), ability (11, 12, 177, 265, 288) and age (117, 171, 399, 404, 414) groups. Therefore, much of golf's scientific findings are specific to the cohort investigated and should not be assumed generalisable (15). Researchers should not assume homogeneity of different gender, ability and age groups when analysing and interpreting their findings. In addition to knowledge gaps for some cohorts, there is also limited understanding of the causation between health variables such as blood pressure, body composition (4) injury (53) and the physical activity associated with playing golf.

A limitation of many golf studies is the inconsistent reporting of ability-related participant characteristics, such as HCP and ability levels. Within the GP testing literature, there are clear differences in characteristics between elite and sub-elite golfers, (11, 307, 354, 355) which continue to differentiate golfers as ability level decreases (11, 177, 288). Therefore, establishing scientific consensus on ability levels is required prior to the quantifying the literature relative to each golfing cohort.

This century, golf has reaped the benefits of comprehensive reviews in the areas of:

- golf S&C programs (19)
- golf injuries (52, 53)
- warm-ups (55)
- the relationships between golf and health (3)
- electromyography during the golf swing (192, 211)
- physiology and GP (15)
- elite GP (14)

However, a gap in this body of evidence is a review of GP related testing. The breadth and complexity of the interplay between the various GP parameters and different golfing cohorts warrants a review of the current GP testing literature, as is periodically required in most sports disciplines (415, 416).

This review will direct future golf research towards the areas of need, inform practitioners and enable governing bodies to make evidence-based decisions. Therefore, this study aims to produce a quantified map of what *has* and *has not* been investigated for each area of performance testing, for each cohort of golfer.

3.3 Methods

The methods for this review were informed by a previous comprehensive mapping review in the sport sciences (415). A search for peer-reviewed literature pertaining to physical, technical and competition performance testing was conducted across three stages: 1) article search, 2) article retrieval, 3) 'snow-balling' technique for examining retrieved article reference lists for further retrieval of articles. Initial article search terms used combinations and truncations (using an asterisk in the EBSCO host database at the end of an abbreviated version of the common word for multiple variations of the following: 'golf' and 'test*' OR 'assess*' OR 'strength*' OR 'physical* fit*' OR 'strength and conditioning' OR 'condition*' OR 'physiol*' OR 'flexib*' OR 'range of mo*' OR 'resistance train*' OR 'exercis*' OR 'balanc*' OR 'fit*' OR 'measure*' OR 'performance' OR 'techni*' OR 'biomechanic*' OR 'kinematic*' OR 'compet*' OR 'tournament*'. Further titles were identified through reading and inspection of reference lists of articles identified in the structured searches.

Data were extracted from all retrieved articles for analysis.

3.3.1 Study identification

The literature search was undertaken between August 2017 and December 2019. A total of 1084 titles were initially identified and sorted through a multi-stage process displayed in Table 3.1. A resulting 192 peer-reviewed journal articles met the criteria for this mapping review of the GP testing literature.

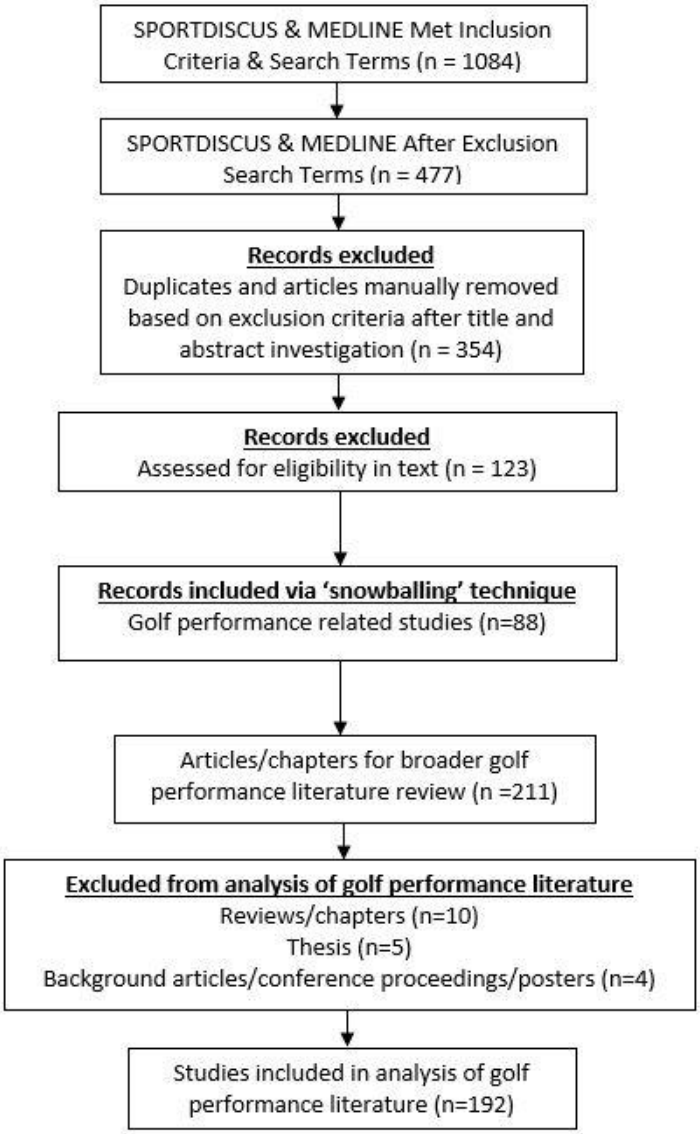


Figure 3.1 Multi-stage search process for GP testing literature

3.3.2 Inclusion and exclusion criteria for the mapping review of the GP testing literature

Inclusion criteria for the mapping review included: a) peer-reviewed; b) article primarily focused on technical testing, physical testing or competition performance testing. Exclusion criteria were then applied to the retrieved articles via in-text examination. Those excluded from this mapping review were:

- review articles
- non-peer-reviewed articles
- abstracts, posters and proceedings from conferences
- abstracts and poster presentations from other conferences
- book chapters
- articles that primarily focused on any of the following: putting; club-fitting; mental game

3.3.3 Data extraction

A systematic approach was utilised for data extraction from each of the identified articles to reduce the likelihood of missed data. Key information was identified within the GP testing article, including:

- the authors
- collaborative arrangements
- research design and environment
- physical parameter tests
- technical parameter tests
- competition performance tests
- cohort and participant information
- inclusion/exclusion criteria
- research design
- research environments
- data collection methods

To quantify the prevalence of each research approach and design in the GP literature, clear criteria were needed to classify each of the identified studies. The research design definitions used for the current analyse were based on current research practice in sport, health and medicine (84, 123, 417-424). In most cases, the research design utilised by each study was well described in the abstract of the article, however, for clarification, the methods section was also consulted. Research design and methodology aspects that were extracted included: number of cohorts used; the duration of the study; time point/s at which data was collected; data collection methods; any additional research design complexity had been included such as a cross-over design, use of a control group, or the inclusion of a classification or methodological component. In each article, the results section was also consulted to determine whether any of the cohorts were then separated into smaller groups for analysis after data collection had occurred, as a cohort is defined as more than just whether an intervention is received or how the data is collected, but also how it is analysed (123).

3.3.4 Identifying participant & cohort characteristics: gender, ability and age

Gender

Each article was reviewed to ascertain the gender of the cohort investigated. This information was obtained from the participants section in the methods. In the few cases where the studies investigated both genders (studies $n = 5$) but did not specifically report

the n for each gender, the total n was split in half to provide an estimate of each gender for the study. If the study did not provide a description of the participants gender (studies n = 8), the sample was assumed to be male only, as male were more commonly measured.

Ability

Existing GP testing studies including comparisons across ability levels have previously been divided into anywhere between two and five ability levels. Importantly, the three studies that divided their sample population into four (82, 177, 288) and the one study with five categories (267) continued to find different results in the golfers' technical and physical test scores, although the five-category study had $n < 3$ in two of its cohorts. Therefore, 4 ability levels were selected to classify our analysis. The four ability levels and how they are represented in the Australian golf participant population is shown in Table 3.1 (412).

Table 3.1 Established golf ability levels based on the mean ranges from GP peer-reviewed literature

Level	HCP Range	Description	Golfer's Without Reported HCP Assigned Level	Australian Male HCP Distribution%	Australian Female HCP Distribution%
1	<0.5	Elite	Tour Players & Professionals	1.5	0.5
2	0.5-7.4	Low-HCP	Elite Amateurs, College	9.1	1.3
3	7.5-17.4	Mid-HCP	Club	44.9	15.2
4	17.5+	High-HCP	None	44.5	83.5

These four ability levels were determined by the means of the upper and lower HCP ranges of all adequately sampled ($n > 9$) cohorts found in studies that investigated two or more ability levels and provided a HCP range across the entirety of the GP testing literature, shown in Table 3.2. Only Tour Players and Professionals were considered for the Elite category. Therefore, for the two studies by Betzler et al (2012 & 2014) that analysed 4 separate ability cohorts and did not include Elite golfers a decision was made that the middle two cohorts would be counted towards the Mid-HCP category.

Table 3.2 GP literature cohort comparisons defined by HCP range and description

Researcher's Cohort Description	Ability Rank* / # Cohorts in Study	n	HCP Low Range	HCP High Range	Ref.
Elite					
Elite-Amateur: Low-HCP	1st/3	45	-	<0	(11)
Professional & Elite Amateur: Low-HCP	1st/2	10	0	1	(12)
Professional & Elite Amateur: Low-HCP	1st/2	10	0	1	(278)
Tour, Professional & Elite Amateur	1st/2	26	-	0	(355)
Professional: Skilled	1st/3	15	-	<0	(328)
Professional: Skilled	1st/3	12	-	<0	(324)
Professional & Elite Amateur	1st/2	14	-	0	(354)
Tour	1st/2	11	-	0	(307)
Totals & Mean		**143**	**0**	**0.25**	**8**
Low-HCP					
Club: Mid-HCP	2nd/3	120	0	9	(11)
Club: High Skilled Category 1 CONGU	1st/2	27	0	5	(345)
College: Skilled	1st/2	11	0	5	(332)
Elite Amateurs & Club	2nd/2	23	0	5	(355)
Amateur: Advanced	2nd/3	12	1	14	(328)
Amateur: Advanced	2nd/3	13	1	14	(324)
Club	1st/3	13	2	10	(226)
Club: Low-HCP	2nd/2	10	0	10	(323)
Elite Amateur	2nd/2	16	0	5	(354)
Elite Amateur	2nd/2	21	0	2	(307)
Elite Golfers	1st/2	15	0	3	(286)
Club: Category 1 CONGU	1st/4	91	0	5	(288)
Club: Category 1 CONGU	1st/4	91	0	5	(82)
Totals & Mean		**466**	**0.31**	**7.08**	**13**
Mid-HCP					
Club: Category 3 CONGU	3rd/4	47	13	20	(288)
Club: Category 3 CONGU	3rd/4	47	13	20	(82)
Club	2nd/2	14	11	20	(226)
Club: Mid-HCP	2nd/3	92	10	20	(11)
Club: Category 2 CONGU	2nd/4	93	5.5	12.4	(288)
Club: Category 2 CONGU	2nd/4	93	5.5	12.4	(82)
Club: Intermediate Skilled	2nd/2	25	10	18	(345)
Totals & Mean		**411**	**9.57**	**17.54**	**7**
High-HCP					
Club: High-HCP	2nd/2	10	18	25	(12)
Club: High-HCP	2nd/2	10	18	25	(278)
Club: Low Skilled	2nd/2	14	20	36	(332)
Amateur: Novice	3rd/3	10	15	36	(324)
Club: Category 4 CONGU	4th/4	15	21	36	(288)
Club: Category 4 CONGU	4th/4	15	21	36	(82)
Club	3rd/3	18	21	27	(226)
Club: High-HCP	2nd/2	10	20	36	(323)
Recreational Golfers	2nd/2	14	18	36	(286)
Amateur: Novice	3rd/3	10	15	36	(328)
Totals & Mean		**126**	**18.6**	**32.9**	**10**

Ability Rank*, 1st denotes the highest ability level cohort in the study, 2nd the second highest ability cohort. E.g., /3, denotes that the study analysed 3 separate ability cohorts

As many high-ability golf cohorts compete in tournaments where lowest gross score wins, they are not required to maintain an accurate golf HCP. Players from these study cohorts where a description was provided (e.g., elite amateur), but no HCP, were assigned to an ability level. This classification was based on the combined mean HCP of cohorts with the same description across the literature (Table 3.3). In this case, only the cohorts that reported a mean and SD were used to calculate the combined mean and variance for this golf cohort description. For example, in Table 3.3, in relation to club golfers:

- 88 studies included golfers described as 'club golfers'.
- These 88 studies included a total of 121 club golfer cohorts (i.e., some used 2 or 3 different ability levels of club golfers).
- 57 (47.1%) of these cohorts (*N* = 3092) provided a mean and SD – this was used to calculate the combined mean and variance to determine where the club golfer cohorts, *without* a reported HCP, would be assigned for classification purposes.
- The combined mean HCP and variance for club golfers was 11.45 ± 44.88. Therefore, the remaining 64 cohorts (*N* = 825), without a reported HCP, were assigned to the Mid-HCP (7.5 – 17.4) ability level.
- Hence, studies investigating a parameter with club golfer cohorts, without a reported HCP, will be counted towards the Mid-HCP category in the results section of this study.

Additionally, tour players and professionals with reported HCP were always HCP < 0, and thus were assigned to the *Elite* group.

Table 3.3 Research data used to categorise golfers without a reported HCP

Golf Cohort Description	# Studies with HCP Mean ± SD Reported	Cohorts with reported HCP Mean ± SD /Total cohorts (% with HCP)	Golfers with HCP Mean ± SD Reported	Combined Mean HCP ± Variance	Golfers without a reported HCP – to be Categorised	Ability Level assigned to Golfers without a reported HCP
Club Golfers	88	57/121 (47.1%)	*N* = 3092	11.45 ± 44.88	*N* = 825	Mid-HCP (7.5–17.4)
Elite-Amateurs	35	33/49 (67.3%)	*N* = 593	3.43 ± 12.85	*N* = 1292	Low-HCP (0.5–7.4)
Collegiate Golfers	16	6/16 (37.5%)	*N* = 64	1.43 ± 2.02	*N* = 318	Low-HCP (0.5–7.4)

In addition to the four HCP levels of performance, three subjective golf ability levels were also included in the analysis. These cohorts, based on current GP literature, included: *Recreational golfers*, an individual who plays golf but doesn't possess an official HCP; *Non-golfer* cohorts who do not play golf but are used for comparison to golf populations;

and *Practitioner* cohorts that include coaches and service providers who have been surveyed or interviewed regarding technical and physical assessments.

To systematically classify each cohort from the literature to an appropriate ability level group descriptor (Figure 3.2), a two-level approach was taken. This approach can be described as 'HCP first – golfer description second'. If HCP mean and SD or ranges (the use of lower and upper HCP range is described in Figure 3.2) were reported, cohorts were assigned to an ability level on this basis. If not, they were arbitrarily assigned based on where the combined mean for the group belonged. The resultant four golf ability levels including HCP ranges and golfer descriptions along with three additional descriptive categories for non-elite groups without HCP. Importantly, the thresholds of the ability levels tend to accurately characterise the four distinctly different types of golfers in the participation pathway, with two industry experts being consulted to assess these thresholds for face validity. The primary objective for defining the four ability groups was to analyse the volume and type of research undertaken on male and female cohorts of differing age and ability levels.

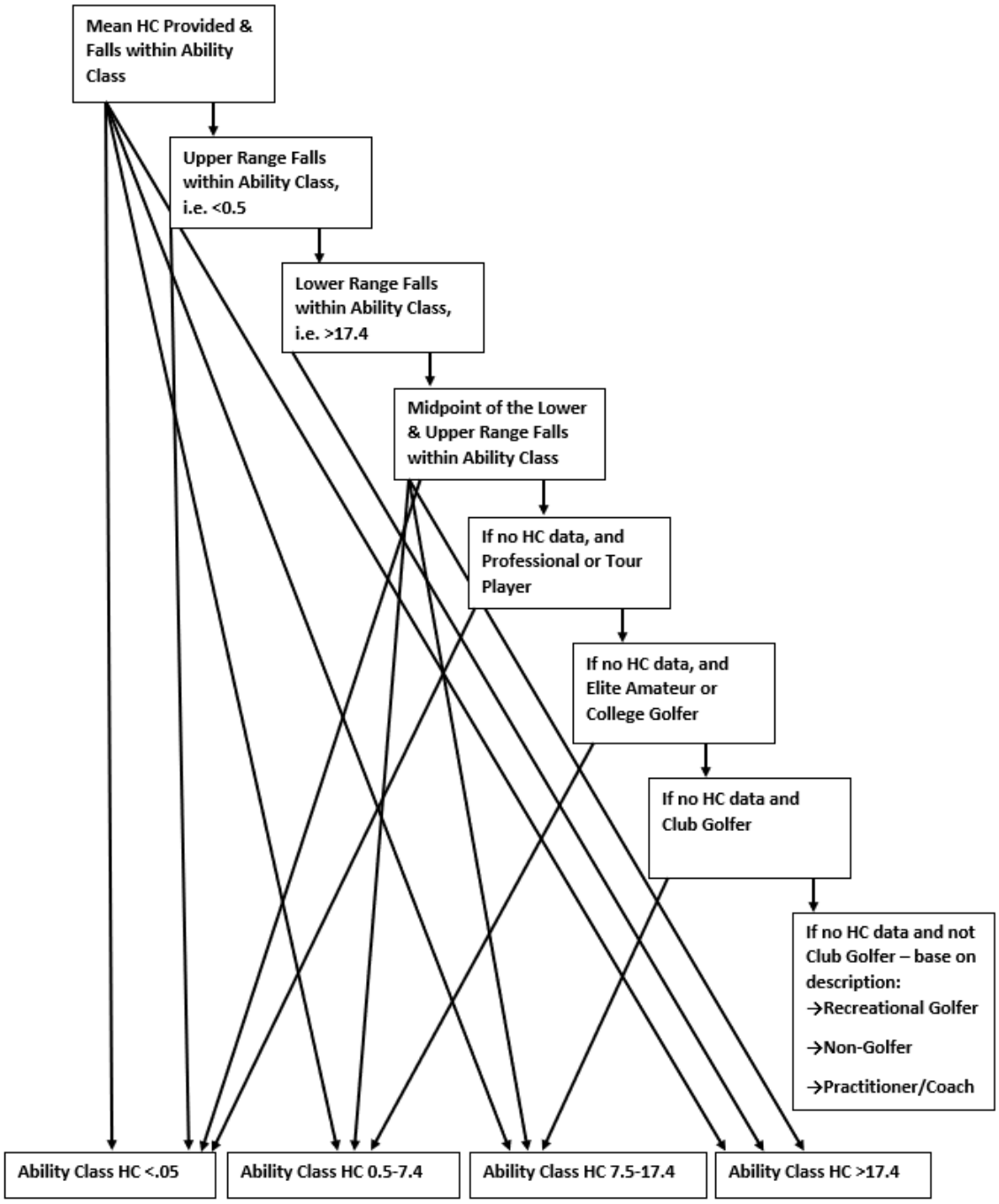


Figure 3.2 Golfer ability classification flow chart to determine cohorts studied

Age

Age was also grouped with categories determined based on the developmental and participative stages in golf (425-427) that align with distinct differences for each cohort: < 18 years of age, 18 to 49 years of age, and > 50 years. Golfers < 18 years of age, may enter junior competitions and are eligible for junior talent identification programs (426). Athletes <18 years also reportedly have unique needs due to incomplete psychological (17, 428) and biological maturation (17, 429) and display different golf swing biomechanics to adults (307). Golfers 18 to 49 years of age reflect the bulk of competitive elite golf, although it should be noted some professional tours have players both above and below this age range. Within this age bracket golfers typically reach their physical peak. Golfers who reach > 50 years are eligible to compete on various seniors tours across the globe (430) and represent the bulk of club golfers (65% of males and 84% of females in Australia) with the average Australian club golfer being 57.5 years (2) with similar representation in England (376). In addition, from this age club golfers typically begin to increase their level of participation in golf due to increased time and resource availability in many countries around the world (431). Further, although marked with wide variance, the physical and cognitive effects of ageing typically begin to increase from this point onwards (117). 23 of the 192 studies omitted age data as the authors did not perceive the information as necessary or relevant to their research. These studies and cohorts were assigned to the *age not reported* (NR) cohort category, as the findings of one age group cannot be generalised to another.

3.3.5 Identifying parameters tested

The analysis of the GP testing literature can be undertaken at different levels of granularity. Granularity as a concept emerged from the science of computer modelling and human-centred information processing (432). A central theme is an information-processing pyramid with multiple levels; each level involving different types of processing (433). This principle was recently used to assess the influence of athlete development to elite performance across a multitude of sports (41). It also aids in the analysis of the GP testing literature to avoid conflation of these levels of detail. In this chapter, aggregation of the elements covered by studies is delimited to the bottom three levels of the pyramid in Figure 3.3. In this study, *parameter* was defined as a measurable factor forming a set that defines a capacity that influences GP (e.g., strength is a physical parameter and body kinematics is a technical parameter). Furthermore, hand grip dynamometry is a strength *test* or *assessment* whose output is a *measure*, and if considered relative to bodyweight would be considered a *derived metric*. Due to the breadth of the GP testing

literature, *parameter-categories* were formed for similar parameters, such as strength and power.

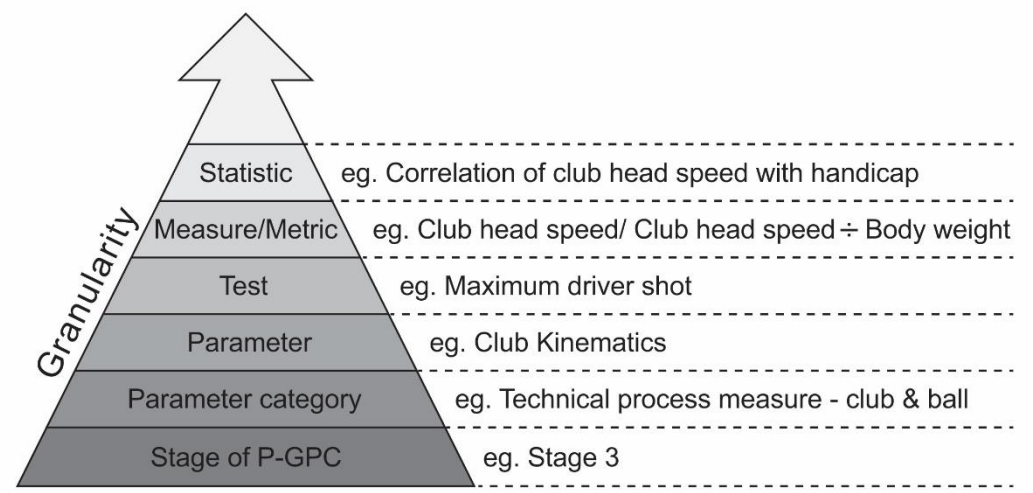


Figure 3.3 Levels of granularity to assess the golf performance testing literature

Technical, physical and competition performance parameters were identified within the abstract with further analysis of the methods and results sections if necessary. Parameters were categorised based on the similarities of their performance mechanisms and thus each category contained multiple parameters that investigated GP. In addition to parameter categories investigated in the current study, some studies also included sport psychology-related tests, however, analysis of these were considered outside the scope of this study and were therefore not reported.

Physical parameter tests

For the purposes of this analysis, only dependent and independent variables were quantified (i.e., their parameters tested, not participant kinanthropometric characteristics such as height and weight). However, it should be noted, in some studies these kinanthropometric variables *were used* as dependent and independent variables and were thus included in the analysis in these instances.

Due to the wide range of physical tests within the literature, five distinct parameter-categories were established based on how these physical capacities are typically trained and tested in the field (i.e., the parameters inform a similar area of athlete development).

- *Kinanthropometry* included the variables which inform the areas of training and testing of body composition, and body proportion measurement for research testing and talent identification. Specific variables that were extracted and categorised into the kin-anthropometry parameter included:

    - body composition
    - muscle cross-sectional area
    - weight
    - height
    - somatotype
    - age
    - body mass index
    - hydration.
- *Balance and Posture* included the variables that inform neurological, postural and movement quality testing and training. Specific variables extracted included:
    - balance
    - stability
    - posture and postural alignment
    - symmetry of ROM, muscle cross-section or strength
    - neuro-muscular measures such as electromyography of exercise and proprioception
    - motor control measures such as segmental movement quality, fundamental movement skills and hand-eye coordination.
- *Flexibility and Injury* identified variables that inform the training and testing of joint ROM and injury prevention. Specific variables extracted included:
    - mobility
    - pain
    - injury prevalence
    - movement screens
- *Strength and Power* included variables that inform the areas of resistance and speed training and testing. Specific variables extracted included:
    - strength
    - muscular endurance
    - power
    - musculo-tendinous stiffness
    - speed
    - rate of force development
    - agility.
- *Cardio-Vascular and Respiratory* parameter-category identified the variables which inform the areas of aerobic and metabolic testing and conditioning. The specific variables extracted included:
    - aerobic fitness measured with maximum volume of oxygen uptake or similar

- heart rate measures and metrics such as variability and recovery
- blood pressure
- respiration measures such as inhalation, exhalation, breath holding and rate
- energy expenditure
- exercise-intensity
- salivary cortisol
- self-reported fitness

Technical parameter tests

Technical parameters were aggregated into two parameter-categories that are functionally different for the process of researchers and practitioners, namely *technical process measures* and *technical outcome measures*.

- *Technical process measures* grouped variables associated with the training and testing of golf swing biomechanics. The specific variables extracted included:
  - 3-dimensional (3D) swing models
  - body measurements and metrics such as kinematics, swing events, segment coordination and speeds
  - swing electromyography
  - effect of different golf clubs
  - 3D ground reaction forces and moments
  - joint torques and work calculations
  - centre of pressure
  - centre of mass and weight transfer
  - plantar pressure distribution
  - movement variability
  - effect of coaching on biomechanics
  - swing faults
  - club kinematics such as CHS and attack angle
  - angular and dynamic positional measurements of the golf club
  - launch parameters
  - impact measurements such as smash factor and impact point
  - launch measures such as back spin, launch angle and direction
  - consistency or variance of impact and club-head presentation
  - ball kinematics such as speed, spin rate and axis
  - composite technical test scores
  - monitoring of golf practice

- *Technical outcome measures* was the second golf swing related category. This category groups variables associated with golf skill outcome measures, but not in on-course competition settings. This included skill-test related variables such as:
    - shot accuracy or score on skills test
    - shot quality subjective rating
    - ball-kinematic measures where the ball has made contact with the ground such as driver carry or total distance and landing angle etc.

Competition performance parameters

Due to the relative paucity of research in (on-course) competition performance, only one category was required.

- *Competition performance* included on-course measures and metrics:
    - tournament results such as field position
    - order of merit position and prize money
    - competition statistics such as stroke average, traditional statistics (greens in regulation, fairways hit) and strokes gained metrics
    - ability level metrics such as HCP index
    - categorical identifiers such as professional, club golfer or elite amateur.

3.3.6 Aggregation of parameter testing prevalence by cohort

The prevalence of each GP parameter was measured by the number of cohorts, total size of combined samples and the number of studies that investigated a variable belonging to the GP parameter category as defined above. Cohorts were categorised as either: treatment (T) group, if they were investigated in an experimental or quasi-experimental study and received an intervention; an analysis (A) group who were observed or assessed in a non-experimental study, where no intervention was received; or as a control (C) group if they were used as a control in an experimental study. Several studies used a cross-over design and therefore used a cohort as both a treatment and control group. In these instances, the cohort was only counted once, as it was the same group of golfers.

3.3.7 Data analysis

Microsoft Excel was utilised to filter all recorded data to count and tabulate the prevalence of each research design feature in the peer-reviewed GP testing research. Next, each GP parameter, (e.g., strength-related or technical-process-related), was

parsed out, counted and colour-coded to indicate the relative prevalence of research for each of the 24 differentiated golf cohorts were relative to each parameter-category. The golf cohorts were differentiated by gender (male or female), age (< 18 years, 18 – 49 years, > 50 years), and ability level (by HCP: < 0.5, 0.5 – 7.4, 7.5 – 17.4, > 17.5). Further information about how the cohort was investigated was also provided denoting each cohort as either a Treatment, Analysis or Control group as well as the sample sizes for each. Where needed, clarification was sought from an additional researcher to ensure the reliability of all extracted data.

3.4 Results

3.4.1 Research design, environments and data

Articles in the sample ranged from 1982 to the end of 2019. The peer-reviewed research in GP has grown exponentially over the past four decades with:

- four studies in the 1980's
- 13 in the 1990's
- 48 in the 2000's
- 125 in the 2010's

This growth in GP testing research has also allowed for an increase in experimental research designs, built on the earlier base of non-experimental descriptive and exploratory designs. The proportion of non-experimental studies is now 60% and experimental designs are now 40%. Not surprisingly, given the nature of GP testing, much of the peer-reviewed literature was quantitative in its approach to data collection and analysis (Table 3.4).

Table 3.4 Prevalence of GP research designs

Research Design	Quantitative	Mixed	Qualitative	Total
NE – Descriptive	12	2	1	15
NE – Exploratory	100	1	0	101
E – Observational	21	0	0	21
E – Quasi-Experimental	39	1	0	40
E – True-Experimental	15	0	0	15
Total	187	4	1	192

NE = Non-experimental, E = Experimental

Table 3.5 and Table 3.6 demonstrate that male golfers have been highly investigated relative to female golfers, and most of the female golf research includes male golfers. There is also a paucity of true experimental designs with female golfers.

Table 3.5 Prevalence of research designs for gender-based cohorts in GP research

Level	Male Only	Female Only	Mixed	Nil Participants	Total
NE – Descriptive	10	1	3	1	15
NE – Exploratory	65	4	31	1	101
E – Observational	14	0	4	3	21
E – Quasi-Experimental	26	2	12	0	40
E – True-Experimental	12	1	2	0	15
Total	127	8	52	5	192

NE = Non-experimental, E = Experimental

From a sampling perspective, the most common research design was to investigate one cohort. Although studies with two or more cohorts are increasing as are experimental designs.

Table 3.6 Prevalence of gender-cohort sampling in GP research

# Cohorts	Male Only	Male & Female	Female Only	Nil Participants	Total
Case Studies/Series, Single-Subject	3	0	0	0	3
Single	67	26	5	0	98
Double	38	18	3	0	59
Multiple	4	11	0	0	15
Total	127	55	8	2	192

Table 3.7 presents the prevalence of the research environments and data collection methods used in the GP testing literature across studies and cohorts investigated. Many of the 192 studies were conducted in multiple environments, used a variety data collection methods and multiple cohorts for analysis. For example, a cohort of young adult male golfers and senior male golfers' physical and technical performance were measured in a biomechanics laboratory and in the gym. A laboratory-based research environment was the most common, utilised by 159 of the 192 studies.

Table 3.7 Environments and data collection methods used in GP research

Research Environments Utilised	Studies	Cohorts
Laboratory	159	252
Gym	29	46
Driving Range	17	26
Post-Competition Analysis	14	11
On-Course	10	14
Computer-Simulated Swing Model	5	5
In-Tournament	4	5
Survey	3	4
Interview	2	2

A common limitation of GP research is sample size, with 75.3% of the 284 total cohorts investigated, including less than 20 participants. Only five cohorts have been investigated with experimental-control studies with sample-size $n \geq 20$, including one with $n > 50$. Additionally, 16 large cohorts, with $n > 100$, have been investigated with non-experimental designs including two exceptionally large sample-size (> 1000 golfers) cohorts which consisted of a survey and retrospective longitudinal post-competition on-course data analysis. The most prevalent GP testing research design, with 71 cohorts (25%) investigated, is a non-experimental design with a sample size of n = 10 to 19.

3.4.2 Participant & cohort characteristics: gender, ability and age

The combined mean age and variance across the male and female cohorts investigated differed between ability levels. Each ability-level cohort's mean age and variance was calculated from those studies where it was reported.

Male golfers

Elite male golfers had a combined mean age of 27.1 ± 17.3 years, calculated from 34 (*N* = 484) of the 57 (*N* = 2902) cohorts, possessing the least variance of the ability levels. Low-HCP (0.5 – 7.4) male golfers had a combined mean age of 25.9 ± 42.4 years, calculated from 79 (*N* =1498) of the 111 (*N* = 1819) cohorts. Mid-HCP (7.5 – 17.4) male golfers had a combined mean age of 46.4 ± 87.2 years, calculated from 57 (*N* = 2901) of the 77 (*N* = 3108) cohorts, revealing this to be the oldest and most varied in age of the male cohorts. High-HCP (≥ 17.5) male golfers had a combined mean age of 37.5 ± 51.3 years, calculated from 12 (*N* = 156) of the 20 (*N* = 235) cohorts. *Recreational* male golfers without an official HCP had a combined mean age of 34.9 ± 43.9 years, calculated from four (*N* = 130) of the five (*N* = 139) cohorts. *Non-golfing* males, typically used for comparison against golfing cohorts, had a combined mean age of 29.2 ± 25.2 years, calculated from 10 (*N* = 240) of the 17 (*N* = 253) cohorts.

Female golfers

Elite female golfers had a combined mean age of 30.8 ± 10.5 years, calculated from four of the six elite cohorts. Low-HCP female golfers had a combined mean age of 20.6 ± 11.6 years, calculated from 32 (*N* = 332) of the 36 (*N* = 341) cohorts, defining them as the youngest female golf cohort. Mid-HCP female golfers had a combined mean age of 44.6 ± 22.8 years, calculated from 15 (*N* = 186) of the 19 (*N* = 208) cohorts. High-HCP female golfers were the oldest cohort with the greatest age variance with a combined mean age of 53.1 ± 79.5 years, calculated from four (*N* = 212) of the nine (*N* = 235) cohorts. Recreational female golfers without an official HCP had a combined mean age of 25.7 ± 3.3 years, calculated from two (*N* = 16) cohorts. Non-golfing females, typically used for comparison against golfing cohorts, had a combined mean age of 21.4 ± 10.3 years, calculated from three (*N* = 43) of the five (*N* = 52) cohorts.

3.4.3 Golf performance parameters by gender, age and ability cohorts

An aggregated summary of the total studies, cohorts and parameter-categories provides an initial view of the GP testing research (Table 8). In addition to the detail provided in the Table 3.8, further cohort-parameter prevalence data includes:

- 177 studies investigating a total of 275 cohorts tested technical parameters,
- 80 studies with 126 cohorts included physical parameters.

Across all golf cohorts, the most highly investigated parameter categories in rank order were:

1. Technical process measures (cohorts = 149)
2. Technical outcome measures (cohorts = 141)
3. Competition performance (cohorts = 82)
4. Strength & power related (cohorts = 61)
5. Flexibility & injury related (cohorts = 58)
6. Balance & posture related (cohorts = 48)
7. Kin-anthropometric related (cohorts = 33)
8. Cardio-vascular & respiratory related (cohorts = 16)

Table 3.8 Prevalence of technical and physical parameters in GP research

Scope of GP Investigated	Studies	Cohorts
Technical Multiple Parameter Tests	98	153
Mixed Technical-Physical Tests	65	105
Technical Singular Parameter Tests	14	17
Physical Multiple Parameter Tests	11	16
Physical Singular Parameter Test	4	5
Total	192	296

To highlight the breadth of the current GP literature, aggregates are colour coded as illustrated in Figure 3.4. Each parameter category included in studies for each cohort, parsed out by gender, ability and age are shown in Figure 3.5, Figure 3.6, Figure 3.7 and Figure 3.8. The aggregated totals on the right side of figures provide a true (not duplicated) total for each gender/ability/age cohort the number of cohorts, sample size and studies that have been investigated. The columns to the left of these aggregated totals provide the breakdown of how often the parameter had been examined by cohort type (i.e., Treatment, Assessment or Control Group). Parameter totals are provided at the bottom of the table section, with males in the top half and females in the bottom half of each table (see Figure 3.5). For example, Elite male golfers were primarily in the 18-49 years age bracket with the technical process parameter-category the most highly investigated for this cohort with 33 studies, 39 cohorts and 426 participants. Low-HCP golfers are the most highly investigated for male and female golf cohorts, the breakdown of which is shown in Figure 3.6. Mid-HCP golfers were moderate to highly investigated and exhibit the highest prevalence of research on >50 years male golfers (Figure 3.7). And finally, the prevalence of research for High-HCP golfers, who are typically the least investigated of the ability levels, is presented in Figure 3.8.



Figure 3.4 Colour code for research prevalence per cohort and parameter

Age (years) M = Male F = Female	Cohort Type	Physical Assessments															Technical Assessments									Totals		
		Kin-anthropometry			Balance & Posture			Flexibility & Injury			Strength & Power			Cardio-respiratory			Technical Process			Technical Outcome			Competition Performance					
		Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	# Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	**Cohorts**	**Total *n***	**# Studies**
M Elite <18	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	21	1	1	21	1	0	0	0	**1**	**21**	**1**
	A	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	0	0		0	0		0	0		0	0		0	0		1	21		1	21		0	0		**1**	**21**	
M Elite 18-49	T	0	0	5	1	10	4	1	10	7	2	16	9	0	0	3	12	153	33	8	75	17	0	0	0	**13**	**153**	**37**
	A	6	119		4	110		9	166		0	0		3	27		25	256		11	186		0	0		**32**	**487**	
	C	0	0		0	0		0	0		1	7		0	0		2	17		1	7		0	0		**2**	**17**	
	Tot	6	119		5	120		10	176		3	23		3	27		39	426		20	268		0	0		**47**	**657**	
M Elite 50+	TAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
M Elite Age NR	T	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	14	3	1	14	2	1	14	11	**1**	**14**	**13**
	A	1	96		0	0		0	0		0	0		0	0		2	14		1	1		12	4989		**14**	**5003**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	1	96		0	0		0	0		0	0		0	0		3	28		2	15		13	5003		**15**	**5017**	
Male Totals		**7**	**215**	**6**	**5**	**120**	**4**	**10**	**176**	**7**	**3**	**23**	**9**	**3**	**27**	**3**	**43**	**347**	**33**	**23**	**304**	**20**	**13**	**5003**	**11**	**63**	**5695**	**51**
F Elite <18	TAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
F Elite 18-49	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	4	0	0	1	0	0	2	**0**	**0**	**5**
	A	0	0		0	0		0	0		0	0		1	6		4	21		1	6		2	8		**5**	**27**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
F Elite 50+	TAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
F Elite Age NR	TAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
Female Totals		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**6**	**1**	**4**	**21**	**4**	**1**	**6**	**1**	**2**	**8**	**2**	**5**	**27**	**5**

Figure 3.5 Elite (HCP < 0.5) male and female elite golfer cohort prevalence of GP parameter category in the peer-reviewed literature (T = treatment/experimental cohort, A = analysis/non-experimental cohort, C = control)

Age (years) M= Male F= Female	Cohort Type	Physical Assessments															Technical Assessments									Totals		
		Kin-anthropometry			Balance & Posture			Flexibility & Injury			Strength & Power			Cardio-respiratory			Technical Process			Technical Outcome			Competition Performance					
		Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	**Cohorts**	**Total *n***	**# Studies**
M Low HCP <18	T	1	8	2	0	0	3	1	25	4	1	8	5	1	6	1	3	50	5	2	16	2	1	6	1	**4**	**47**	**9**
	A	1	6		3	57		3	60		4	96		0	0		2	48		0	0		0	0		**5**	**101**	
	C	0	0		0	0		1	25		1	8		0	0		2	16		2	16		0	0		**3**	**41**	
	Tot	2	14		3	57		5	110		6	112		1	6		7	114		4	32		1	6		**12**	**189**	
M Low HCP 18-49	T	3	43	9	4	39	10	7	132	13	5	61	12	1	31	2	26	371	49	11	151	14	4	76	17	**32**	**502**	**65**
	A	7	270		6	173		7	196		7	268		1	15		31	795		10	230		15	197		**43**	**825**	
	C	1	7		2	18		3	48		2	12		1	7		13	151		5	57		2	20		**13**	**153**	
	Tot	11	320		12	230		17	376		14	341		3	53		70	1317		26	438		21	293		**88**	**1480**	
M Low HCP 50+	TAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
M Low-HCP NR	T	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	3	29	7	2	21	3	1	16	3	**3**	**29**	**7**
	A	0	0		0	0		1	1		1	38		0	0		4	57		1	8		2	18		**4**	**57**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	0	0		0	0		1	1		1	38		0	0		7	86		3	29		3	34		**7**	**0**	
Male Totals		**13**	**334**	**11**	**15**	**287**	**13**	**23**	**477**	**18**	**21**	**491**	**18**	**4**	**59**	**3**	**51**	**864**	**49**	**33**	**499**	**19**	**25**	**333**	**21**	**107**	**1680**	**81**
F Low-HCP <18	T	1	6	1	0	0	3	1	23	3	0	0	3	1	6	1	3	32	5	1	13	1	2	19	2	**4**	**55**	**8**
	A	0	0		3	33		2	30		3	63		0	0		2	55		0	0		0	0		**4**	**66**	
	C	0	0		0	0		1	23		0	0		0	0		1	13		1	13		0	0		**2**	**36**	
	Tot	1	6		3	33		4	76		3	63		1	6		6	87		2	26		2	19		**9**	**157**	
F Low-HCP 18-49	T	0	0	2	0	0	4	2	15	6	3	19	6	0	0	1	8	36	25	5	29	13	1	1	8	**8**	**45**	**24**
	A	2	25		4	28		4	40		3	25		1	9		16	121		8	79		7	49		**16**	**118**	
	C	0	0		0	0		1	8		2	11		0	0		3	16		2	11		0	0		**3**	**16**	
	Tot	2	25		4	28		7	63		8	55		1	9		27	173		15	19		8	50		**26**	**179**	
F Low-HCP 50+	TAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
F Low-HCP NR	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	1	1	5	1	0	0	0	**1**	**5**	**1**
	A	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**1**	**5**	
Female Totals		**3**	**31**	**3**	**7**	**61**	**7**	**11**	**139**	**9**	**11**	**128**	**9**	**2**	**15**	**2**	**27**	**184**	**25**	**17**	**137**	**15**	**10**	**69**	**10**	**36**	**341**	**33**

Figure 3.6 Low-HCP (0.5-7.4) male and female golfer cohort prevalence of GP parameter category in the peer-reviewed literature

Age (years) M = Male F = Female	Cohort Type	Physical Assessments															Technical Assessments									Totals		
		Kin-anthropometry			Balance & Posture			Flexibility & Injury			Strength & Power			Cardio-respiratory			Technical Process			Technical Outcome			Competition Performance					
		Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	# Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	**Cohorts**	**Total *n***	**# Studies**
M Mid HCP <18	T	1	24	2	0	0	1	1	20	2	2	44	3	0	0	1	1	24	1	1	24	1	1	20	2	**2**	**44**	**3**
	A	1	56		1	56		1	56		1	56		1	56		0	0		0	0		1	56		**1**	**56**	
	C	1	15		0	0		1	10		2	25		0	0		1	15		1	15		1	10		**2**	**25**	
	Tot	3	95		1	56		3	86		5	125		1	56		2	39		2	39		3	86		**5**	**125**	
M Mid HCP 18-49	T	0	0	3	6	112	11	0	0	6	0	0	5	0	0	1	6	112	20	10	144	24	0	0	7	**15**	**230**	**46**
	A	3	84		7	94		7	90		6	90		1	11		15	293		14	1078		6	73		**33**	**1309**	
	C	0	0		0	0		0	0		0	0		0	0		2	43		1	20		1	5		**3**	**43**	
	Tot	3	84		13	206		7	90		6	90		1	11		23	448		25	1242		7	78		**51**	**1582**	
M Mid HCP 50+	T	0	0	2	3	31	5	5	64	6	6	80	8	1	13	1	6	80	9	2	25	6	1	9	4	**7**	**91**	**13**
	A	2	22		2	103		1	92		2	1242		0	0		3	114		4	1264		3	1175		**6**	**1288**	
	C	0	0		1	8		3	25		3	25		1	5		3	25		0	0		0	0		**3**	**25**	
	Tot	2	22		6	142		9	181		11	1347		2	18		12	219		6	1289		4	1184		**16**	**1404**	
M Mid HCP NR	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	4	0	0	3	0	0	1	**1**	**8**	**4**
	A	0	0		0	0		0	0		0	0		0	0		3	19		3	19		1	9		**3**	**19**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	0	0		0	0		0	0		0	0		0	0		4	27		3	19		1	9		**4**	**27**	
Male Totals		**8**	**201**	**7**	**20**	**404**	**17**	**19**	**357**	**14**	**22**	**1562**	**16**	**4**	**85**	**3**	**41**	**733**	**34**	**36**	**2589**	**34**	**15**	**1357**	**14**	**76**	**3138**	**66**
F Mid HCP<18	TAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
F Mid HCP 18-49	T	0	0	0	1	7	4	1	7	3	1	7	3	0	0	1	3	10	8	3	10	5	1	2	5	**3**	**10**	**11**
	A	0	0		3	29		2	25		2	25		1	5		5	64		2	47		4	15		**8**	**85**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	0	0		4	36		3	32		3	32		1	5		8	74		5	57		5	17		**11**	**95**	
F Mid HCP 50+	T	2	18	2	0	0	1	3	23	4	3	23	3	1	4	1	4	36	7	2	20	4	0	0	3	**4**	**24**	**7**
	A	0	0		1	6		1	6		0	0		0	0		4	65		2	79		3	84		**3**	**84**	
	C	1	5		0	0		1	5		1	5		1	5		1	5		1	5		0	0		**1**	**5**	
	Tot	3	23		1	6		5	34		5	34		2	9		9	106		5	104		3	84		**8**	**113**	
F Mid HCP NR	TAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
Female Totals		**3**	**23**	**2**	**5**	**42**	**5**	**8**	**66**	**7**	**7**	**60**	**6**	**3**	**14**	**2**	**17**	**180**	**15**	**10**	**161**	**9**	**8**	**101**	**8**	**19**	**208**	**18**

Figure 3.7 Mid-HCP (7.5-17.4) male and female golfer cohort prevalence of GP parameter category in the peer-reviewed literature

Age (years) M = Male F = Female	Cohort Type	Physical Assessments															Technical Assessments									Totals		
		Kin-anthropometry			Balance & Posture			Flexibility & Injury			Strength & Power			Cardio-respiratory			Technical Process			Technical Outcome			Competition Performance					
		Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	Cohorts	Total *n*	# Studies	**Cohorts**	**Total *n***	**# Studies**
M High HCP <18	TAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
M High HCP 18-49	T	0	0	1	2	14	2	1	6	2	0	0	1	0	0	0	4	27	15	3	17	6	1	8	10	**5**	**33**	**15**
	A	1	10		0	0		1	10		1	10		0	0		11	130		3	29		9	101		**10**	**115**	
	C	0	0		0	0		0	0		0	0		0	0		1	10		0	0		0	0		**1**	**10**	
	Tot	1	10		2	14		2	16		1	10		0	0		16	167		6	46		10	109		**16**	**158**	
M High HCP 50+	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**0**	**0**	**1**
	A	0	0		0	0		0	0		0	0		1	42		0	0		0	0		0	0		**1**	**42**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	0	0		0	0		0	0		0	0		1	42		0	0		0	0		0	0		**1**	**42**	
M High HCP NR	T	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	8	4	0	0	1	0	0	2	**1**	**8**	**4**
	A	0	0		0	0		0	0		1	18		0	0		3	37		1	9		2	19		**3**	**37**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	0	0		0	0		0	0		1	18		0	0		4	45		1	9		2	19		**4**	**45**	
Male Totals		**1**	**10**	**1**	**2**	**14**	**2**	**2**	**16**	**2**	**2**	**28**	**2**	**1**	**42**	**1**	**20**	**212**	**19**	**7**	**55**	**7**	**12**	**138**	**12**	**21**	**245**	**20**
F High HCP <18	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
F High HCP 18-49	T	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	4	0	0	3	**0**	**0**	**5**
	A	1	10		0	0		0	0		0	0		0	0		5	16		4	13		3	5		**5**	**16**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	1	10		0	0		0	0		0	0		0	0		5	16		4	13		3	5		**5**	**16**	
F High HCP 50+	T	1	15	2	0	0	0	1	15	1	1	15	1	0	0	1	1	15	2	1	15	3	0	0	1	**1**	**15**	**4**
	A	1	11		0	0		0	0		0	0		1	24		2	23		2	181		1	170		**3**	**205**	
	C	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		**0**	**0**	
	Tot	2	26		0	0		1	15		1	15		1	24		3	38		3	196		1	170		**4**	**220**	
F High HCP NR	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
Female Totals		**3**	**36**	**3**	**0**	**0**	**0**	**1**	**15**	**1**	**1**	**15**	**1**	**1**	**24**	**1**	**8**	**54**	**7**	**7**	**209**	**6**	**4**	**175**	**4**	**9**	**236**	**8**

Figure 3.8 High-HCP (≥17.5) male and female golfer cohort prevalence of GP parameter category in the peer-reviewed literature

Recreational golfers were only represented in the 18 – 49-year age category:

- Male recreational golfers were prevalent in four cohorts (three in analysis groups, one as a control group) across four studies with *N* = 120 participants.
- Females were represented in two cohorts (one for analysis, one as a control group) across two studies with *N* = 16 participants.

Non-golfers were also included in studies as either a comparison or inactive control group. Their prevalence in the literature can be summarised as:

- Non-golfers were utilised across all three age categories (< 18 years, 18 – 49 years and ≥ 50 years) for males and females, except for ≥ 50 years for females.
- Across age groups, male non-golfers were utilised in 10 studies with 15 cohorts (four treatment groups, three analysis groups and eight control groups) with total participants *N* = 299.
- Female non-golfers were utilised in five studies with six cohorts (four treatment groups, one analysis group and one control group) with total participants *N* = 74.
- Two studies included 16 and 21 male practitioners in an analysis cohort and one study included an analysis cohort of 100 female practitioners.

All recreational and non-golfing male and female cohorts that were investigated had their age ranges sufficiently reported, therefore none were assigned to the 'age not reported' (NR) category. Currently, no studies have directly investigated the following male cohorts in relation to GP:

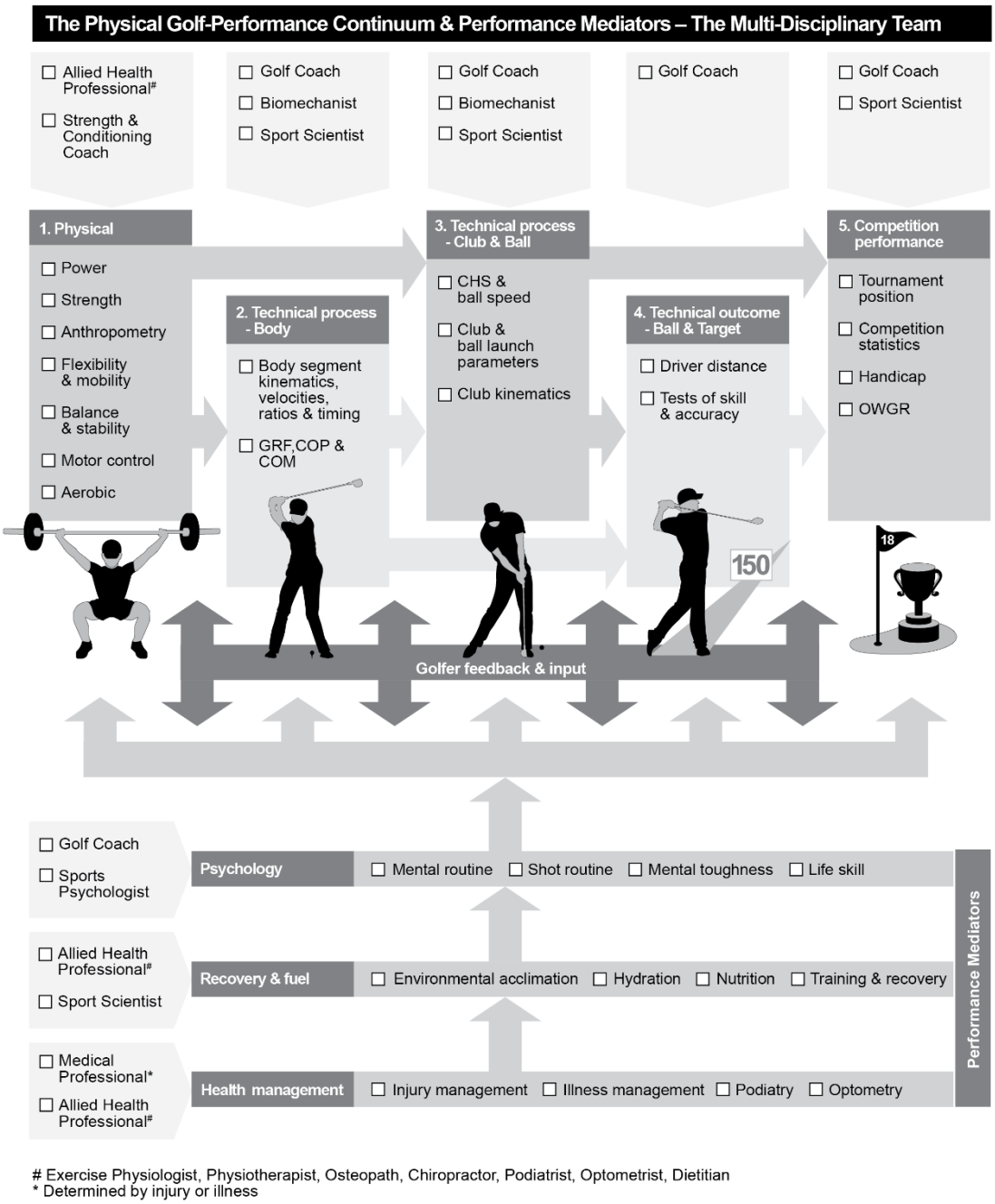
- Recreational golfers < 18 years or > 50 years of age
- Non-golfers < 18 years of age
- Practitioners < 18 years or > 50 years of age.

From the female perspective, currently there are no studies which have investigated:

- Recreational golfers < 18 years or > 50 years of age
- Non-golfers under 18 years or > 50 years.

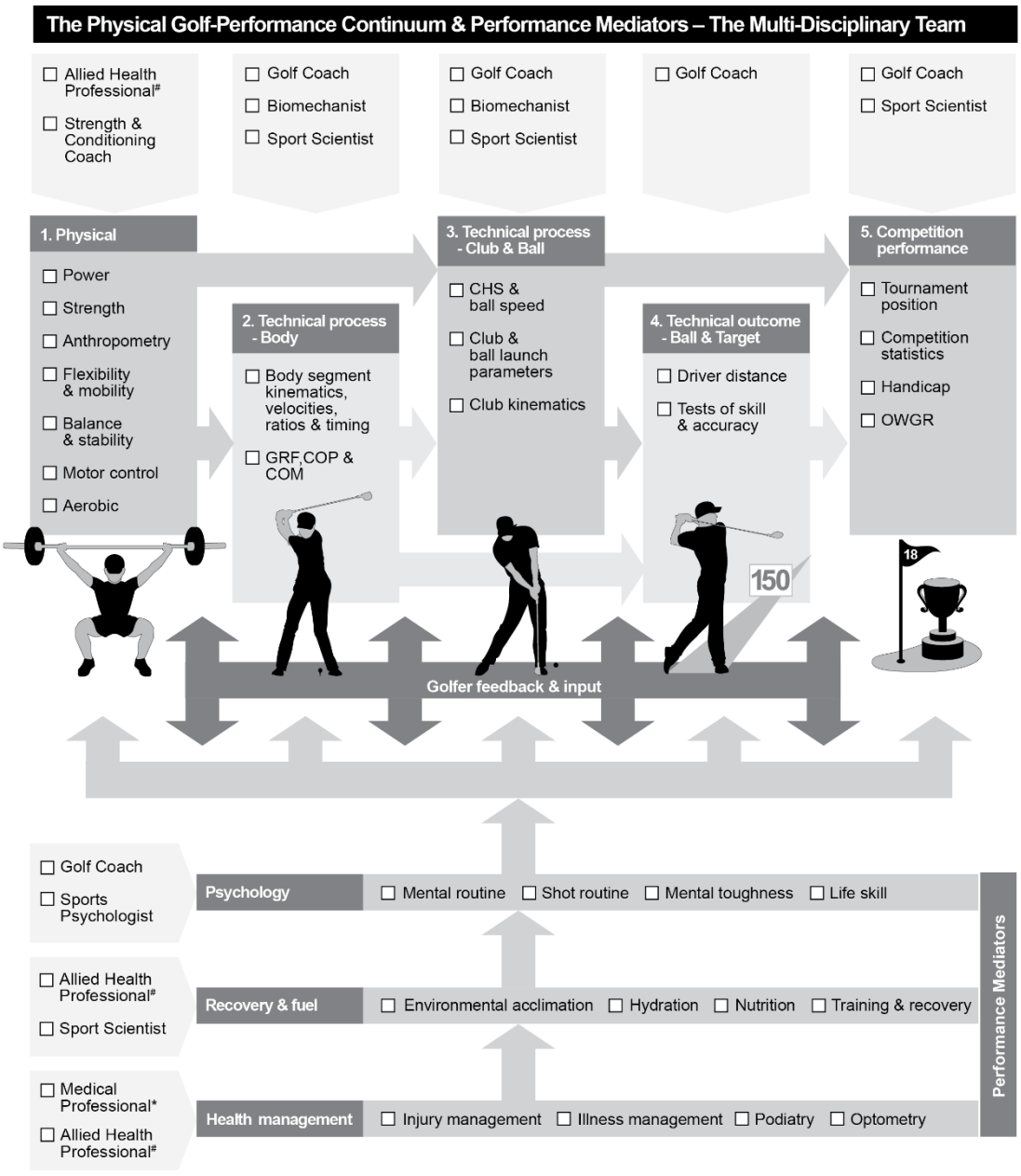
3.4.4 The Physical-Golf Performance Continuum & Performance Mediators

Smith's original (2010) model (Figure 1.1, page 22), the Literature Review in Chapter 2 (page 93) and the mapping review provided in this chapter the basis for the inclusion of parameter categories for the *Physical-Golf Performance Continuum & Performance Mediators* (



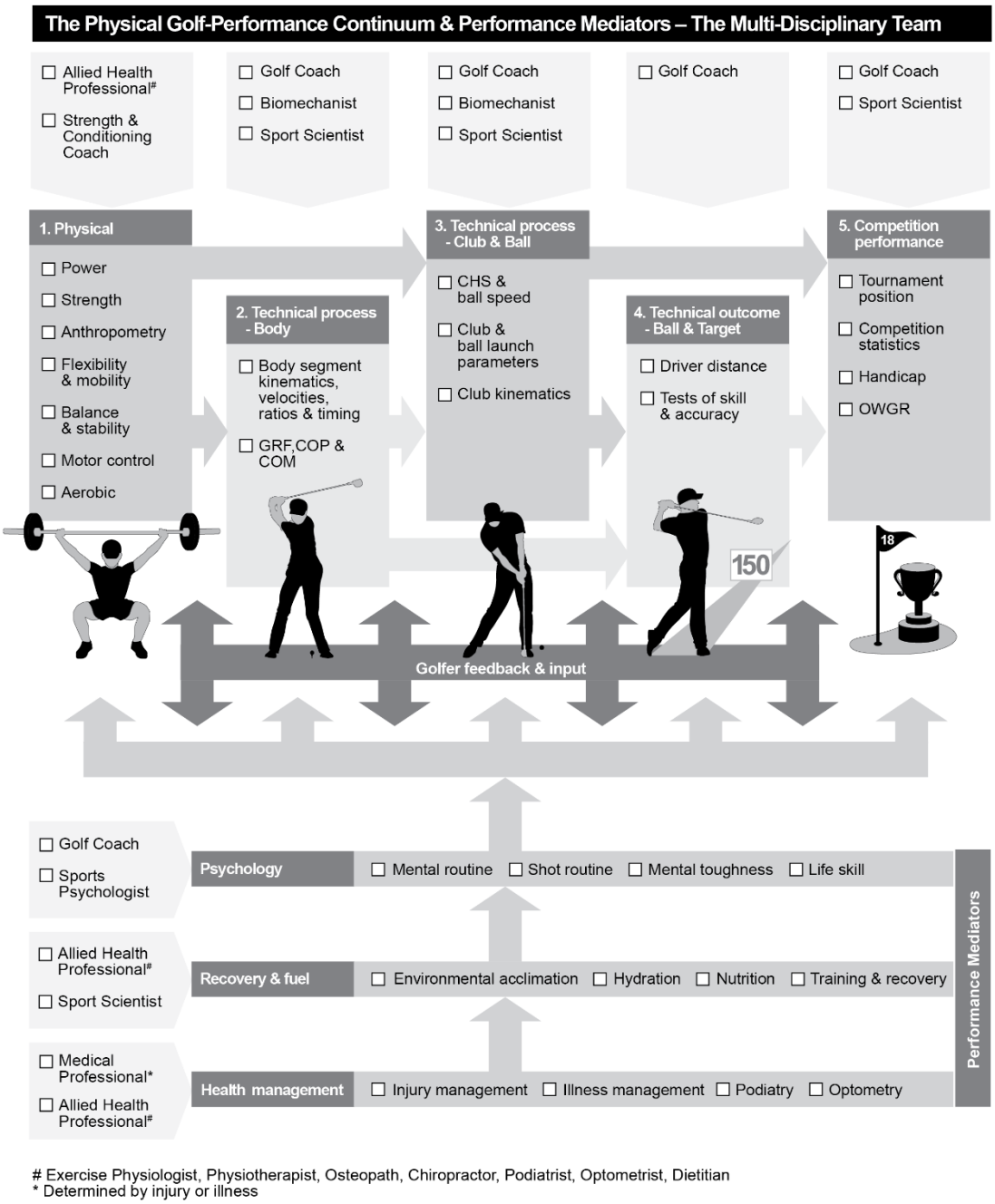
Exercise Physiologist, Physiotherapist, Osteopath, Chiropractor, Podiatrist, Optometrist, Dietitian
* Determined by injury or illness

). This P-GPC is divided into five actionable stages containing physical and technical parameters indicating how they may sequentially contribute to competition performance at *Stage 5*. The large number of measures and temporal differences defined two stages within the technical process parameter-category: *Stage 2 technical process* – body, and *Stage 3* t*echnical process club and ball*. A checklist of practitioners is provided at the top of



Exercise Physiologist, Physiotherapist, Osteopath, Chiropractor, Podiatrist, Optometrist, Dietitian
* Determined by injury or illness

whose scope of practice involves the parameters at different stages of the P-GPC. These practitioners are candidates for multi-disciplinary teams in Australian golf.



Exercise Physiologist, Physiotherapist, Osteopath, Chiropractor, Podiatrist, Optometrist, Dietitian
* Determined by injury or illness

Figure 3.9 The Physical-Golf Performance Continuum & Performance Mediators

3.5 Discussion

This study provides the first mapping review of the peer reviewed GP testing literature, almost 40 years after the first published article. Several measures were taken to ensure an exhaustive sample, resulting in 192 analysed articles. It is contended that this analysis of literature, and the results herein, are comprehensive and reflective of the published articles in the field GP testing. The following summary findings were observed: a) an exponential increase in publications across the four decades, with a shift towards more experimental designed studies, b) a greater focus on adult male in the Low-HCP and elite categories, c) a broad range of GP parameters but a greater focus on technical process and outcome measures than any physical parameters, d) quantitative studies were by far the most prevalent type of research.

3.5.1 Research design, environments and data collection methods

Given the accuracy of testing is vital to the quality of GP research, not surprisingly the most common research environment was a climate-controlled laboratory (

Table 3.7). However, to increase the ecological validity, studies have also attempted to include mixed environments, including gyms, driving ranges and on-course testing (434, 435). GP research bears similarity to sports science in general with primarily quantitative study designs and a lack of mixed research that incorporate qualitative techniques (418). Only five mixed or qualitative studies were found in the analysis. Qualitative research tends to be more open-ended and suited to generating a broader range of hypotheses, that can then be investigated quantitatively (418, 436). On this basis it could be surmised that the GP testing literature could contain 'blind spots' that are yet to be investigated (418).

To draw inferences from research that can inform the training of athletes, adequately powered sample sizes for longitudinal and experimental study designs are required. If executed successfully, these research designs provide practitioners with the highest level of clinical evidence (123, 422). The hypotheses generated for these interventions should be grounded in earlier observational, exploratory and analytical studies (51, 422). This includes a recent trend of harnessing practitioners and experts from the field to gain consensus on clinical phenomena (98, 148, 437). GP research has recently seen in the inclusion of practitioner-interfacing *Delphi-method* study designs which exhibit a greater integration of research and practice (98, 425, 438). The Delphi-method includes surveying experts in the field via multiple rounds, leading to a consensus and can be used to generate hypotheses or experimental interventions, increasing the ecological validity of the research (438). The GP research appears to be appropriately transitioning from primarily non-experimental cross-sectional, correlational research to more robust experimental designs such as randomised controlled trials. However, the feedback loop approach purported by Bishop 2008 (Figure 1.3, page 25) coupled with the parameter-cohort gaps identified in this study will first need to be addressed with hypothesis-generating approaches if interventional studies are to be well-targeted (51).

The golf S&C literature is an example of research design progression. In 2011, authors of a systematic review of golf S&C programs highlighted a key concern in the golf literature relating to a lack of methodological quality (19). This still may be an issue today with only 17 of the 284 cohorts investigated with experimental designs with a sample size > 20 (and only 5 of these including a control group) (Figure 3.5, Figure 3.6, Figure 3.7 & Figure 3.8). Encouragingly, however, 16 of these 17 cohorts have been investigated since the 2011 review, suggesting an improvement in the quality of golf research. When all experimental studies are counted, there is still a large discrepancy between male and female golfing cohorts investigated with 52 for males and 17 for females. This discrepancy is, however, proportionate to participation levels across the

pathway (2, 376) as well as proportional with recent reviews of research in other sports with male and female participation (439). This analysis suggests that the gaps in GP research exist more in the cohort-parameters that are yet to be addressed, rather than the progress of research designs towards more experimental studies.

3.5.2 Participant & cohort characteristics: gender, ability and age

There is ample evidence of technical and physical differences between different gender, ability and age cohorts across the golfing population. Therefore, accurate and detailed reporting of participant characteristics is imperative in golf. Male golfers are largely represented in the GP research with 127 male-only studies, 52 studies with male and female cohorts, eight female-only studies and five without participants. Despite gender differences in golf swing technique (36, 50, 209), physical assessment (36, 49, 50) and golf S&C (118-120), 19 of the 52 studies including male and female cohorts combined genders for analysis (Table 3.6). Studies that combined genders for analysis tend to inflate the importance of male attributes for performance, such as greater strength, power or male technique traits such (e.g., dynamic wrist lag angle in the downswing (172)) as males tend to produce higher scores in the GP dependent variables. This diminishes the interpretability of findings.

A further challenge when interpreting GP research is the inconsistent reporting of ability-related participant characteristics, such as HCP and ability levels. For example, the highest ability for a golfer within a study has been described as ‘tour player’, ‘professional’, ‘expert’, ‘highly-skilled’, ‘Low-HCP’ which are not representative synonyms in the world of competitive golf. This is a key issue to address to evaluate the GP literature as there are clear differences between elite and sub-elite golfers (11, 307, 354, 355). To address this limitation, the current study developed a HCP and description based perspective for identifying golf ability levels (Table 3.1, Table 3.2, Table 3.3 & Figure 3.2). Previous studies have either retrospectively determined HCP or replicated previous HCP thresholds (11, 12). Instead, the four ability levels established in this study were based on a quantitative consensus on all GP studies with a reported HCP range and accompanying description. Four ability-levels were chosen (as opposed to more or less) as it represents the highest number of separate ability levels within studies to still show ($p < .05$) differences in physical and technical measures across multiple studies (82, 177, 288).

This provides an important framework to determine cohort-parameter and research design gaps in the GP literature. This new group classification can also provide golf

researchers with consistent definitions for the classification of participants and enable greater comparison between studies. It is probable that a further golf cohort exists that is yet to be clearly defined in the literature, *Elite Tour Players*. Suggestions to be considered for future research to define this cohort are: active status on major world golf tours (i.e., USPGA Tour, European PGA Tour, LPGA Tour, Seniors Tours); a certain world ranking threshold (e.g., top 100); major winners; and would sit above the current Elite category. To date, more investigation is needed to define this cohort.

The combined mean and variance of age for each cohort provided further descriptive insights into each golfing cohort. Low-HCP male and female cohorts had the lowest combined mean ages, suggesting they comprise young sub-elite, aspiring golfers, for example, collegiate or elite amateurs. Elite golfers were slightly older with a lower variance in age. This reinforces golf as a late specialisation sport (429) and that elite golf cohorts are more homogeneous than the other cohorts. The high variance in age, for both male and female Mid- and High-HCP golfers, suggests the need to investigate these cohorts in smaller age ranges. This would reduce the confounding effects of ageing, which has demonstrated a strong influence on the technique and physique of golfers young and old (116, 117). Researchers must consider the confounding effects of gender, age and ability on the interpretability of their findings and conduct participant sampling accordingly. When the GP literature is divided based on these three categories, cohort-parameter gaps can be identified.

3.5.3 Prevalence of GP parameter categories: gender, ability and age

Each physical or technical parameter category aggregated for the cohorts in Figure 3.5, Figure 3.6, Figure 3.7 and Figure 3.8, includes between three and 21 different related items. For example, the *strength & power parameters* category included: strength, muscular endurance, power, musculo-tendinous stiffness, speed, and rate of force development. Therefore, greater granularity of future analysis may identify further gaps for each cohort and parameter, as described in Figure 3.3.

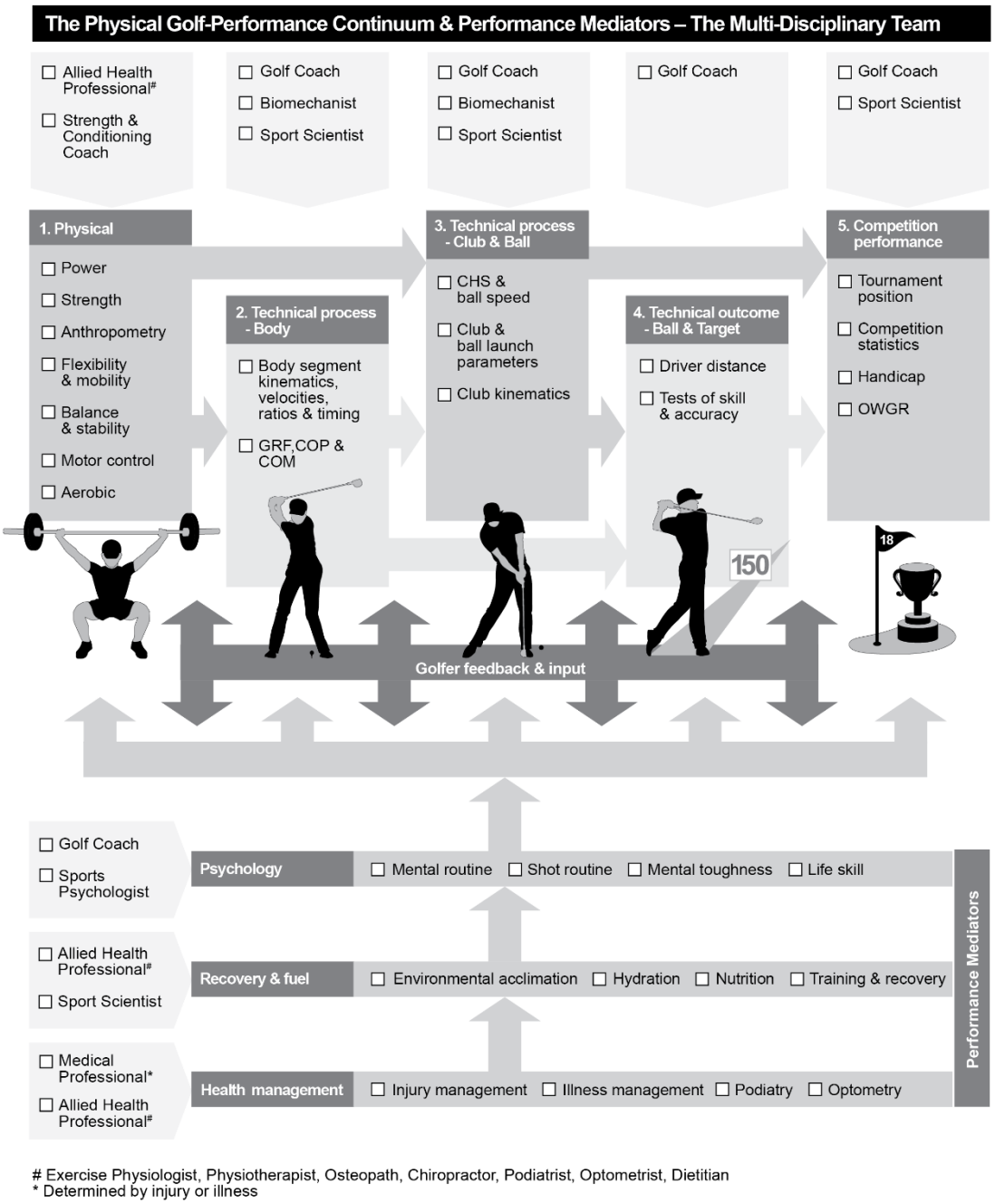
Physical parameters

Based on the prevalence in the GP research both strength/power-related and flexibility/injury-related parameters are equally valued by researchers (Figure 3.5 to Figure 3.8). This is despite the overwhelming findings in support of strength and power parameters (39, 46, 100, 131, 176) and mixed findings for flexibility-related parameters (45, 48, 66, 140, 181) for performance. This suggests that some of the research was

based on commonly held, but not evidence-based, beliefs that golf was a flexibility-based sport (118, 242, 440). However, there is growing evidence that both a threshold-based approach (24, 25, 110) and neuro-muscular view of ROM (107) provide better context to the importance of flexibility. Balance-related parameters are the third most investigated physical parameter, the rationale for which is supported by the moderate correlations with desirable golf swing technical aspects and ability level (36, 48, 328). A lack of consensus on the best method for assessing the balance of golfers is apparent. Kinanthropometric-related parameters were the fourth most prevalent physical parameter. Arm span, height and weight often show a small to moderate correlation with and driver CHS and ball speed (47, 176). This is likely due to greater lever length and increased weight with greater ground reaction force (176). Although common in other sports, measures of physical dimension should not be used to exclude potential candidates from talent identification or development programs (47). After all, the relationships are only associative and kin-anthropometry has shown a poor ability to discriminate between golf ability levels (12). Cardio-vascular-respiratory-related parameters were the least investigated physical parameter in the literature. This is likely due to the physiologically lower-intensity nature of golf (213, 441). Typically, measures of aerobic fitness have not shown ability to discriminate between technical measures or ability level (181, 194), despite being considered a foundational element of GP (14, 15).

Technical parameters

The heavy focus of research on technical process and outcomes in golf is presumably driven by the general fascination with a sport that requires a complex blend of precision and power (192). In these studies, researchers are typically looking for common differences between players of varied ability levels (40, 172), to inform technical coaching decisions. This may have been exacerbated by gaps in knowledge that have been uncovered, only in the most recent decade or so. To this end, advancements in technology and data analytics have created greater understanding in the technical mechanisms of GP, such as the *new ball flight laws* (442, 443). As an example, these new laws have brought greater understanding to researchers and practitioners such as 4:1 ratio of influence of face angle versus club path on ball flight (16, 299) and have superseded earlier cited work in this discipline (444). Given the large number of measures included in the technical process category, and temporal differences, this category was split into two categories for the P-GPC (



Exercise Physiologist, Physiotherapist, Osteopath, Chiropractor, Podiatrist, Optometrist, Dietitian
* Determined by injury or illness

). These are Stage 2 – *body measures* and Stage 3 – *club and ball measures*.

The large focus on technical outcome-related parameters suggests the strong appetite of researchers to draw inferences about how the body influences shot outcomes (8, 27, 142, 176). Another common approach was investigating the relationship between technical outcome-related variables and ability level. Skill-based golf research aims to establish the commonalities of high performing golfers (226, 354, 355), creating opportunities for performance bench-marking in talent development programs (68, 70, 83).

Competition performance parameters

The predominant parameters investigated for competition performance were retrospective on-course statistics and HCP. Competition measures are vital to anchoring earlier parameters in the P-GPC to an ecologically valid outcome. Prospective longitudinal studies investigating competition performance can provide a true indication of the effectiveness of an intervention if adequate detail is provided (51). Four studies used competition performance measures to quantify the benefit of an S&C program on small homogenous samples. Three of these provided full details of the S&C intervention: two showed significant HCP improvements (28, 29) and one no change in HCP (234). The fourth study provided scant details of both program and professional tournament performance (150). More research is needed to determine the relationships between physical, technical and competition parameters across golfing cohorts.

Female golfers

Evidence suggests that female golfers differ physically (52, 369, 386, 391, 413, 445) and technically (137, 138, 172, 173, 383) from men. These differences tend to increase as ability levels decrease and age increases (171, 388, 389). Therefore, each female golfing cohort (age and ability) requires its own comprehensive investigation of parameters to determine their unique attributes and needs (115). The current GP literature demonstrates that more than half of the technical and physical parameters in female cohorts have had low investigation, if at all. This implies that the physical and technical training of junior (< 18 years), senior (> 50 years) and High-HCP (≥ 17.5) females is poorly informed. Furthermore, despite the increased professionalisation of female golf, elite female golfers' technical and physical training still relies primarily on a practitioner's own experience and/or generalising the research on elite male golfers.

These gaps create challenges for both the talent development pathway. Equally, the female golfers aged over 50 years or with High-HCPs – the most populous female golfing cohorts – remain largely under-investigated (2, 412). The results of this mapping review mirror previous findings that females are under-represented in the industry, the literature and often an after-thought when developing golf coaching programs (15, 413, 446).

Junior male golfers

Junior male golfers (< 18 years) have had all parameter categories investigated, but only with between one and five studies for both Low-HCP and Mid-HCP ability levels.

Strength, power, speed and endurance parameters are of the highest interest to researchers for this cohort at both ability levels, followed closely by flexibility parameters. The junior male cohorts were the only cohorts where physical parameter categories were more prevalent than technical parameter categories. This suggests that informing the S&C for junior male golfers is viewed as relatively important; the modern understanding that physical capacity is required to prevent injury and create a stable foundation for skill execution in young athletes (22, 25).

Low and Mid-HCP 18-49-year male golfers

Low and Mid-HCP male golfers are the most highly investigated of all cohorts (Figure 3.6 and Figure 3.7). This is possibly due to the convenience they offer researchers for gathering a homogenous sample of golfers. In our analysis Low-HCP male golfers include collegiate and elite amateur golfers, who are often part of development programs of similar age and ability. Golfers within development programs are often accessible at regular days and times over an extended period. Mid-HCP male golfers are also highly available to researchers as they represent the most populous participant group in Australian golf (412) and are often recruited as regular attending members of a golf club. Furthermore, multiple studies have included these two golf cohorts in studies to compare physical and technical traits between the two ability levels to better understand what enables good GP.

Older male golfers

Despite representing the highest participating cohort of golfers across the globe, male golfers over the age of 50 are the least researched male golfing cohort. As a result, technical and physical understanding of this cohort must be generalised findings from younger or more-proficient golfers. Although, post-competition statistical analysis studies have used samples from seniors' tours and not reported age. It could also be argued that if any cohort could generalise findings across ability levels, it would be the older golfer. Despite differences across golf ability levels in this cohort, they share one common trait that they must combat, *the effect of ageing* (117). The effect of ageing would not necessarily differ greatly across ability levels. Therefore, until the evidence-base becomes more robust, pooling the findings for all older golfer within their genders would, it seems, provide the best available information for practitioners.

Elite male golfers

Research on elite golfers is used to derive exemplary traits for physical and technical benchmarks for aspiring golfers (i.e., those who wish to progress to elite). These could be adopted in the talent development pathway and used to create individualised profiles for athletes to guide interventions. All parameters have been investigated for this cohort (Figure 3.5). However, each study should be assessed for its utility to create benchmarks (i.e., are the samples used adequately powered?). All elite golf cohorts were in the 18-49 age category, although it was common for studies on tour statistics to omit age. Kin-anthropometric, flexibility/injury and strength/power parameters can provide some guidance for S&C with elite golfers (8). However, balance and cardio-respiratory related parameters are the least investigated physical parameters. Given the close mechanistic association between balance and golf technique (48, 324, 328, 329), further research is recommended to assess balance-related parameters with elite golf cohorts.

3.5.4 Practical applications and limitations

The evidence for the sequential interactions between physique, technique and competition performance (8, 14, 15, 27) require a conceptual model to guide the investigation of these relationships (447). The synthesis of findings from the literature review in Chapter 2, this mapping review and the original multi-disciplinary model of Smith (2010) provides the basis for the P-GPC (15). The P-GPC extends on Smith's (2010) model (Figure 1.1, page 22) because it a) provides a temporal organisation of the mechanisms of GP, indicating inter-parameter relationships that require investigation, b) provides the tester with a checklist of parameters from each stage of the P-GPC, to assist comprehensive combine formation, c) provides a list of end-user practitioners involved in the multi-disciplinary approach at each stage of the P-GPC. In research and GP programs, the P-GPC can be used as a conceptual framework to investigate the sequential mechanistic contribution of physical and technical measures to competition performance, at the group or individual level. The peer-reviewed golf research and readily available technologies allow for valid and reliable data to be collected at each of these five stages. Indeed, the P-GCP can be added to, extended upon or even re-ordered by future research. Therefore, investigating the relationships both within and between each stage of the continuum provides improved specificity to the evidence-base for practitioners. Analysis guided by the P-GPC can be undertaken at the group or individual level, by researchers or practitioners in the field.

A limitation of this mapping review was the exclusion of conference proceedings, which may have resulted in an under-representation of certain parameters and cohorts being assessed – although it is likely that the ratios of investigation are similar to what is presented in this analysis. The decision to exclude this section of the literature was due to uncertainty around the peer-review process for some conference-based publications and the desire to constrain the search to high-quality publications. Future mapping reviews may wish to include these publications for thoroughness. Despite this limitation, further exploration of the relationships presented in the P-GPC, particularly in the gaps identified by this mapping review, will lead to better informed benchmarks and interventions for golfers.

3.6 Conclusion

This was the first mapping review of the GP testing literature. The findings provide researchers, practitioners, and programs with a 'quick view' of the evidence-base across the golf participation pathway to inform decision-making. The study detected a recent increase in research dedicated to understanding GP. GP research has grown to almost 200 original journal articles spread over multiple cohorts and parameters. Since the 1980's, the research has progressed from primarily cross-sectional and observational studies to a larger proportion of experimental study designs in the most recent decade. Technical parameters have been studied more highly than physical parameters, although a higher proportion of physical parameter studies were integrated with technical parameters. Far more is known about male golfers than female golfers. Junior and older golfers are far less investigated than 18 – 49-year-old golfers, which presents a challenge to both the talent development pathway and retention of older golfers.

Despite positive steps towards more experimental longitudinal designs, golf researchers could ensure appropriate scientific rigour and contribution by a) aiming for larger sample sizes per cohort analysed, b) accurately reporting participant characteristics, c) analysing genders separately, d) targeting gaps in performance parameters and cohorts, and e) utilising comprehensive combines that span the P-GPC. This approach will lead to further growth in understanding GP across cohorts.

Chapter 4: Study II – Formation of comprehensive golf combine to inform golf performance

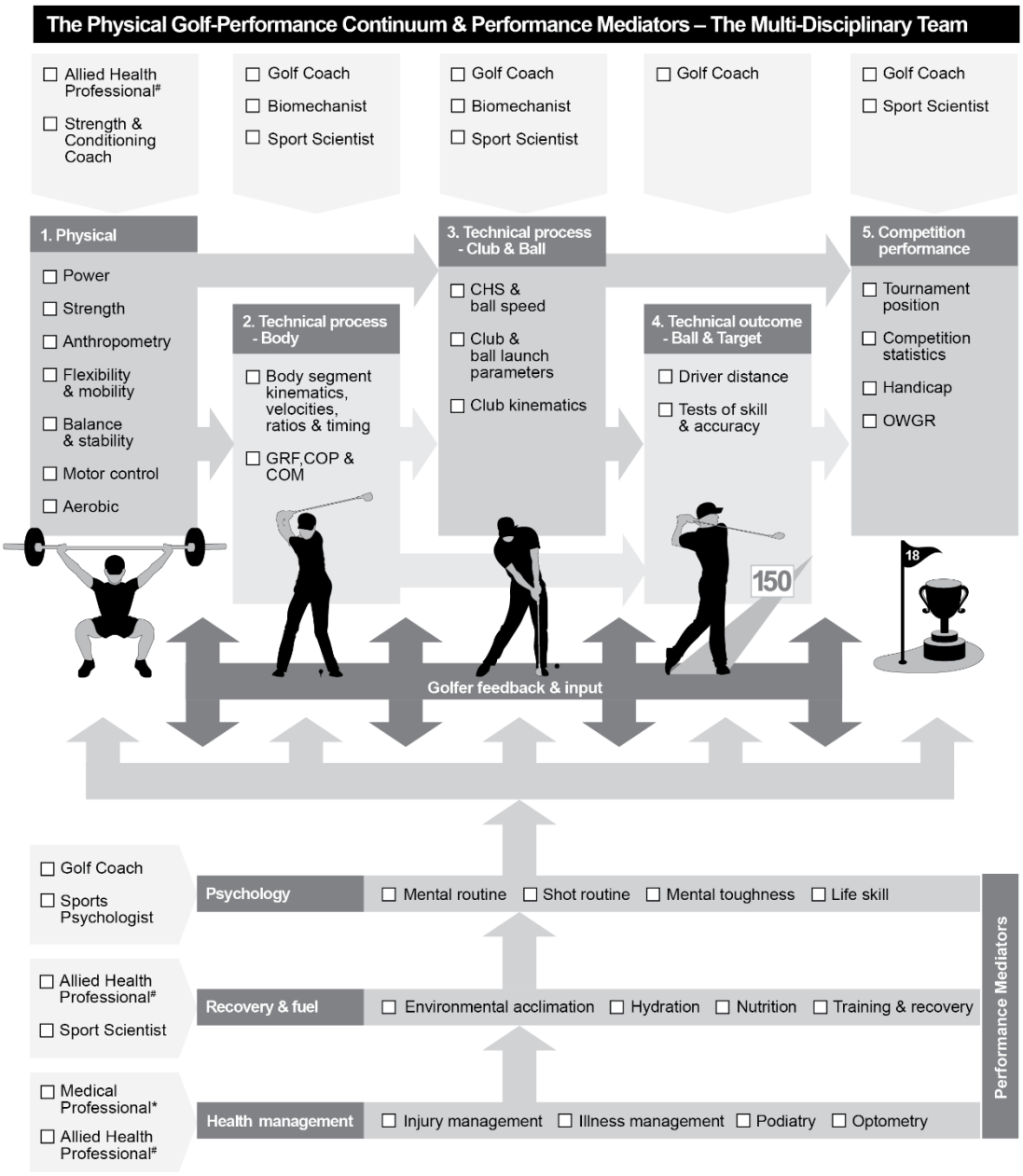
4.1 Abstract

Golf performance is influenced by the sequential, mechanistic contributions of physical and technical parameters described by the Physical-Golf Performance Continuum. Therefore, a comprehensive golf combine (i.e., that includes tests from each stage of the continuum) can provide profiles of the athlete's strengths and weaknesses relative to benchmarks or existing data sets, informing physical and technical training programs. In this study, an exemplar comprehensive golf combine of 25 tests with established measurement properties was formed. The 22 physical tests selected included: three kin-anthropometry tests – Arm Span, Height, Weight; six flexibility tests – Sit and Reach, Thorax Seated Rotation, Shoulder External Rotation, Seated Hip External and Internal Rotation, Modified Thomas Test; one balance test – Modified Star Excursion Balance Test; five strength tests – Grip Strength, Hip Adduction, Hip Abduction, Hip External Rotation, Trunk Rotation; seven power tests – Vertical Counter-Movement Jump and Reach (including estimated power), Counter-Movement Jump (Hands on Hips) Peak Vertical Force, Seated 3 kg Medicine Ball Throw, Sit-Up 3 kg Medicine Ball Throw, Lateral 3 kg Medicine Ball Throw; and one endurance test – YMCA 3 min Step Test Heart Rate Recovery at 45 s. The two technical tests selected included: a Maximum Driver Test – including simultaneous measurement of ground reaction force, three-dimensional biomechanics, club and ball kinematics; a 120 m Approach Shot Test – including measurement of club and ball kinematics. The tests from this combine produce 156 measures (74 physical, 82 technical) to gain insight into the physical-technical-competition performance relationships of golfers. The resultant output of this study is an evidence-based golf combine to investigate the mechanisms of golfer performance and inform the multi-disciplinary approach to training of golfers.

4.2 Introduction

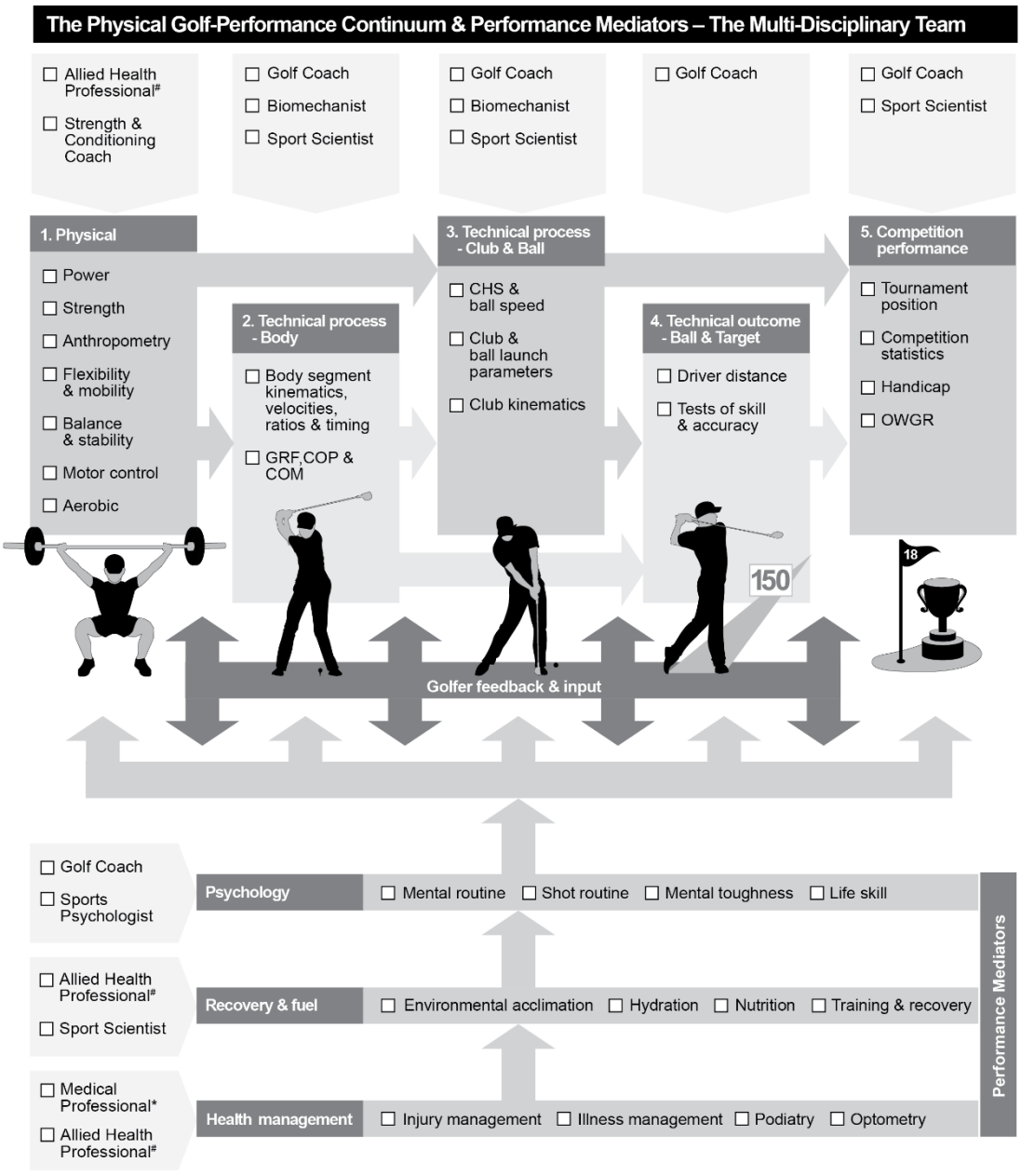
4.2.1 Background of golf combines

Like many sports, successful player development in golf requires a comprehensive and integrated approach to physical and technical development (8, 15, 34). Although the multi-disciplinary approach is indicated as best practice (15), parameter-omissions from combines in the literature have made it difficult to determine the mechanisms that specifically contribute to performance gains (27). Therefore, gaps still exist in the evidence-base that informs practitioners (e.g., golf coaches, allied health, S&C coaches, medical practitioners) who operate at various intersections of the P-GPC. This confusion is compounded by many commercially available technologies that instantly produce dozens of metrics for every golf shot. Although data mining techniques are available to assist, it is often necessary to utilise domain knowledge to determine whether discovered patterns are novel and general (295). Furthermore, in applied GP settings, findings also have to be actionable to be valuable (295). Therefore, forming a combine to assess golfers in a comprehensive manner is an important step to fostering an integrated, multidisciplinary approach.



Exercise Physiologist, Physiotherapist, Osteopath, Chiropractor, Podiatrist, Optometrist, Dietitian
* Determined by injury or illness

(



Exercise Physiologist, Physiotherapist, Osteopath, Chiropractor, Podiatrist, Optometrist, Dietitian
* Determined by injury or illness

, page 126) can inform the formation of a comprehensive combine to assess golfers. However, covering the breadth of all 5 Stages of the P-GPC *and* Performance Mediators requires an in-depth knowledge of many disciplines that contribute to GP. A doctoral investigation that attempted this target could only do so in cursory manner, due to the time and volume of work required. Consequently, this thesis is delimited to the physical, technical and competition performance disciplines.

There are multiple combines in the golf literature that cover at least one parameter from between two and four stages of the P-GPC, each with varying complexity and cohorts investigated (11, 12, 36, 50, 143, 225, 239). This study will extend upon the existing

literature by forming a comprehensive combine (i.e., one that investigates parameters from all stages of the P-GPC) from the checklist of parameters from the 5-Stage section of the model only (Figure 4.1), and thus pertains to the practitioners or researchers with an interest in these stages. From a research perspective, gaps in the evidence base of the P-GPC can be addressed by analysing grouped data from physical (Figure 4.2) technical (Figure 4.3), and competition (Figure 4.4) profiles.

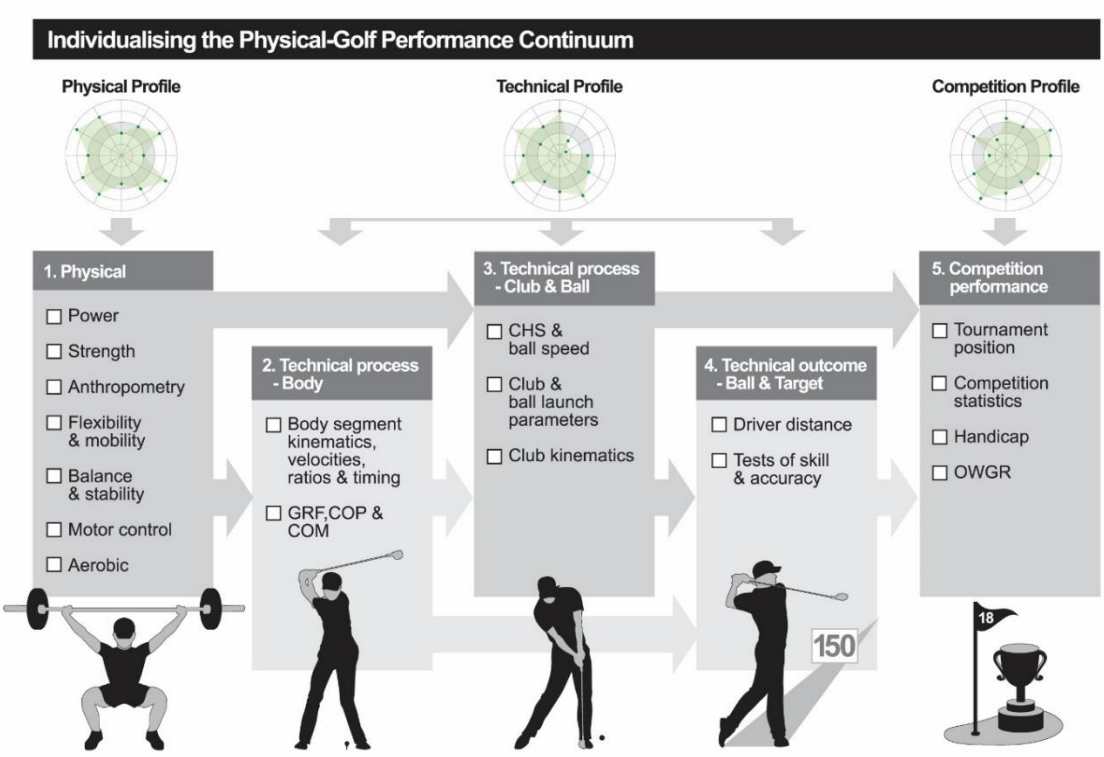


Figure 4.1 Individualising the Physical-Golf Performance Continuum (P-GPC) with Physical, Technical and Competition Profiles

4.2.2 Golf athlete profiles

A common output from a combine is an athlete profile which can guide physical and technical interventions for the individual. Athlete profiles are used in many sports to provide an efficient snapshot of the relative strengths and weaknesses and can inform targeted physical and technical training programs (31-33). To ensure the validity of this process in golf, competition aspects must be included so that interventions don't just target the player's weakness, but also address needs that are specific to competition. 'Golf-athlete profiles' (Figure 4.2, Figure 4.3, Figure 4.4) can be visualised by radar plots to provide a concise 'snapshot' of the players capacities relative to their peers or their golf ability (8). Although the specific tests represented will be explained in further detail later in this chapter, it is Important for the reader to note that each radar plot is devoted

to each distinct discipline (i.e., *Physical*, *Technical* and *Competition Performance*). If a simplified combine is used, these parameter categories could instead be represented as three wedges within a single radar plot. Targeting areas of need identified in the radar plots can guide interventions that are both individualised and specific to the demands of golf – increasing the likelihood of optimal transfer of the golfer's training to GP (8, 10, 34). For example, from a technical perspective, understanding the biomechanics of the golfer can facilitate a golf swing the individual is capable of achieving (8, 35), using the individuals' strengths and not exposing their body's weaknesses (36, 37). Conversely, physical training programs can target and negate the effects of these limitations thereby increasing the golfer's performance potential (15, 448). To execute an integrated approach of this nature, the most important relationships between physical parameters, technical parameters and competition performance need to be determined. Therefore, from a practical perspective, we first need to understand what 'normal' is from a physical, technical, and competition perspective to know what is above or below average (8, 449). Therefore, the potential outcomes of a comprehensive golf combine are the ability to develop golf-athlete profiles to inform interventions in the physical, technical, and competition domains.

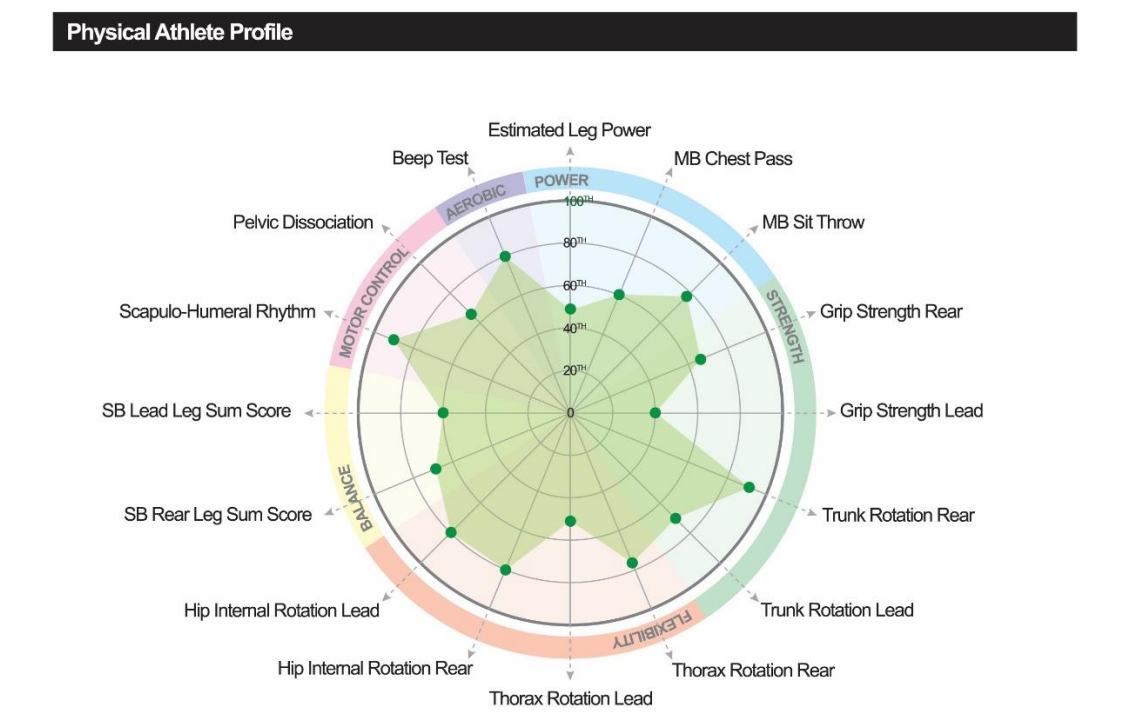


Figure 4.2 Sample physical golf athlete profile of a golfer (by percentile rank) relative to their ability-level cohort

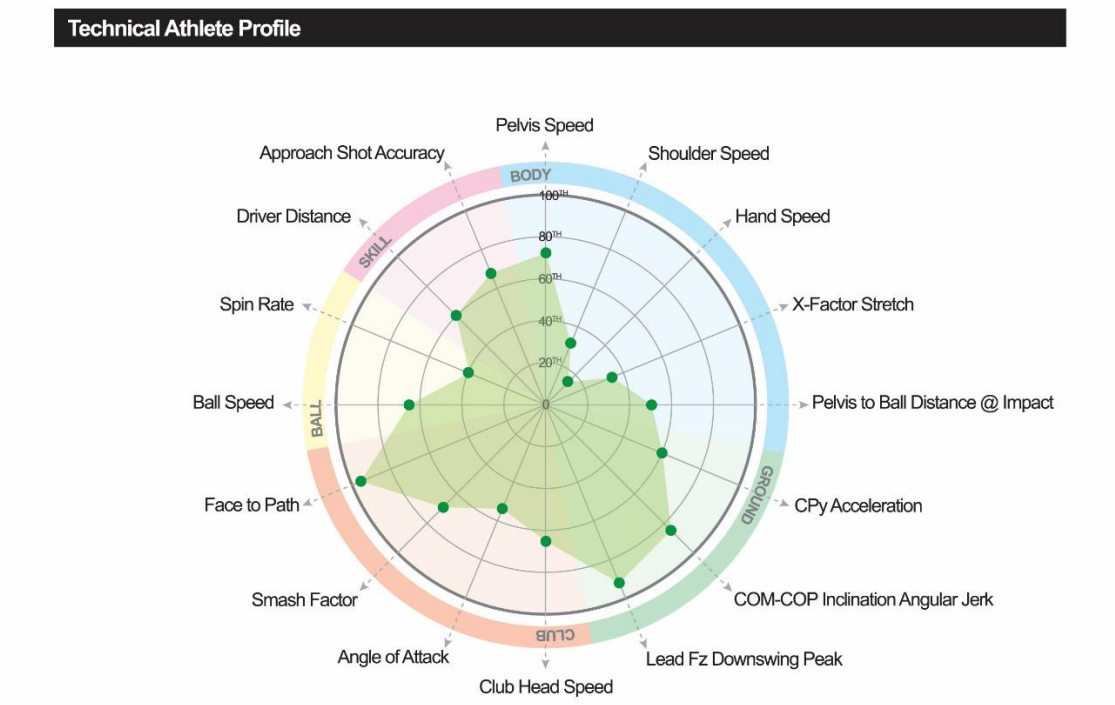


Figure 4.3 Sample technical golf athlete profile of a golfer (by percentile rank) relative to their ability-level cohort

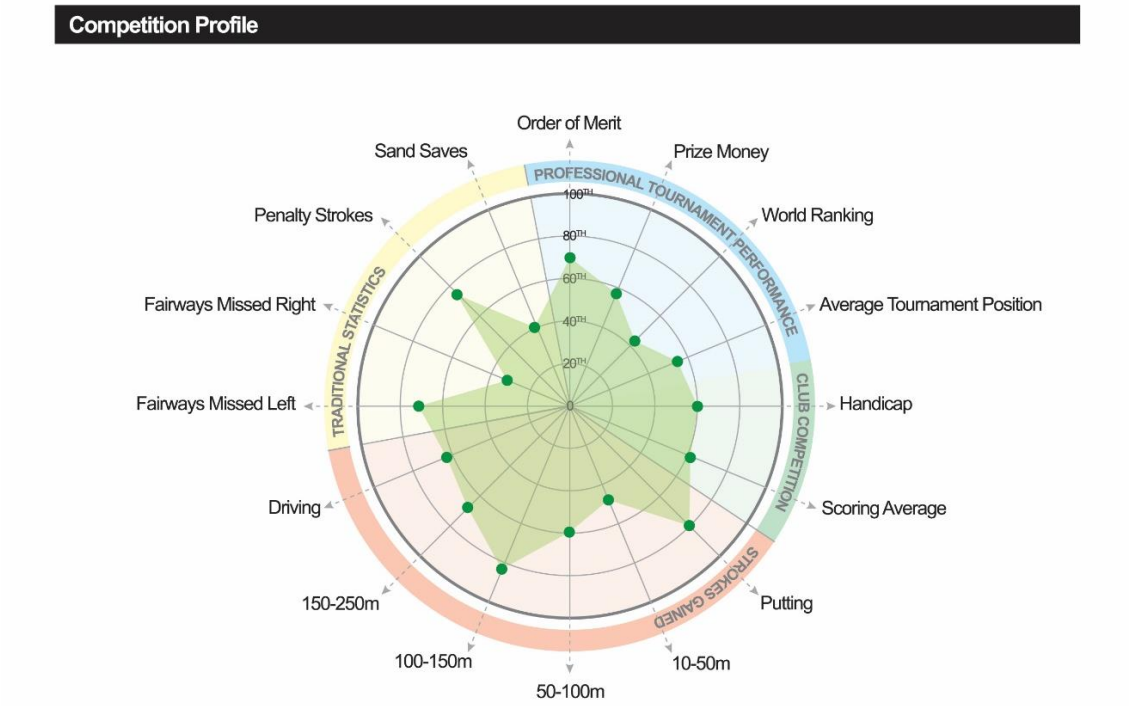


Figure 4.4 Sample competition golf athlete profile of a golfer (by percentile rank) relative to their ability-level cohort

4.2.3 Forming a golf combine

Test combines are often developed through collaboration between clinicians, practitioners and researchers (144). Initially, combines need to ensure they cover all

relevant parameters that determine performance or another construct of interest (450), known as *content validity*. The content validity of a combine can be established by either an expert panel or a detailed synthesis of the literature (147). Furthermore, understanding the relative importance of each parameter for GP can allow practitioners to maximise further training efficiency for athletes under their care (31-33). The current golf science literature supports a comprehensive combine to include assessments of:

- **Stage 1: Physical** parameters: kinanthropometry; flexibility; balance; strength; power; and endurance (8, 14, 15, 34). These parameters should address all body segments (i.e., lower body, core and upper body) and movements relevant to the golf swing (8, 27).
- **Stage 2: Technical process – Body** parameters: golf shot body kinematics and ground reaction forces (84, 304, 336).
- **Stage 3: Technical process – Club and Ball** parameters: golf shot club and ball kinematics (47, 82, 247, 263, 304).
- **Stage 4 Technical outcome** – **Ball and Target** parameters: skills tests such as Driver distance (8) and approach shot accuracy (47, 355) and are defined by measurements of shot result where the ball has hit the ground (i.e., Carry) or come to rest (i.e., total distance or accuracy). Skill assessments should be included in a golf test combine to validate the relationships Stage 1-3 variables for individual golfers as many inter-individual differences exist in golf biomechanics (299).
- **Stage 5 Competition performance** parameters: golf handicap index (HCP) (98, 226); tournament position and scores (98); Strokes gained related metrics (8, 362) or Official World Golf Ranking (98, 347). Competition measures are required as both an initial validation of Stage 1 – 4 parameters and validation that transfer of training is occurring over time.

As there is an extensive array of tests for parameters at each stage of the P-GPC that have appeared in the literature, the next step in developing a comprehensive combine is to ensure appropriate test 'quality'. Therefore, test selection should be based on the measurement properties they possess, namely: reliability, validity, responsiveness and feasibility (148, 447). Previously published test quality for prospective tests can be evaluated from the literature in a two-tier hierarchical manner (Figure 4.5). *Level 1* measurement properties are deemed essential, and *Level 2* properties provide further robustness to measures, without being essential. In essence, Level 2 measurement properties can be used as a selection tool when multiple high-quality tests are available to assess a given parameter (148).

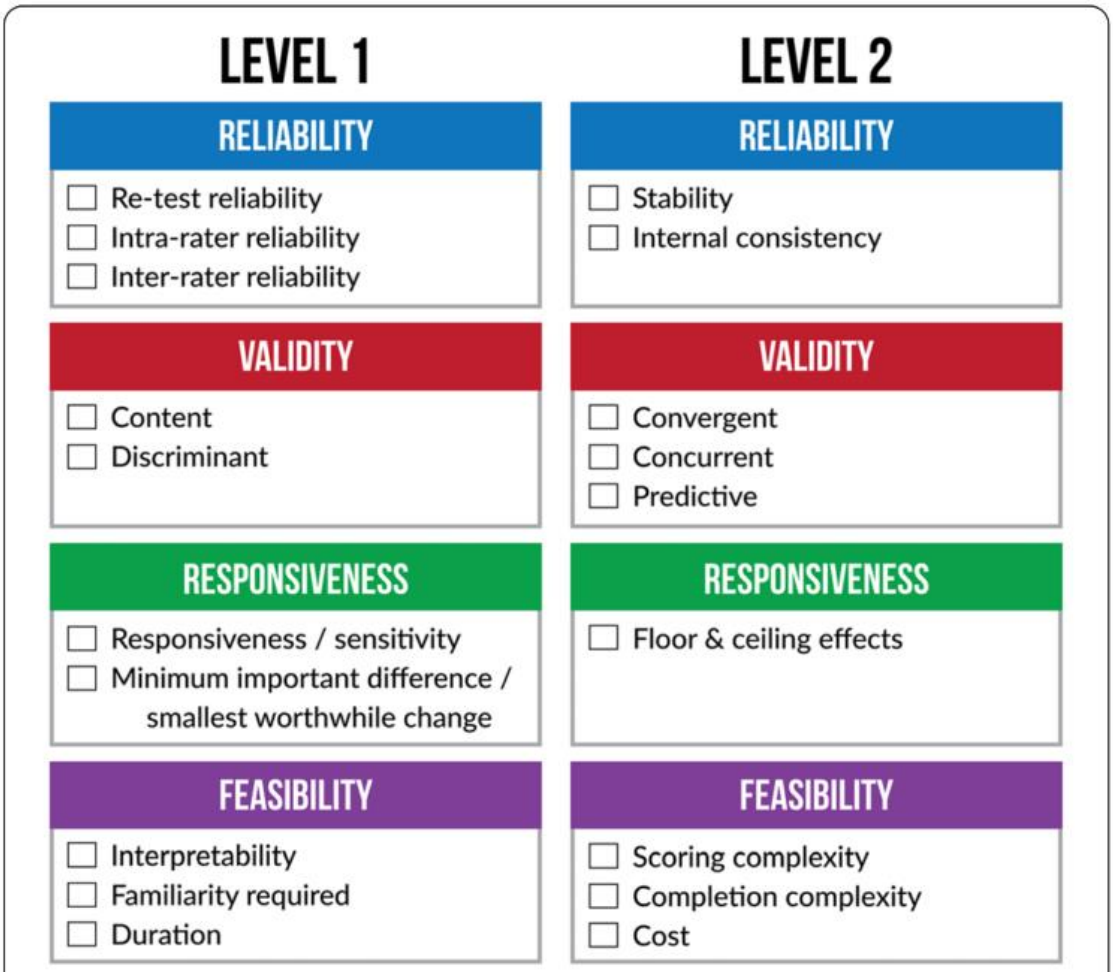


Figure 4.5 Robertson et al. 2017. Level 1 and 2 items important for consideration in evaluating an exercise and sport science performance test (with author permission)

Therefore, when forming a golf combine, baseline test quality should be sought utilising previously published results for the following *Level 1* measurement properties (i.e., a minimum of one from each category):

- Intra/inter-rater and re-test *reliability* must be established (49), with ICC of > 0.75 -0.80 (147, 450, 451) or a CoV of < 5% across trials (452) considered acceptable for use in sport science. Although an ICC = 0.5 – 0.75 is still considered 'good' for some clinical research (451). These are measures of relative reliability are important for cross-sectional assessments that aim to discriminate among individuals (447). Therefore, tests with the highest possible ICC should be selected, with ICC > 0.5 set as a minimum.
- The tester can assume that *content validity* is present if the test has been previously shown to cover the target parameter within the P-GPC. *Discriminant validity* is a measure that shows a statistically significant ability of the test to

discriminate between ability levels or uniquely target outcome measures over and above other tests (148).

- The *sensitivity* of a test is another essential measurement property that demonstrates a test's ability to detect real change instead of test error. A sensitive test will typically have low error and established *minimal detectable change* (MDC), which is calculated from the accuracy-based *standard error of measurement* (SEM), and/or *smallest worthwhile change* (SWC) values (148). SEM is a measure of absolute reliability which are required to evaluate tests to monitor changes over time (447). Further, change over time in response to an intervention describes the *responsiveness* of the test, although the descriptions are often used synonymously in the literature (447).
- The *feasibility* of a given test is often subject to the setting, facilities and available equipment (148). If multiple test options of similar quality are available, features such as the *interpretability* of scores and the *familiarity* and *duration* required to complete the test can determine selection into a combine (148). The golf science literature provides many test options for each parameter within the P-GPC. Although the strength of evidence may vary, a primary consideration in forming a combine is the risk profile and athletic attributes of the participants that will undergo testing (453-455).

These Level 1 measurement properties can form the basis for appropriate use of various inferential statistical techniques to obtain Level 2 measurement properties such as *convergent* and *predictive validity* (81, 148). Understanding the relative test quality and *feasibility* where multiple tests are available for a given parameter can ensure that only superior quality tests are used and improve combine feasibility.

4.2.4 Aim

This study aims to develop a comprehensive golf combine with previously established reliability, validity and sensitivity of tests from the literature. This combine will include *at least* one test (multiple where possible – within the limits of feasibility in our testing environment) of physical-parameters, technical-parameters and competition performance from each stage of the P-GPC. This combine will have utility for research – including Study III, IV and V in this thesis – to explore the gaps in the GP literature identified in Study I. The subsequent analysis from the combine outputs can inform golf athlete profiles that lead to individualised golf-specific training and coaching interventions.

4.3 Methods

4.3.1 Test selection process

Attempts were made to form a comprehensive combine to address all parameters identified in the P-GPC (Figure 4.1), with the purpose of assessing a large heterogenous sample of Australian golfers. Limited by feasibility factors, tests were provided for all parameters except for:

- Motor Control – due to lack of equipment and expertise to deliver tests identified in the literature;
- OWGR – as a large proportion of golf participants do not possess an OWGR;
- Tournament Position and Competition Statistics – as there was likely to be too much variation in tournament field size, level of competition and great difficulty collecting competition data between test dates.

Nonetheless, 14 of the 18 parameter categories identified in the P-GPC were addressed and, importantly, including tests from all five stages of the P-GPC. Test selection was based on balancing the feasibility of a test and the desire to assess the golfer as comprehensively as possible. Constraints on the test sessions included:

- 150-minute duration per test session
- Each test had to be completed within 10 minutes
- A maximum of 15 golfers per session
- 5 testers required (one tester per three golfers)
- Equipment and tester expertise were available to the researcher

If multiple tests were available for a given parameter, the candidate tests were examined with a two-level hierarchical test quality checklist (Figure 4.5) (148). Although the checklist contains 19 items for consideration, feasibility items are context-specific, and measurements of test sensitivity are more appropriate for measuring individual change than responsiveness (456). Hence, tests were deemed suitable for selection into this comprehensive combine where an *a priori* measure of *reliability*, *validity* and *sensitivity* was reported in the literature. However, measures for sensitivity are less common in the golf science literature, as is the case across the sport science literature (147, 447). Hence, where the author/s did not provide this, the Standard Error of Measurement (SEM) for a given test was estimated from the SD of the grand mean of all trials at baseline and the re-test reliability ICC from its study data, as suggested by the work of Swinton (457), using the equation: $SEM = SD/\sqrt{[ICC(1-ICC)]}$ which is purported to be the

most robust equation for the estimation of SEM for the true score of a test (458). To establish the measurement property of sensitivity, Minimal Detectable Change (MDC_{95}) was estimated from SEM with a confidence interval of 95%, using the equation:

$$MDC_{95} = SEM \times 1.96 \times \sqrt{2}$$ (456, 458, 459)

The MDC_{95} value represents the change to which the contribution of real modifications in performance is likely to be greater than that of systematic and/or random measurement error. For definitions of the various forms of validity, the reader is referred to the systematic review by Robertson and colleagues (148). Where possible, different metrics derived from the same tests are included. This facilitates investigation into whether absolute or relative measures show greater validity to GP. For example, leg power is assessed as vertical jump, estimated power calculated from the vertical jump (231), lateral jump for distance, lateral jump relative to bodyweight and peak force from a countermovement jump on a force plate. These tests were selected as they have shown potential for different relationships for change of direction ability which may be pertinent to the golf swing (460). For the same purpose, strength was assessed in terms of absolute (kg), torque (kg/m) and torque relative to body weight, as differences in the influence of these metrics on GP (238, 239) have been reported in the golf literature (176).

4.4 Results

Tables 4.1 to 4.7 present the sequential approach to constructing a comprehensive golf combine of tests that address parameters across all five stages of the P-GPC. Units of measurement, available *Level 1* measurement properties (i.e., measures of reliability, validity and sensitivity) and the literature source are provided for each test. HCP is selected as the stage 5 parameter measure. At times, throughout Study II, III, IV and V there is a need to present measures and metrics from this combine in truncated or slightly altered form for visualisation purposes, due to lengthy nomenclature. For the full list of alternate names see Appendix D (page 377).

Table 4.1 P-GPC Stage 1 physical measures

Physical Measures (Parameter): *Equipment & Description* 	Unit	Reliability (Source)	Validity (Source)	Sensitivity (Source)
Arm span (Kin-anthropometry): Tape measure on wall	cm	Test-retest ICC = 0.89 - 0.94, TE = 1% (12)	Convergent with Ball Speed r = 0.61, p = .01 (66), CHS R^2 = 0.20, p < .05 (175)	MDC_{95}^ = 1.4 - 2.0cm (12)
Height (Kin-anthropometry): *Seca* Stadiometer	cm	Test-retest ICC = 0.89 - 0.94, TE = 1% (12)	Convergent with Ball Speed r = 0.70, p = .01 (66), CHS R^2 = 0.26, p < .05 (175)	MDC_{95}^ = 1.4 - 2.0cm (12)
Weight (Mass) (Kin-anthropometry): *M301 Column Scale* (TGA approved)	kg	Accuracy .1 kg (Manufacturer)	Convergent with CHS r = 0.51 p < 0 .01 (176) & Ball Speed r = 0.40, p < .01 (47)	Accuracy .1 kg (Manufacturer)
Sit & reach (Flexibility): Sit & reach box	± cm	Inter-rater ICC = 0.97, SEM = 2cm (461)	Concurrent with hamstring flexibility in females and males r = 0.66 & .75 p < .05 (462), Convergent to max backswing pelvis rotation r = 0.53 p = .11	MDC_{95}^ = 5.5cm (461)
Thorax seated rotation, L&T angular ROM, (Flexibility): *Seated, knees against wall, stick across shoulders*	°	Test-retest ICC = 0.86, SEM = 4.59° (11)	Convergent with CHS (L) r = 0.71 p < 0.01 (T) r = 0.52 p < 0.05 (383).	MDC_{95}^ = 12.7° (11)
Supine passive shoulder girdle external rotation, L&T angular ROM (Flexibility): *Supine arm off edge of treatment table supported by practitioner*	°	Test-retest ICC = 0.94, SEM = 3.34° (11)	Discriminates proficiency level, T arm, p < .05 (11)	MDC_{95}^ = 9.2° (11)
Seated hip external rotation, L&T angular ROM, (Flexibility): *Seated on treatment table*	°	Test-retest Inter/Intra-rater ICC = 0.65–.82 (463)	Convergent with low back pain in male tour players, L hip, p < .05 (189)#	MDC_{95} = 6.1° (463)
Seated hip internal rotation, L&T angular ROM, (Flexibility): *Seated on treatment table*	°	Inter/Intra-rater ICC = 0.64–0.71 (463)	Discriminates > lumbo-pelvic movement in swing, p = .02 – .004. Max pelvis rotation r = 0.60, p < 0.05 (186)#	MDC_{95} = 8.6° (463)
Modified Thomas Test, L&T angular hip extension ROM,	±°	Test-retest ICC = 0.86, SEM = 2.318°	Discriminates proficiency level p < .05 (11), Improvement	MDC_{95}^ = 6.4° (11), SEM = 3° (461)

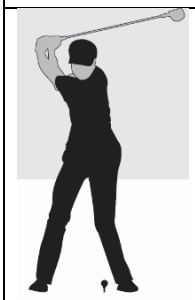
(Flexibility): *Edge of treatment table*		(11) , Inter-rater ICC = 0.92 (461)	convergent with improved impact pelvis rotation (140)	
Modified star excursion balance test (MSEBT), L&T multi-directional reach, (Balance): *MSEBT Mat with measuring grid*	cm or cm/m	Median Inter-rater ICC = 0.87 -0.88, Intra-rater ICC = 0.88 -0.90 across 3 positions in 7 studies in systematic review (202)	Content validity – recommended by author (8). Predictive validity, $p < .05$ for dynamic balance deficits (464).Criterion validity 3x increase in lower extremity injury risk if anterior reach difference >4 cm = 2.7-fold increase in injury risk in basketball (465)	Postero-medial: MDC_{95} = 2.02 – 8.18 cm or 7.5 – 10.41% for relative score (202)
Grip, L&T isometric peak force, (Strength): Hand-held dynamometer – TTM Original Dynamo Meter, Tokyo	kg	Intra-tester ICC = 0.97 & .98 (466)	Convergent T grip to CHS $r = 0.36$ p <0 .05 (176) L grip to CHS $r = 0.54$ $p < 0$ .05 (383), T & L grip to CHS $R^2 = 0.29$, $p < .05$ (175)	MID = 5.0-6.5Kg (467)
Hip adduction, L&T isometric peak force, (Strength): *Kanga-tech electronic dynamometers*	kg or kg/m or kg/m/kg	Test-retest ICC = 0.96 & .96, SEM = 2.27 & 2.4 kg (468)	Discriminates between elite & Low-HCP golfers, approaching significance (11)	MDC_{95} = 3.93 & 6.65 kg (468)
Hip Abduction, L&T isometric peak force, (Strength): *Kanga-tech electronic dynamometers*	kg or kg/m or kg/m/kg	Test-retest ICC = 0.96 & .95 SEM = 2.27 & 2.4 kg, (CI95), (468)	Convergent to HCP $p < .001$ (11, 122), Gluteal strength convergent to pelvis rotational speed $r = 0.42 – 0.49$, $p < .01$ (122)	MDC_{95} = 4.10 & 6.65 kg (468)
Hip external rotation, L&T isometric peak force, torque and torque relative to body weight, (Strength): *Kanga-tech electronic dynamometers*	kg or kg/m or kg/m/kg	Test-retest ICC = 0.55 & .64 inter-rater = 0.60 & .63 (CI95), SEM = 0.8 & 0.7 kg (469)# (Supine off table edge)	Discriminates > lumbo-pelvic movement in swing $p = 0.025$ (186)# Predicts hop performance (470), hop test recommended by author (8)	MDC_{95} = 1.94 & 2.22 kg (469)# (Supine off table edge)
Trunk rotation L&T isometric peak force, (Strength): *Kanga-tech electronic dynamometers*	kg or kg/m or kg/m/kg	Test-retest ICC = 0.89 - 0.91 (CI90), CoV = 8.4-8.7%, SEM = 0.803 kg (471)# (Seated)	Discriminates proficiency level $p <$ .05 (11)#	MDC_{95}^ = 1.90 & 1.90 kg (CI95) (471)# (Seated)
Lateral jump, L&T distance, (Power): 1-leg countermovement to 2-leg landing	m or m/m or cm/kg	Test-retest ICC = 0.94, CoV = 4.4% (460) SEM^ = 3.3 cm (472)	Convergent with L medial MSEBT $r = 0.45$, $p = 0.01$ (204). Convergent with throwing velocity $r = 0.688$, $p = 0.003$) (472). Content validity suggested for COD	MDC_{95}^ = 9.1 cm (472)

			striking sports by Author (460).	
Vertical (countermovement) jump & reach height (Power): Swift vertical jump testing pole	cm	Test-retest ICC = 0.96, CoV = 6.7% (460) SEM = 1.2 cm (473) (473)	Convergent with CHS r = 0.45 p <0 .01 (176). Concurrent (criterion) to 3 camera video system r = 906, p < 0.01 (474)	MDC_{95} = 3.5 cm (473)
Estimated peak power from Vertical (countermovement) jump & reach, (Power): *Swift vertical jump testing pole*	W	Test-retest ICC = 0.96, CoV = 6.7% (460) SEM = 202 W (231)	Convergent with CHS r = 0.61 p <0 .01 (176). Concurrent validity against force plate Adjusted R2 = 0.78, SEE = 562 W (231)	MDC_{95}^ = 560 W (231)
CMJ, peak vertical force, (Power): Hands on hips, jumping & landing on 3D Kistler force plate	N or N/kg	TE (SEM) = 77N (CI 59-115N), CoV = 3.5% (475), Test-retest ICC = 0.98 (39)	Convergent with ball speed, carry & total distance ES = 0.66, .57, .31, p = 0.01 (235)	SWC = 41 N (CI95: 59-115N) (475)
Seated 3 kg MB throw distance, (Power): Landing within 1.5 lane from 45° bench	m	Test-retest ICC = 0.95 (CI = 0.93 -0.97) (476) Test-retest ICC = 0.89 (39) TE = 0.5 m (477)	Convergent with CHS r = 0.67, p < .05 (39). Concurrent with bench press power r = 0.86 p < .05 (478)	TE = 0.5 m, SWC = 0.2 m (CI90), MCIC = 0.7m (CI75) (477)
Sit-up 3 kg MB throw distance, (Power): *Landing within 1.5 lane from floor*	m	Test-retest ICC = 0.84, p < .001, SEM = 26.02 cm (CI95) (479)# (From knees)	Convergent with TPI 90/90 shoulder test r = 0.433, p = 0.04 (169). Content validity TPI Power test battery (230). Discriminant validity for power training vs control group and p < .05 correlation to power not strength measures (480)	MDC_{95} = 72.13cm (479)# (From knees)
Lateral 3 kg MB throw, Lead side distance, (Power): *Landing within 1.5 lane from golf stance*	m	Test-retest ICC = 0.91, p < .001, SEM = 17.44cm (CI95) (479)# (From knees) Test-retest ICC = 0.89, CoV = 4.1% (45) Test-retest ICC = 0.90 (39)	Concurrent with Isometric rotational trunk torque r = 0.74 p < .01 (481), Convergent with CHS R^2 = 0.63, p < .05 (175) and r = 0.54, p < .05 (45)	MDC_{95} = 48.34cm (479)# (From knees)
YMCA 3 min step, HRR @45 s, (Endurance): *Finger pulse oximeter 45 s after completion*	bpm	Test-re-test reliability or HRR @ 60 s, ICC = 0.79, SEM = 5.8 bpm (CI95)	Concurrent with gold standard (Open circuit spirometry), r = 0.75, p < .05 (484) and treadmill test with respired gases r =	MDC_{95} = 16.1 bpm (482)

		(482) difference between days $p > .05$ (483)	0.75 – 0.94, SEE = 9-15% (483)	

L&T = Lead and trail side of body: Measurement properties are presented lead side first and rear side second. #Similar but not identical protocols. SEM, Standard error of measurement. SEE, Standard error of the estimate; ^ Calculated from study data. TE (SEM), Typical error/Technical Error of Measurement, synonymous with SEM in these studies. CoV, Coefficient of variation. COD, Change of direction. ICC, Intra-class coefficient. HCP, Handicap. CI95, Confidence interval of 95%. MDC_{95}, Minimal detectable change at 95% confidence interval (also described as MID, Minimum important difference). HRR, Heart rate recovery. Bpm, (heart rate) beats per minute. MCIC, Minimal clinically important change.

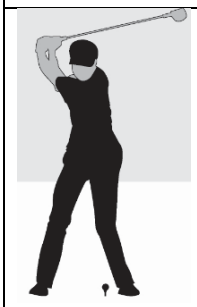
Table 4.2 P-GPC Stage 2 Technical Process: Body (3D body kinematics) measures

Equipment & Description	Measure	Units	Reliability (Source)	Validity (Source)	Sensitivity (Source)
 Indoor hitting bay with projected virtual fairway behind net. Best of 4 shots selected that finished on 40m wide fairway, using Driver and instructed to hit for maximum distance with accuracy. K-Vest™ outputs for Driver Shot.	Pelvis peak velocity	°/s	Re-test reliability ICC = 0.945 SEM^ = 11.65 °/s (CI95) (485)# Internal consistency 1.7 – 2.8% (232)	Convergent with proficiency level, p < .001 & .011(13, 122)	MDC95^ = 32.3 °/s (485)#
	Thorax peak velocity	°/s	Re-test reliability ICC = 0.945 SEM^ = 15.0 °/s (CI95) (485)# Internal consistency 0.9 – 1.1% (232)	Convergent with proficiency level, p = .011 (13) and ball speed r = 0.59, p < .001 (312)	MDC95^ = 41.5 °/s (485)#
	Lead shoulder peak velocity	°/s	Internal consistency 0.8 – 7.7% (232)#	Convergent with proficiency level, p = .011 (13)	Not reported
	Lead hand peak velocity	°/s	Internal consistency 0.8 – 7.7% (232)	Lead hand force couple increases CHS (14, 342) Convergent with proficiency level, p = 0.011 (13)	Not reported
	Pelvis-thorax peak velocity ratio	ratio	Re-test reliability ICC = 0.945 SEM^ = 11.65-15.0 °/s (CI95) (485)# Internal consistency 0.9 – 2.8% (232)	Convergent with proficiency level, p = 0.011 (13)	MDC95^ = 32.3-41.5 °/s (485)#
	Thorax-lead shoulder peak velocity ratio	ratio	Internal consistency 0.8 – 7.7% (232)#	Convergent with proficiency level, p = 0.011 (13)	Not reported
	Lead shoulder-lead hand peak velocity ratio	ratio	Internal consistency 0.8 – 7.7% (232)#	Lead hand force couple increases CHS (14, 342) Convergent with proficiency level, p = .011 (13)	Not reported
	Pelvis turn top of backswing	°	Re-test reliability ICC = 0.908 SEM^ = 0.92 ° (CI95) (486)# (Vicon) Internal consistency 1.7 – 2.8% (232)#	Convergent with proficiency levels (Low-HCP have less) Cohen's d = 0.82 (182)	MDC95^ = 2.5 ° (486)# (Vicon)
	Thorax turn top of backswing	°	Re-test reliability ICC = 0.946 SEM^ = 1.4 ° (CI95) (486)# (Vicon) Internal	Convergent with proficiency level, Cohen's d = 0.41 (182)	MDC95^ = 3.9 ° (486)# (Vicon)

			consistency 0.9 – 1.1% (232)#		
	X-factor top of backswing	°	Re-test reliability ICC = 0.901 SEM^ = 0.92 – 1.4 ° (CI95) (486)# (Vicon) Internal consistency 0.9 – 2.8% (232)	Convergent with proficiency level, Cohen's d = 0.56 (182) and ball velocity r = -0.55, *p* < .001 (312)	MDC95^ = 2.5 -3.9 ° (486)# (Vicon)
	Pelvis turn at impact	°	Re-test reliability ICC = 0.977 SEM^ = 1.47 ° (CI95) (486)# (Vicon) Internal consistency 1.7 – 2.8% (232)	Convergent with proficiency levels > Tx & Px rotation at impact (247)	MDC95^ = 4.1 ° (486)# (Vicon)
	Thorax turn at impact	°	Re-test reliability ICC = 0.971 SEM^ = 1.79 ° (CI95) (485)# (Vicon) Internal consistency 0.9 – 1.1% (232)#	Convergent with proficiency levels > Tx & Px rotation at impact (247) and CHS (342)	MDC95^ = 5.0 ° (486)# (Vicon)
	X-factor at impact	°	Re-test reliability ICC = 0.901 SEM^ = 1.47 – 1.79 ° (CI95) (486)# (Vicon) Internal consistency 0.9 – 2.8% (232)	Convergent with ball speed *r* = 0.53, *p* < .001 (312)# last 0.4 s before impact	MDC95^ = 4.1 – 5.0 ° (486)# (Vicon)

3D, Three-dimensional.

Table 4.3 P-GPC Stage 2 Technical Process: Body (Ground Reaction Forces) measures

Equipment & Description	Measure	Units	Reliability (Source)	Validity (Source)	Sensitivity (Source)
 3D ground reaction forces with Driver. Indoor hitting bay with projected virtual fairway behind net. Kistler dual force plates for 3D ground reaction forces.	L&T Fx (anterior-posterior) maximum and minimum force values	N or N/kg	Re-test reliability ICC = 0.844 SEM^ = 20.7 N/BW (CI95) (485)	Convergent to proficiency level in downswing L&T Fx force couple (487)# (Recorded at swing events)	MDC95^ = 57.4 N (485)#
	L&T Fy (medial-lateral) maximum and minimum force values	N or N/kg	Re-test reliability ICC = 0.844 SEM^ = 20.7 N/BW (CI95) (485)	Convergent to CHS (275)# (COPy Max Velocity at swing events)	MDC95^ = 57.4 N (485)#
	L&T Fz (vertical) maximum and minimum force values	N or N/kg	Re-test reliability ICC = 0.844 SEM^ = 20.7 N/BW (CI95) (485)	Convergent to proficiency level Maximum Fz force (%BW) T foot in back swing, L foot in downswing (332)# (Recorded at swing events)	MDC95^ = 57.4 N (485)#
	Time between L&T Fx, Fy, Fz maximum and minimum force values	N or N/kg	Re-test reliability ICC = 0.844 SEM^ = 20.7 N/BW (CI95) (485)	Convergent to proficiency level in downswing L&T Fx force couple (487)# (Recorded at swing events)	MDC95^ = 57.4 N (485)#

L&T = Lead and trail side of body, measurement properties are presented lead side first and rear side second. Fx, anterior-posterior ground reaction force vector. Fy, medio-lateral ground reaction force vector. Fz, vertical ground reaction force vector. Max, Maximum. N/BW, Newtons of force produced per kilogram of bodyweight. (%BW), % relative to bodyweight.

Table 4.4 P-GPC Stage 3 Technical Process: Club (Driver Club Kinematics & Launch Parameters) measures

Equipment & Description	Measure	Units	Reliability (Source)	Validity (Source)	Sensitivity (Source)
 Indoor hitting bay with projected virtual fairway behind net. Best of 4 shots selected that finished on 40m wide fairway, using Driver and instructed to hit for maximum distance with accuracy. Trackman™ for capture of ball kinematics.	CHS Speed of the club head at impact (295)	mph	TE (SEM) = ± 1.5 mph (340), Test-retest ICC = 0.87 (39)	Concurrent with high speed camera system, MD = -0.4, $p < .05$ (333) & stereoscopic system $r = 0.99$, $p < .05$ (288), Convergent to HCP, $r = -612$ $p < 0.05$ (383) $r = -0.44$ (295)	MDC95^ = 4.2 mph (340) MDC90 = 3.6% (488)
	Path Vertical movement of the club through Impact (295)	°	Not reported	Concurrent to Stereoscopic system $r = 0.88$, $p < .05$ (288), Convergent to club face angle at impact (344) and HCP, $r = 0.10$ (295) and total distance, ß = 1.17 (82)	Not reported
	Plane Bottom half of the swing plane relative to ground (295)	°	Not reported	Convergent: only minor influence on club head delivery (344) Convergent with HCP, $r = 0.25$ (295)	Not reported
	Direction Bottom half of the swing plane relative to target line (295)	°	TE (SEM) = ± 1.0 ° (340)	Concurrent with high speed camera system, MD = 1.5 , $p < .05$ (333)	MDC95^ = 2.8 ° (340)
	Dynamic loft Orientation of the club face, relative to the plumb line, at impact (295)	°	TE (SEM) = ± 0.8 ° (340)	Concurrent with high speed camera system, MD = -0.5, $p < .05$ (333), and maximum height, ß = 1.53 (82)	MDC95^ = 2.2 ° (340)
	Face angle Orientation of the club face, relative to target line, at impact (295)	°	TE (SEM) = ± 0.6 ° (340)	Concurrent with high speed camera system, MD = -0.1 (333) & stereoscopic system $r = 0.81$, $p < .05$ (288) Convergent with HCP, $r = 0.37$ (295), and total distance, ß = 1.15 (82)	MDC95^ = 1.7 ° (340)
	Face to path Orientation of the club face, relative to club path, at impact (295)	°	Not reported	Concurrent to Stereoscopic system $r = 0.81$ -0.88 $p < .05$ (288) Convergent with HCP, $r = 0.20$ (295)	Not reported
	Attack angle Vertical movement of the club through Impact (295)	°	TE (SEM) = ± 1.0 ° (340)	Concurrent with high speed camera system, MD = -3.5, $p < .05$ (333) & stereoscopic system $r = 0.81$, $p < .05$ (288) Convergent with HCP, $r =$	MDC95^ = 2.8 ° (340)

				-0.07 (295) and ball speed, ß = 0.371 (82)	
	CHS Speed of the club head at impact (295)	mph	TE (SEM) = ± 1.5 mph (340), Test-retest ICC = 0.87 (39)	Concurrent with high speed camera system, MD = -0.4, $p < .05$ (333) & stereoscopic system $r = 0.99$, $p < .05$ (288), Convergent to HCP, $r = -612$ $p < 0.05$ (383) $r = -0.44$ (295)	MDC95^ = 4.2 mph (340) MDC90 = 3.6% (488)
	Low point Distance from the club head's geometric centre to the lowest point on the swing arc at the time of maximum compression (489)	cm	TE (SEM) = ± 1.0 ° (340)	Not reported (Recent addition to Trackman)	Not reported (Recent addition to Trackman)

ß, beta-coefficient within multiple linear regression model.

Table 4.5 P-GPC Stage 3 Technical Process: Club (120m Target Shot Club Kinematics & Launch Parameters) measures

Equipment & Description	Measure	Units	Reliability (Source)	Validity (Source)	Sensitivity (Source)
 Indoor hitting bay with projected 120m target flag behind net. Trackman™ for capture of club kinematics.	CHS Speed of the club head at impact (295)	mph	TE (SEM) = ± 1.5 mph (340)	Concurrent with high speed camera system, MD = -0.4, $p < .05$ (333)# (7-iron) & stereoscopic system $r = 0.99$, $p < .05$ (288)# (Driver), Convergent to HCP, $r = -61$ $p < 0.05$ (383) $r = -0.44$ (295)# (7-iron)	MDC95^ = 4.2 mph (340) MDC90 = 3.6% (488)
	Path Vertical movement of the club through Impact (295)	°	Not reported	Concurrent to Stereoscopic system $r = 0.88$, $p < .05$ (288), Convergent to club face angle at impact (344) Convergent with HCP, $r = 0.10$ (295)# (7-iron)	Not reported
	Plane Bottom half of the swing plane relative to ground (295)	°	Not reported	Convergent: only minor influence on club head delivery (344) Convergent with HCP, $r = 0.36$ (295)# (7-iron)	Not reported
	Direction Bottom half of the swing plane relative to target line (295)	°	TE (SEM) = ± 1.0 ° (340)	Concurrent with high speed camera system, MD = 1.5 , $p < .05$ (333)# (7-iron)	MDC95^ = 2.8 ° (340)
	Dynamic loft Orientation of the club face, relative to the plumb line, at impact (295)	°	TE (SEM) = ± 0.8 ° (340)	Concurrent with high speed camera system, MD = -0.5, $p < .05$ (333)# (7-iron)	MDC95^ = 2.2 ° (340)
	Face angle Orientation of the club face, relative to target line, at impact (295)	°	TE (SEM) = ± 0.6 ° (340)	Concurrent with high speed camera system, MD = -0.1 (333)# (7-iron) & stereoscopic system $r = 0.81$, $p < .05$ (288)# (Driver), Convergent with HCP, $r = 0.21$ (295)# (7-iron)	MDC95^ = 1.7 ° (340)
	Face to path Orientation of the club face, relative to club path, at impact (295)	°	Not reported	Concurrent to Stereoscopic system $r = 0.81$ -0.88 $p < .05$ (288)# (Driver), Convergent with HCP, $r = 0.23$ (295)# (7-iron)	Not reported

	Attack angle Vertical movement of the club through Impact (295)	°	TE (SEM) = ± 1.0 ° (340)	Concurrent with high speed camera system, MD = -3.5, $p < .05$ (333)# (7-iron) & stereoscopic system $r = 0.81$, $p < .05$ (288)# (Driver), Convergent with HCP, $r = 0.34$ (295)# (7-iron)	MDC95^ = 2.8 ° (340)
	Low point Distance from the club head's geometric centre to the lowest point on the swing arc at the time of maximum compression (489)	cm	TE (SEM) = ± 1.0 ° (340)	Not reported	Not reported

Table 4.6 P-GPC Stage 4 Technical Outcome: Ball & Target (Driver Distance & 120m Shot Accuracy) measures

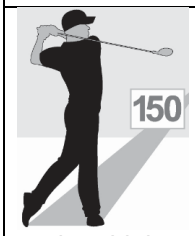
Equipment & Description	Measure	Units	Reliability (Source)	Validity (Source)	Sensitivity (Source)
 Indoor hitting bay with projected virtual fairway/120m Flag behind net. Trackman™ for capture of ball kinematics.	Accuracy of 120m target shot (Distance to target) Calculated total including bounce and roll at zero elevation (295)	m	Not reported	Convergent with PGA tour earnings 2011-13 $r = 0.53 – 0.62$, accuracy $r = 0.33 – 0.43$ (348), Discriminates proficiency level, $p < 0.05$ (355)# (Approach iron test)	Not reported
	Driver carry flat Calculated carry distance at zero elevation (295)	m	Not reported	Convergent with HCP, $r = -0.65$ (295)	Not reported
	Driver total distance Calculated total including bounce and roll at zero elevation (295)	m	Not reported	Convergent with PGA tour earnings 2011-13 $r = 0.53 – 0.62$, accuracy $r = 0.33 – 0.43$ (348), Convergent with proficiency level, $p = .013$ (82)	Not reported

Table 4.7 P-GPC Stage 5 Competition Performance (Handicap) measures

Equipment & Description	Measure	Units	Reliability (Source)	Validity (Source)	Sensitivity (Source)
5. Competition Performance: 	GA HCP Registered to 'Golf Link' website through registered club competition	No.	Not reported	Convergent to CHS, r = -0.61 p < 0.05 (383), r = 0.95 p < 0.05 (226)	Not reported

4.5 Discussion

Comprehensive test combines can be described as those that measure physical, technical and competition performance parameters across the P-GPC. Test scores from such combines can be used to analyse the physical, technical and competition mechanisms of GP to inform the multi-disciplinary team approach required to optimise GP (8, 15, 34). Analysis can be undertaken at the group or individual level. Group data can be used to compare different golf cohorts (e.g., to determine the discriminant validity of each test to determine the most pertinent tests for each cohort). Athlete profiles can compare individual golfers to group data to inform individualised physical, technical and competition training interventions (8, 10). Comprehensive combines foster an integrated and comprehensive approach to the development of the golfer.

Beginning with the end in mind for the golfer (i.e., what they are training for), Stage 5 competition performance measures are vital inclusions for a comprehensive golf combine. Measures of on-course performance provide an ecologically valid outcome for earlier P-GPC measures to be analysed against (e.g., with correlation or predictive modelling). HCP is the most reported Stage 5 outcome measure in the literature and has shown strong relationships with many parameters earlier in the P-GPC (191, 226, 490, 491). In this study, HCP was also the most feasible competition measure given the extensive range of ability levels ranging from professionals who still maintained a HCP, to High-HCP club golfers. As shown in the P-GPC, further assessments of competition performance can also be used. Competition statistics such as *Strokes gained* (362, 492) or traditional on-course statistics (e.g., fairways hit, greens in regulation) are accessible to be recorded by both tour players and club golfers. Tournament position, prize money and official world golf ranking for professional golfers can also be used as a stage 5 P-GPC measure (98).

To ensure the *content validity* of the combine for assessing stage 4 of the P-GPC, skill tests of both Driver distance and approach shot accuracy to a 120 m target were included. Driver distance has demonstrated *discriminant validity* across multiple levels of ability (47, 82) tour standard ability levels (348). Similarly, tests of approach iron play have shown an ability to discriminate between elite and high-level amateurs (354, 355) and tour player performance (347). Although these approach iron play tests exist, the duration of these tests and skill level required for an accurate measure meant these were not feasible for our proposed test combine and sample. Thus, a four shot 120 m target shot is utilised for a similar effect. Whilst short game and putting would complete this section of the combine, our testing environment was laboratory-based with no access to putting, chipping or bunker facilities. Although physical correlations to short game are sparsely reported, some initial findings and hypothesised mechanisms warrant further investigation. These include a 29.6% improvement in putting distance control following an 11 week S&C program (91) and moderate to strong positive correlations between core strength endurance and sand shot/chipping accuracy (66).

Stage 3 Club and Ball kinematics can be comprehensively analysed in our test combine courtesy of the Trackman™ outputs. Trackman™ and other commercially available radar (or similar) devices have had most outputs assessed for concurrent validity against gold standard systems such as high-speed camera systems (295, 333). Although it must be noted that the bulk of the published biomechanical literature has relied on the highly accurate, high-speed optical-reflective marker systems, these are typically only available in research laboratories. Therefore, our combine instead selected an industry-prevalent club and ball tracking system to provide greater utility and relevance of our combine in the field.

Stage 2 Body and GRF-related technical process measures are warranted when working with individual golfers, especially given the relative importance of the kinematic sequence to the golf swing (304, 309). For speed and efficiency, our combine undertook these measures concurrently with the Maximum Driver shot test. The K-Vest system was selected due to its simplicity and reported high levels of accuracy (122). 3D Kistler force plates were also used to assess GRF during the Maximum Driver shot test. In our combine, it was not feasible to synchronise these two devices to assess GRF against swing events. Therefore maximum, minimum and time between peaks were collected from the Fx, Fy and Fz outputs. However, the golf literature provides a variety of detail and sophistication for both researchers and practitioners when measuring golf swing body kinematics and GRF variables. For example, when GRF data is mapped concurrently against body kinematic swing events, assessments of COM as well as

timing based GRF and body kinematics become available. These *swing event* metrics have shown both inter-individuality and discriminant validity across golf proficiency levels (84, 86, 276, 309, 324, 336). Finally, the use of multi-camera high-speed 3D motion capture systems, whilst more time consuming, allow for greater degrees of freedom to be assessed biomechanically and greater nuance in the assessment of X-factor variables such as ‘stretch rate of recoil’ (304, 309). These more sophisticated biomechanical assessments of the golf swing reported in other studies should also be considered where feasible, over and above what is presented in our combine.

To ensure the content validity for the investigation of Stage 1 'physical' parameters, a combine must include tests that cover the mechanistic function of all parameters for all body segments (e.g., lower body, core, upper body) as they are used in the golf swing (50). The presented combine meets this demand with six flexibility, five strength and seven power tests covering both sides of the body across all body segments. Furthermore, each test has previously established validity with GP-related measures. Although novel in experimental golf studies, the Modified Star Balance Excursion Test was included our combine as recommended by recent authors (8). This test has been highly investigated across multiple sports and displays robust measurement properties (202). Anthropometry was included in this combine to describe participants and derive metrics such as relative Driver CHS (to bodyweight). Anthropometry should not be used as an independent variable in investigations that include both juniors and adult participants due to the confounding factor of maturation. Finally, the YMCA step test was incorporated as a sub-maximal aerobic test and is feasible for a broad age and fitness range of participants. Despite the low intensity nature of golf, the P-GPC will guide the novel investigation of relationships between aerobic function and technical measures such as GRF and body, club and ball kinematics as well as describing benchmark levels of function for a variety of ability levels.

The process of combine formation should seek tests that possess the highest available Level 1 measurement properties of reliability, validity, and sensitivity should be selected. In practice, the test selection sequence begins with establishing content validity, or at least a *face validity* of a test. In basic terms, this is the initial evidence that this test is going to be worthwhile undertaking as it has some relationship to performance that the golfer or practitioner is interested in. A combine with a blend of parameters from each stage of the P-GPC can allow the determination of further forms of validity, such as predictive and convergent validity. Multiple forms of validity increase the likelihood that what is tested and trained has a clearly defined relationship to golf performance. All tests

within this combine have a previously established form of validity and the subsequent studies in this thesis aim to add additional forms of validity.

The second measurement property tests require is *reliability*. The established reliability for a test allows greater interpretability of the test score, both initially and over time with repeated testing. Therefore, it must be noted that at least six different methods for *determining re-test (relative) reliability* ICC's have been published (458). Some are designed to account for systematic error, and others not (458). Golf science studies seldom report the method used to determine reliability. During the combine formation in this study, it was assumed that systematic error had been accounted for either in the methods of studies or the statistical technique selected. Thus, the ICC values given represent relative random measurement error. SEM is a measure of absolute reliability and has the advantage of being presented in the same units as the test score (447). This makes the interpretation of the 'signal' versus 'noise' of a test more intuitive. Each test within this combine possessed an existing form of either relative or absolute reliability.

Sensitivity, or responsiveness, and feasibility are the remaining Level 1 measurement properties that improve the rigor of a combine. Sensitivity is typically measured with MDC which is calculated from SEM and can be assessed with different confidence interval widths. The sensitivity of tests is of particular importance when interpreting athlete profiles. For example, factoring in the measurement error of a test can determine whether or not 'real change' has occurred over time or not (102). The feasibility of a test takes into consideration the purpose, environment and participant ability. In this regard, the risk profile and athletic attributes of the participants being tested (141, 453-455) as well as time, expertise and equipment resources (147) may prohibit a test from being selected for a combine. Therefore, a comprehensive golf combine should be constructed to cover all stages of the P-GPC to the highest feasible quality to meet the purpose of the tester and participants.

4.5.1 Practical applications

The primary application of a golf combine in the field is to produce individualised or group-based physical, technical and competition profiles (8, 31). These profiles provide an effective way to identify and monitor the mechanisms of performance for both squads or individual golfers (10). Understanding where a golfer sits relative to their peers, with each identified physical and technical parameter, informs the golfer and their multi-disciplinary team where to focus their interventions. Physical and technical profiles can be anchored against group data in several ways, including percentile rank, z scores,

estimated means or medians (31, 33). However, these profiles should also be presented with measures of sensitivity such as MDC or SWC so that results are interpreted with the inherent inaccuracies of a test explicitly factored in. To support the multi-disciplinary approach to golf performance, the process for forming a comprehensive golf combine, with established Level 1 measurement properties, was presented in this study. Furthermore, the comprehensive combine presented can be used to investigate the relationships between technical, physical and competition measures as one or more tests are included from each stage of the P-GPC.

4.5.2 Limitations

It is worth noting that there are different published equations for calculating absolute reliability via SEM. Arguably, the robustness of SEM calculation can be increased by replacing SD with a sum of squares from a two-way repeat measures analysis of variance (ANOVA) (456, 458) and additionally accounting for sample size with an adjusted multiple (e.g., rather than a consistent 1.96 for CI95) (457). Although, to the author's knowledge, this equation has not been utilised in the golf science literature. Ideally, ascertaining the reliability and sensitivity for every test and metric in our combine would be undertaken as a second step prior to utilising the combine, for a given sample of golfers. This decision is left to the tester, given the scope of their research or rigor required in their sporting or clinical environment. This extra step would add rigor particularly where variations on previous test protocols are used (e.g., K-Vest), or where Level 1 measurement properties not been previously reported for specific output metrics (e.g., a small number of Trackman output metrics). After all, measures without reported levels of adequate reliability, validity and sensitivity should be interpreted with some caution.

4.6 Conclusion

Comprehensive golf combines should aim to examine parameters from all stages of the P-GPC. They should also select feasible tests for the testing environment and participants with the highest available validity, reliability, and sensitivity. Subsequently, physical, technical and competition golf athlete profiles can be produced for groups or the individual golfer to illustrate relative strengths and weaknesses across tests and parameters. Multi-disciplinary training interventions can then focus on the greatest needs of the individual. This approach increases the likelihood of optimal training transfer from one mechanism to the next. Comprehensive golf combines include tests from each stage

of the P-GPC – such as the combine presented in this chapter. Combines that span the P-GPC can address gaps in the GP science by exploring new physical-technical-competition performance relationships to inform training interventions.

Chapter 5: Study III – Physical and technical traits of Australian male golfers

5.1 Abstract

Investigating large heterogenous samples of golfers with comprehensive combines can identify the physical and technical traits that discriminate golf ability. This can lead to simplified combines for specific golf cohorts and benchmarks for athlete profiles for golfers to inform individualised interventions. In this study, a combine including 25 tests spanning the Physical-Golf Performance Continuum was utilised to investigate a large heterogenous sample (n = 122, Handicap range = -6 – 36.4, Age = 29.5 ± 15.2 years) of Australian male golfers. Visualisation of the estimated mean for continuous physical and technical measures, relative to the standardised golf handicap of the sample, are provided. Effect Size, with Cohen's d, of the mean differences and additional measures of central tendency including median and interquartile range for these measures across four ability cohorts (HCP = Elite: -6 – 0.4, Low-HCP: 0.5 – 7.4, Mid-HCP: 7.5 – 17.4, High-HCP:17.5 – 36) are reported. Mostly large effect sizes were seen across all ability levels for tests of golf skill and distance measures. These included Total Driver Distance (d = 0.96 – 1.53) and 120 m Shot Distance to Target (d = -0.75 – -1.34). Large differences across all four ability levels were found in club and ball kinematic measures, including Driver Club Head Speed (d = 0.89 – 1.08) and 120 m Shot Spin Rate (d = 0.87 – 1.07). Physical measures tended to exhibit smaller differences between ability levels, although many medium-to-large effect sizes were present between ability cohorts. Medicine Ball Lateral Throw was the only physical measure to show a large difference (d = 0.84) between Elite and Low-HCP golfers. These results indicate the most important traits to differentiate playing ability and provide tests and benchmarks to assess them.

5.2 Introduction

Comprehensive combines that span the P-GPC (Figure 5.1), can be used to determine the physical and technical traits that discriminate ability levels in golfers. Knowing this, future combines can be simplified for greater feasibility for the tester and athlete. Testing the ability of a measure to differentiate playing ability is common to the GP literature. However, the evidence is undermined somewhat by methodological limitations. Many studies have tended to only report the statistical significance, rather than the magnitude of group differences and confidence-intervals (10). Additionally, many studies have only investigated two ability levels. Therefore, it is difficult to determine the magnitude of discriminant ability the array of available tests can provide the golfer.

It is essential to understand what is 'average' is for a golfer, from a physical and technical perspective, to be able to determine strengths and weaknesses (8, 449). Furthermore, ‘average’ is best interpreted relative to a golfer’s ability cohort, as technical and physical traits have been shown to vary with age and ability level (17, 116, 117). Measures of central tendency (mean and median) provide a basis for benchmarks to be used as ‘triggers’ within athlete profiles to inform training interventions for the golfer. Standardised error about the mean and interquartile ranges for the median provide further clarity about the distribution of test scores, when using group data to inform individual interventions (i.e., larger error or interquartile ranges may lead to a more cautious interpretation of ‘average’). Individualising physical and technical interventions can enhance competition performance for the individual golfer (8, 31, 34).

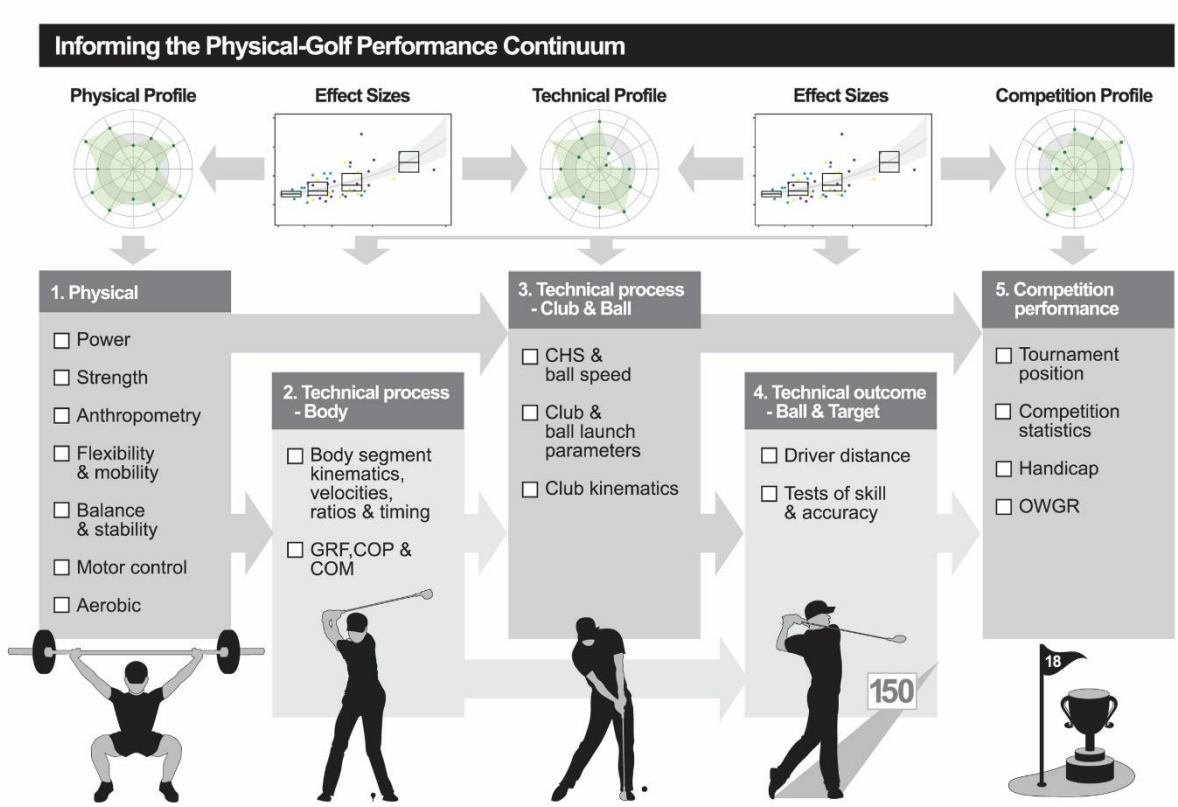


Figure 5.1 Investigating relationships between parameters across stages of the Physical-Golf Performance Continuum using effect sizes of ability-level cohort differences

Several golf combines addressing multiple performance parameters have been evaluated, reporting sufficient measurement properties for many tests. These studies provide tests with established reliability (11, 49), moderate to strong levels of discriminant (11, 12), convergent (37, 39, 45, 46, 50, 66, 176) and predictive validity (36, 193). However, given the broad contribution of golf physiology to performance (15), there are limitations for an individual study to provide insight into all physical-technical-performance relationships across the golf participation pathway. Even when multi-parameter combine studies are aggregated, cohort and performance parameter gaps in understanding remain (15, 19). For example, most comprehensive combine studies have omitted measuring any parameter from a stage of the P-GPC such as balance (39), power (11), and technical outcome measures (11, 36), with only two including technical process measures (e.g., 3-dimensional body kinematics). Furthermore, there is a need for further research on specific golf cohorts. For example, junior, and older High-HCP golfers constitute a large portion of Australian golf participation (2) and are theorised to be different technically and physically from elite golfers (116, 117). However, these cohorts are seldom investigated (15, 19).

Other limitations in golf research are methodological. For example, the reliability, validity and sensitivity of tests are often not reported, and genders are frequently combined for analysis. These errors limit the interpretability of research findings and translation to the field. Additionally, competition performance measures such as HCP have primarily been analysed as a categorical variable, reporting statistical significance for differences reported, typically between two or three ability levels (e.g., HCP 1-9 vs 20-29) (11, 12). However, golfers have been shown to vary from a technical and anthropometry and somatotype perspective when divided into four or more ability levels (82, 177, 267, 288). Furthermore, whilst this direct comparison of ability cohorts illustrates the discriminant validity of various physical and technical measures, different relationships may be identified by also investigating HCP as a continuous dependent variable. Therefore, analysis of HCP as both a continuous variable as well as quantifying the magnitude of differences between HCP groups using ES can provide greater understanding of the differences between cohorts (493) and uses

The aim is to understand what 'average' is for 4 ability cohorts of the male golf participation pathway, from a physical and technical perspective. A number of research design features will be used to achieve this aim:

- utilisation of a comprehensive combine – containing tests that assess at least one parameter from each stage of the P-GPC (often multiple),
- reporting of the previously established reliability, validity and sensitivity of tests within the combine (see Chapter 4, page 149),
- assessment of the physical and technical differences, using ES, between different ability cohorts across a large heterogenous sample of Australian male golfers,
- reporting of two measures of central tendency (mean with standardized error, median with interquartile range) for physical and technical measures that span the P-GPC.

This approach will extend on existing studies due to both the large heterogenous sample used and the statistical methods used – addressing multiple cohort- parameter-specific and methodological gaps in the GP literature identified in Study I. A more precise understanding of the relationships across P-GPC will allow for male golf athlete profiling to guide individualised golf-specific physical and technical development.

5.3 Methods

5.3.1 Study participants

The participants were 122 males aged 12 to 71 years who were active competitive golfers. Our inclusion criteria required participants to a) have played a minimum of 12 competition rounds within the previous 12 months and b) maintain an official GA HCP during the previous 12 months and throughout the study, as this is required for accurate calculation of HCP. To ensure a representative sample of the entire Australian golf pathway, participants were recruited as a convenience sample from secondary (high) school development programs, local golf clubs, the Australian Professional Golfers Association development and trainee programs, and active tour professionals. Unless contraindicated due to injury or pain, each participant completed all assessment protocols on their first visit to a golf test combine session. Risk assessments and test completion decisions were made on a case by case basis by an attending accredited exercise physiologist, with assistance from the information provided by participants in their adult pre-exercise questionnaire (494).

5.3.2 Study Design

This study collected and analysed cross-sectional data from 122 male golfers of different age and ability. A comprehensive combine (see pages 150 – 161) was utilised that includes most parameters presented in the P-GPC. Table 5.1 shows all parameter categories that were investigated with this combine and subsequently analysed in this study, denoted with a tick (✓). The additional parameters contained within the P-GPC that are not investigated in this study are denoted with a cross (X). The measures and metrics derived from the tests that assess each parameter were analysed for the group differences across ability groups displayed with forest plots and bivariate charts where the measure is plotted against standardised HCP.

Table 5.1 P-GPC stage parameters investigated by comprehensive combine

1 Physical	2 Technical process – Body	3 Technical process – Club & Ball	4 Technical outcome – Ball & Target	5 Competition performance
✓ Power	✓ Body segment kinematics	✓ CHS & Ball speed	✓ Driver distance with accuracy	X Tournament position
✓ Strength	✓ Body segment velocities	✓ Club & Ball launch parameters	✓ Approach shot skill & accuracy	X Competition statistics
✓ Anthropometry	✓ Body segment velocity ratios	✓ Club Kinematics	X Short game skill & accuracy	✓ Handicap
✓ Flexibility & mobility	✓ Body segment velocity timing	✓ Ball Kinematics		X OWGR
✓ Balance & stability	✓ GRF			
X Motor control	X Centre of pressure			
✓ Aerobic	X Centre of mass			

✓ Investigated in our combine, X not investigated in our combine

5.3.3 Statistical analysis

HCP was investigated both as a categorical variable via ability level cohorts and as a continuous variable, relative to each technical and physical measure. The magnitude of differences between ability level cohorts were quantified with ES, visualised by forest plots. The relationship between measures and HCP as a continuous measure are shown in bivariate plots.

Power analyses were conducted to determine the number of subjects required in this study to ensure a practically-useful proportion of measures would show significant differences between ability cohorts (i.e., where effect sizes would not be non-trivial in both the positive and negative direction (495)). A correlation of $r = 0.5$ can be considered large and according to different authors equates to an effect size of 0.8 – 1.2 (57, 495). Keogh (2009) found that 12 subjects per ability cohort in total would be required for a correlation coefficient of $r = 0.5$ to be significant, with 80% power and a risk of type I error of 5% (12). Moreover, measures of power have shown even larger correlation to ability than strength and flexibility measures investigated in Keogh (2009), across multiple studies (39, 176{Sell, 2007 #91)}. Therefore, a minimum of 12 golfers per cohort was set as a minimum for this study.

Four HCP classifications used for analysis were based on the means of the upper and lower ranges of participant HCPs for previous studies (11, 12, 82, 124, 278, 286, 288, 307, 323, 324, 328, 332, 345, 354, 355) as detailed in Chapter 3. Mean and SD for all

golfer measures were grouped by the abovementioned HCP classifications. Pairwise ES estimates between the HCP classifications were also obtained for each of the 156 measures (74 physical, 82 technical). ES were calculated using Cohen's *d* method with Hedge's correction within the *effsize* package (496).

Forest Plots

Forest plots were created using Microsoft Excel. Black (Elite vs Low-HCP), blue (Low-HCP vs Mid-HCP) and red (Mid-HCP vs High-HCP) colour coding denotes the cohort comparison for each ES. The value of ES ± CI95 for each cohort comparison is provided on the right-hand side of the chart. Dashed and dotted lines denote large (d > .8) and medium (d > .5) ES for a given cohort, positive to the right, negative to the left of zero.

Bivariate analysis

Bi-variate plots present the various technical and physical measures against standardised HCP with the fitted line as the estimated mean and shaded grey area as the standard error for the estimate (SEE) of the mean. Box plots displaying medians and interquartile ranges are provided for Elite (yellow), Low-HCP (green), Mid-HCP (aqua) and High-HCP (dark blue) ability level cohorts. Furthermore, the age category is colour coded with each data point as either > 18 years (purple), 18-49 years (aqua) or 50+ years (yellow).

5.4 Results

The bivariate charts are presented in rank order of the bi-directional aggregate of the ES for each measure. The intention of the presentation order of measures within each parameter category is to aid the chapter's readability rather than interpreted literally. 84 of the 156 measures provided at least one medium ES for a given cohort comparison and are therefore included in the results section of this chapter. Additionally, to enhance clarity of the Results section, where two similar metrics were derived from the same test (e.g., torque and torque relative to bodyweight) and one was superior in all measures, only bivariate charts for the superior metric are presented in the results section. The remaining 72 bivariate charts (i.e., the measures with only trivial to small ES) can be found in Appendix B (page 318).

5.4.1 Participant characteristics

Participant characteristics are provided for 122 male golfers across ability level cohorts (Table 5.2).

Table 5.2 Male participant characteristics

Ability Level	Handicap Mean ± SD (Range)	n	Age (years) Mean ± SD (Range)	Height (cm) Mean ± SD (Range)	Weight (kg) Mean ± SD (Range)
1. Elite	-1.9 ± 2.1 (-6 – 0.4)	18	28.8 ± 8.1 (19.4 – 46.9)	182.8 ± 6.3 (174 – 190.5)	83.0 ± 7.0 (73.2 – 96.4)
2. Low Handicap	3.1 ± 1.9 (0.5 – 7.4)	56	28.0 ± 12.3 (13.8 – 64.9)	177.6 ± 8.3 (152.5 – 193)	78.7 ± 18.6 (54.9 – 105.7)
3. Mid Handicap	12.1 ± 2.7 (7.5 – 17.4)	35	32.2 ± 19.6 (12.6 – 71.7)	170.8 ± 6.3 (145 – 190.5)	73.9 ± 21.4 (36 – 109.9)
4. High Handicap	28.5 ± 6.4 (17.5 – 36.4)	13	30.2 ± 21.0 (12.5 – 67.1)	174.2 ± 10.4 (154 – 191)	77.4 ± 23.7 (42.2 – 115.9)
All	7.66 ± 9.2 (-6 – 36.4)	122	29.5 ± 15.2 (12.5 – 71.7)	175.7 ± 10.2 (145 – 193)	77.5 ± 19.1 (36 – 115.9)

As shown in Figure 5.2, differences were reported across cohorts - trivial to small for age (d = -0.26 – .1) and weight (d = -0.15 – .26). Limb lengths and endurance (heart rate 45 s after YMCA step test) provided greater differences. The bivariate charts (Figure 5.3 and Figure 5.4) below show how participant characteristics varied across the ability cohorts in our sample.

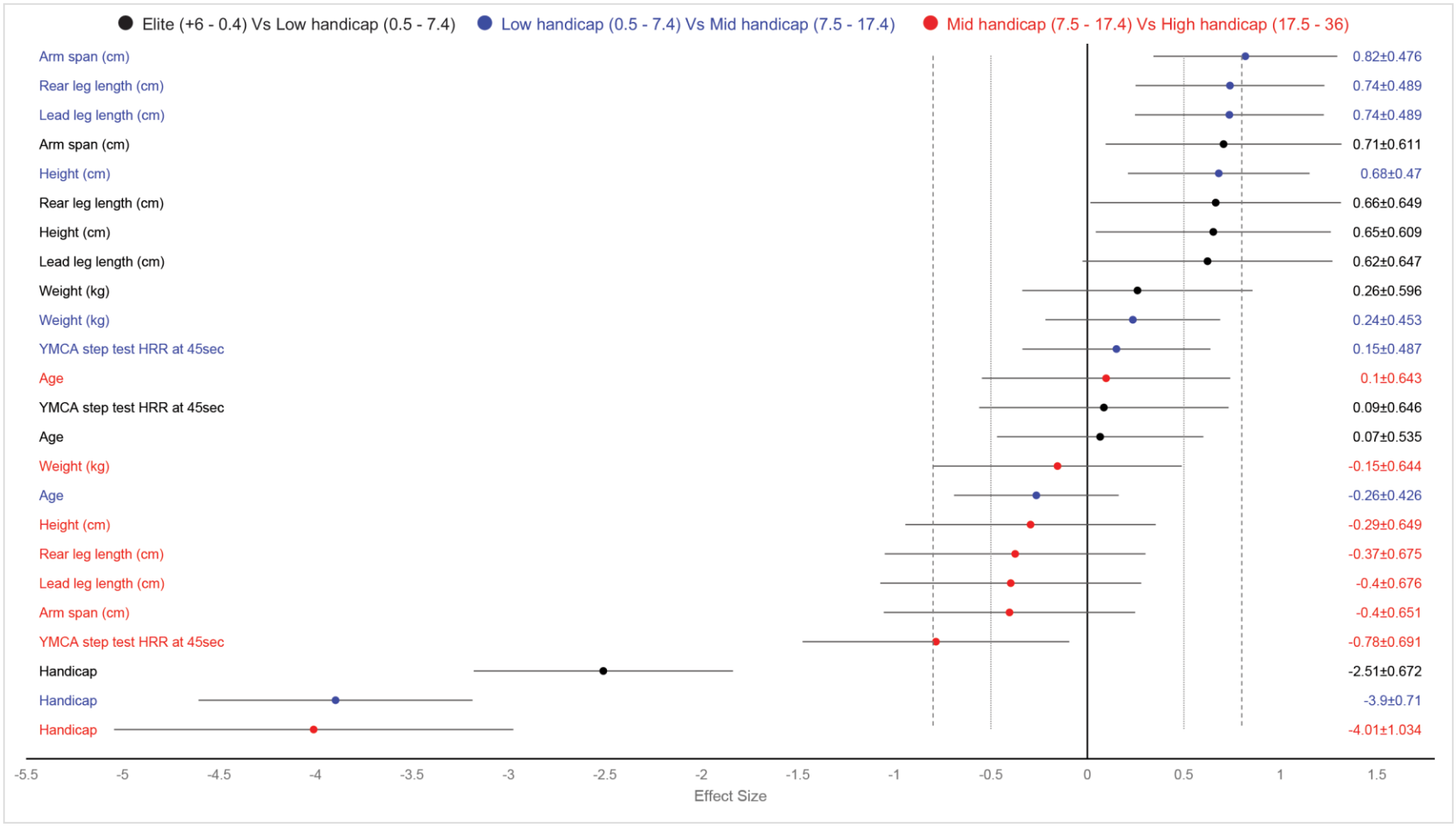


Figure 5.2 Ability cohort differences – handicap, anthropometry, age and step test recovery

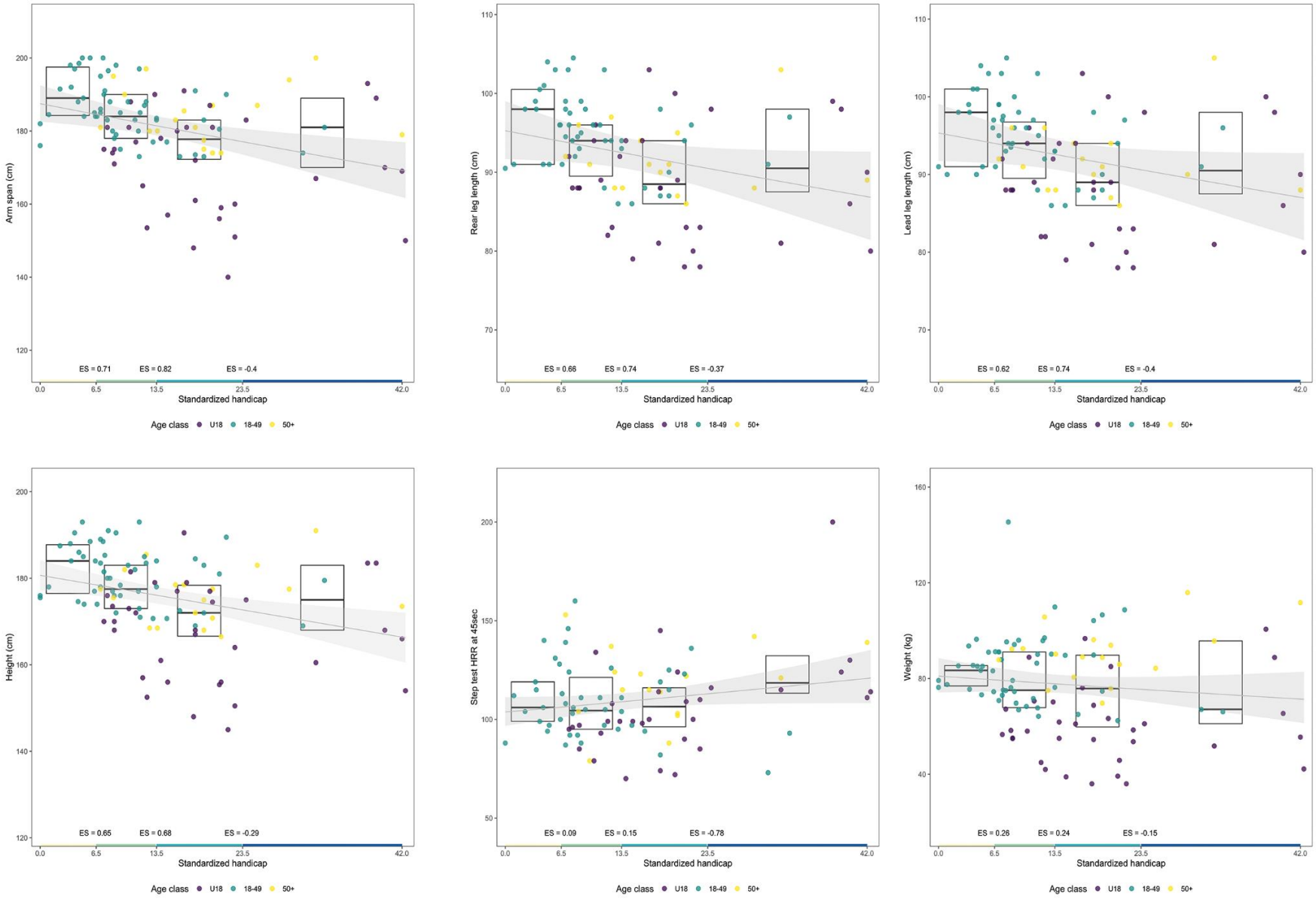


Figure 5.3 Left to right, top to bottom (L-R, T-B) a) arm span, b) rear leg length, c) lead leg length, d) height, e) heart rate recovery, f) weight. Measures plotted with standardised HCP. Box plots of interquartile range and median for ability cohorts.

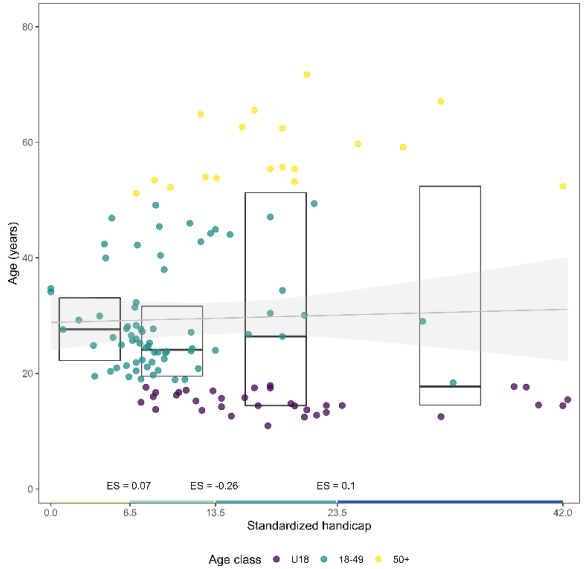


Figure 5.4 Age

5.4.2 Stage 3 & 4 Maximum Driver Shot: Ball kinematic and distance measures

Large ES for Max Driver Shot ball kinematics were found across all cohort comparisons for measures specifically relating to distance. Ball Speed, Driver Carry (Distance), Distance of Maximum Height and Total Length also showed large ES (d = 0.89 – 1.56). between the Mid-HCP and High-HCP groups. Large ES were also found between one or more cohort comparisons for Carry Time, Maximum Height, Carry Ball Speed and Spin Rate. See the forest plot of group difference ES (Figure 5.5) and the bivariate charts (Figure 5.6 and Figure 5.7) for all details.

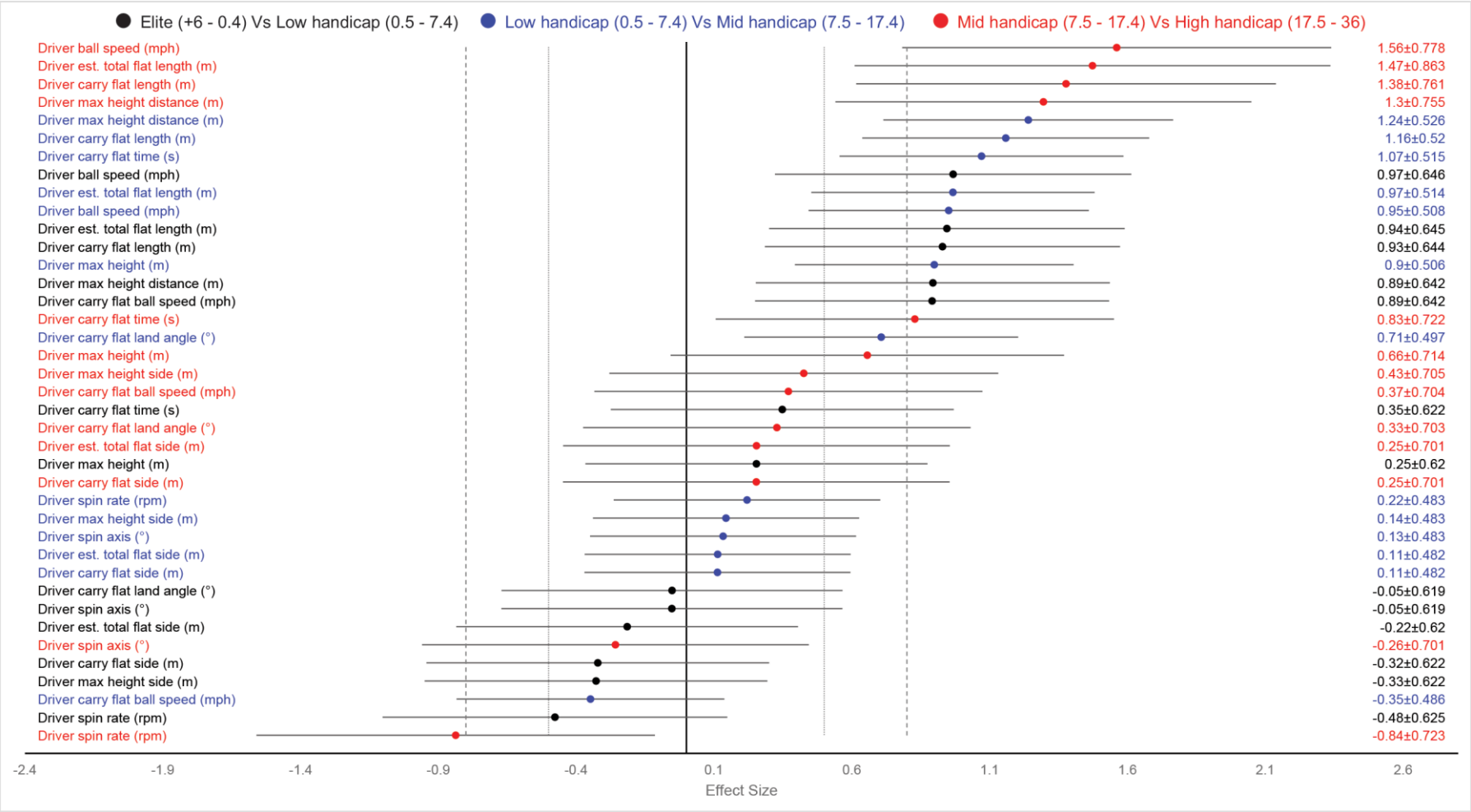


Figure 5.5 Ability cohort differences – ball kinematic measures from Maximum Driver Distance Test captured by Trackman™

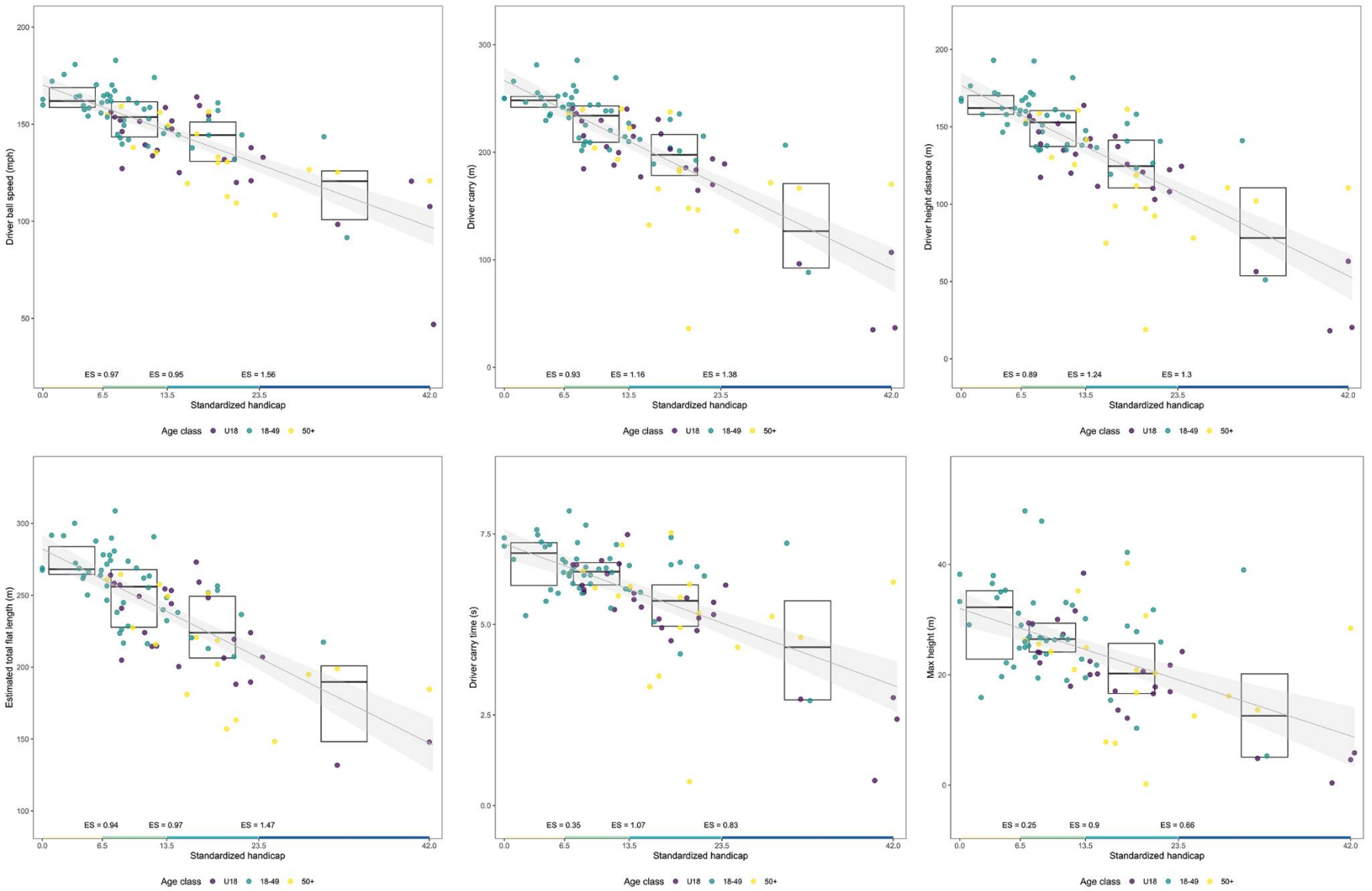


Figure 5.6 (L-R, T-B) a) Driver ball speed, b) Driver carry distance, c) Driver maximum height distance, d) Driver total distance, e) Driver carry time, f) Driver maximum height

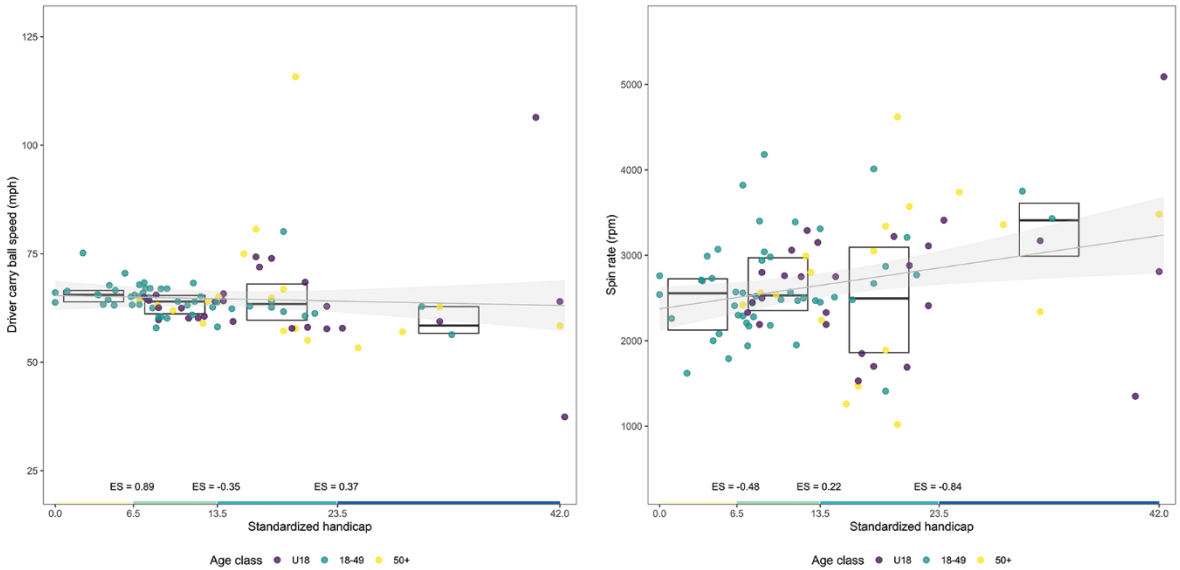


Figure 5.7 (L-R, T-B) a) Driver carry (landing) ball speed, b) Driver spin rate

5.4.3 Stage 3 Maximum Driver Shot: Club kinematic & launch measures

Most of the largest ES for Max Driver Shot club kinematics were found between the Mid-HCP and High-HCP groups. The largest aggregated uni-directional ES were from CHS metrics, Smash Factor and Attack Angle (d = .08 – 1.57) and Low Point (d = -.09 – -1.21). Launch Direction and Face Angle also provided some small to medium ES between cohorts, although these were bi-directional. See the forest plot of group difference ES (Figure 5.8) and the bivariate charts (Figure 5.9 and Figure 5.10) for all details.

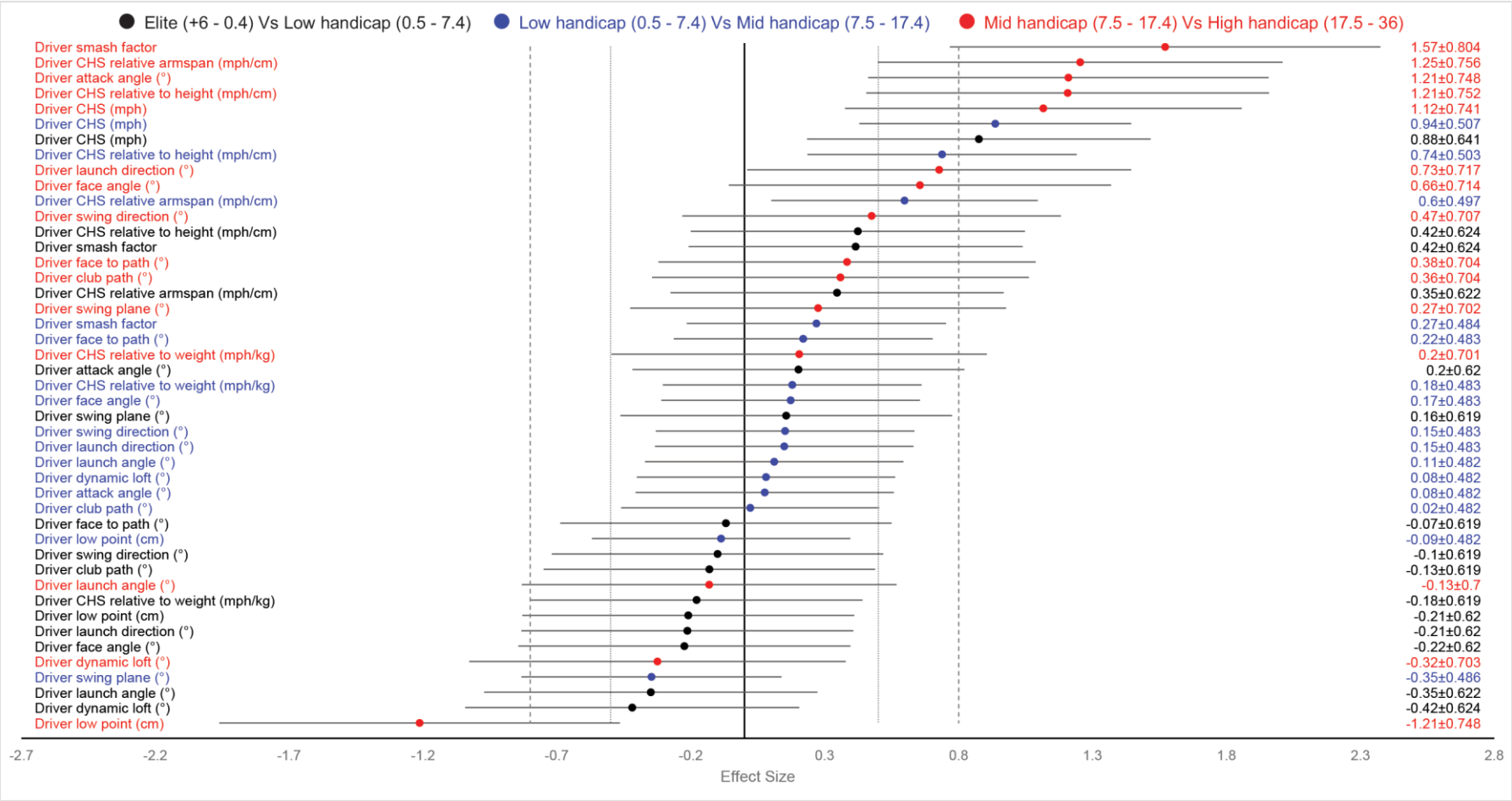


Figure 5.8 Ability cohort differences – club kinematic measures from Maximum Driver Distance Test captured by Trackman™

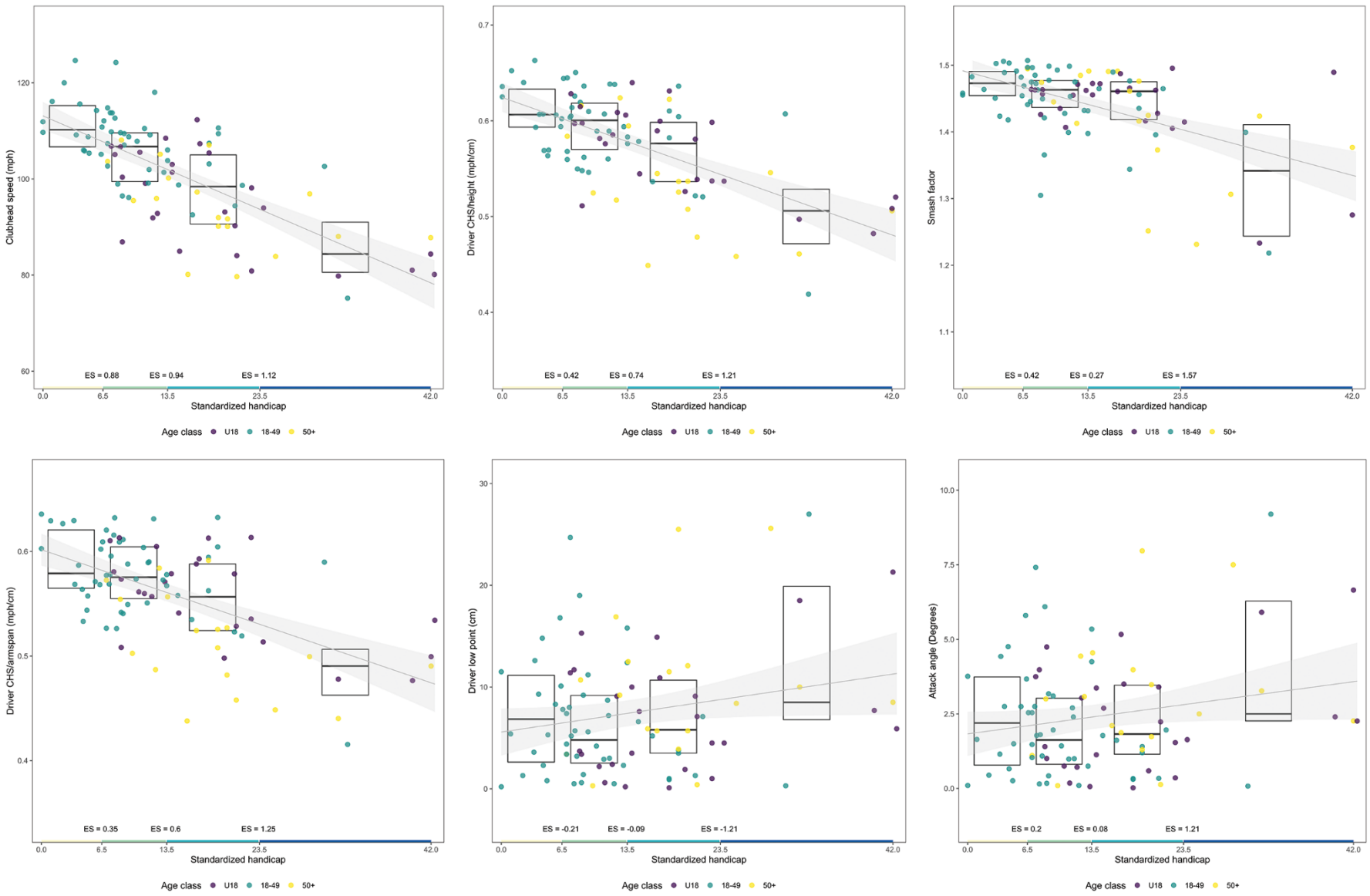


Figure 5.9 (L-R, T-B) a) Driver CHS, b) Driver CHS/height, c) Driver smash factor, d) Driver CHS/arm span, e) Driver low point, f) Driver attack angle

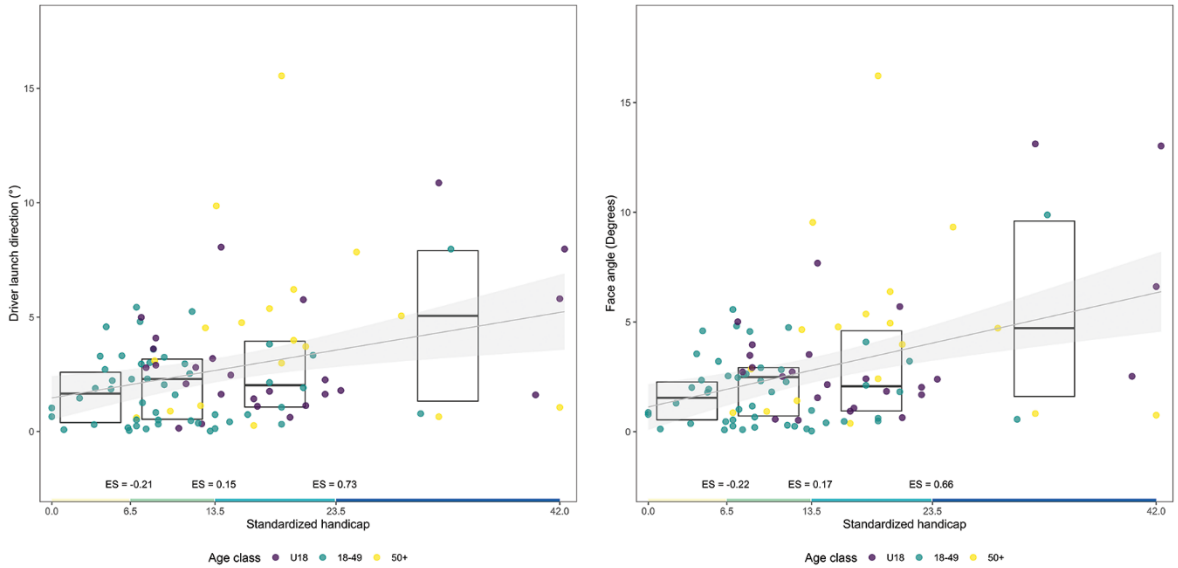


Figure 5.10 (L-R) a) Driver launch direction, b) Driver face angle

5.4.4 Stage 3 & 4 120 m Target Shot: Ball Kinematics & Accuracy

Medium to Large ES for 120 m Shot ball kinematics were found uni-directionally across all cohort comparisons for measures specifically relating to accuracy and hitting a high shot that would be expected to land with minimal roll. These ball measures included: Spin Rate, Distance to Target, Carry Landing Angle, Maximum Height and Carry Time (d = 0.59 – 1.33). Medium to Large ES were also found between one or more cohort comparisons for 120 m Shot: Maximum Height Distance, Carry Length, Ball Speed and Carry Ball Speed. See the forest plot of group difference ES (Figure 5.11) and the bivariate charts (Figure 5.12 and Figure 5.13) for all details.

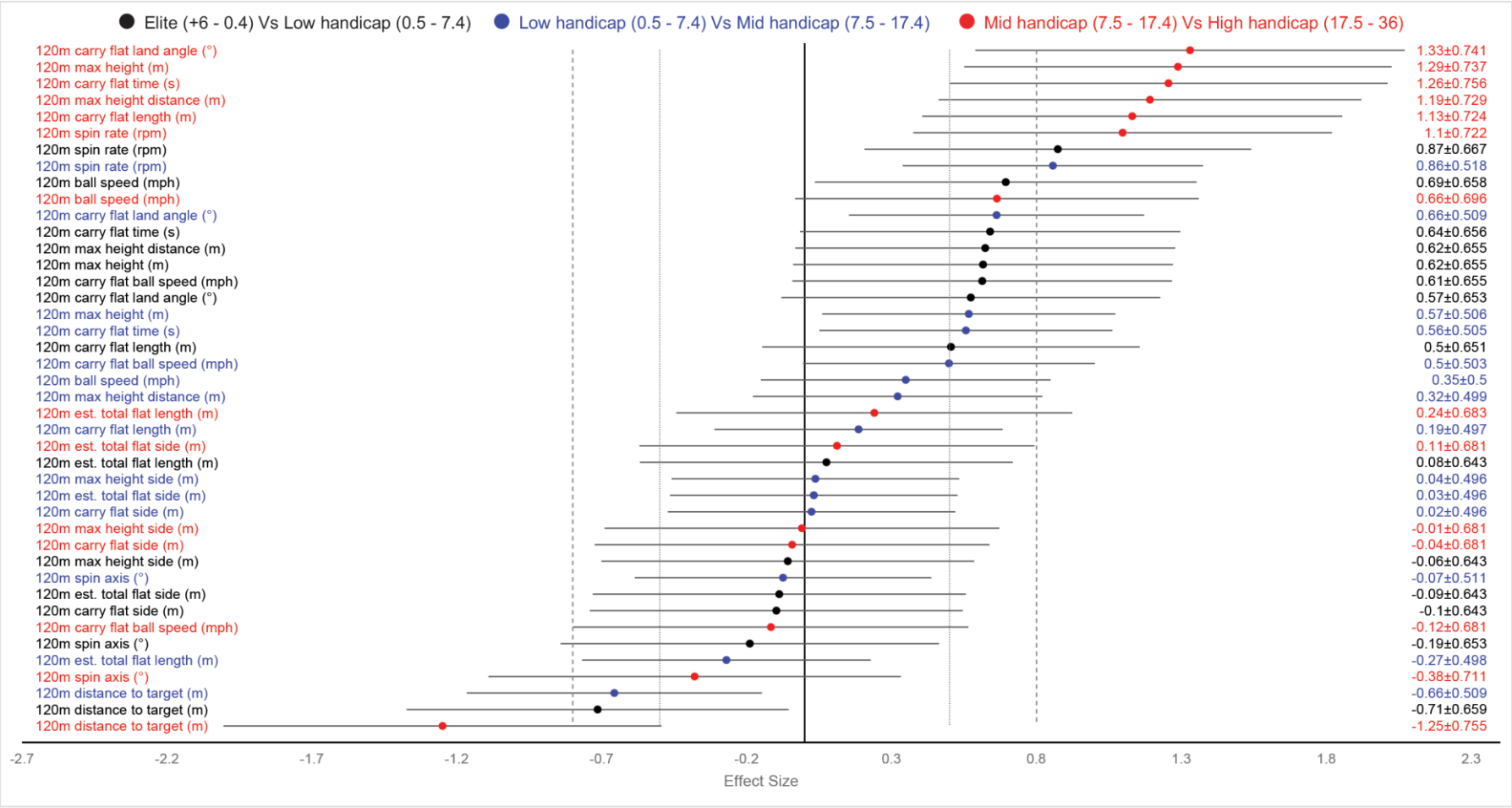


Figure 5.11 Ability cohort differences – ball kinematic measures from 120 m Target Shot Test captured by Trackman™

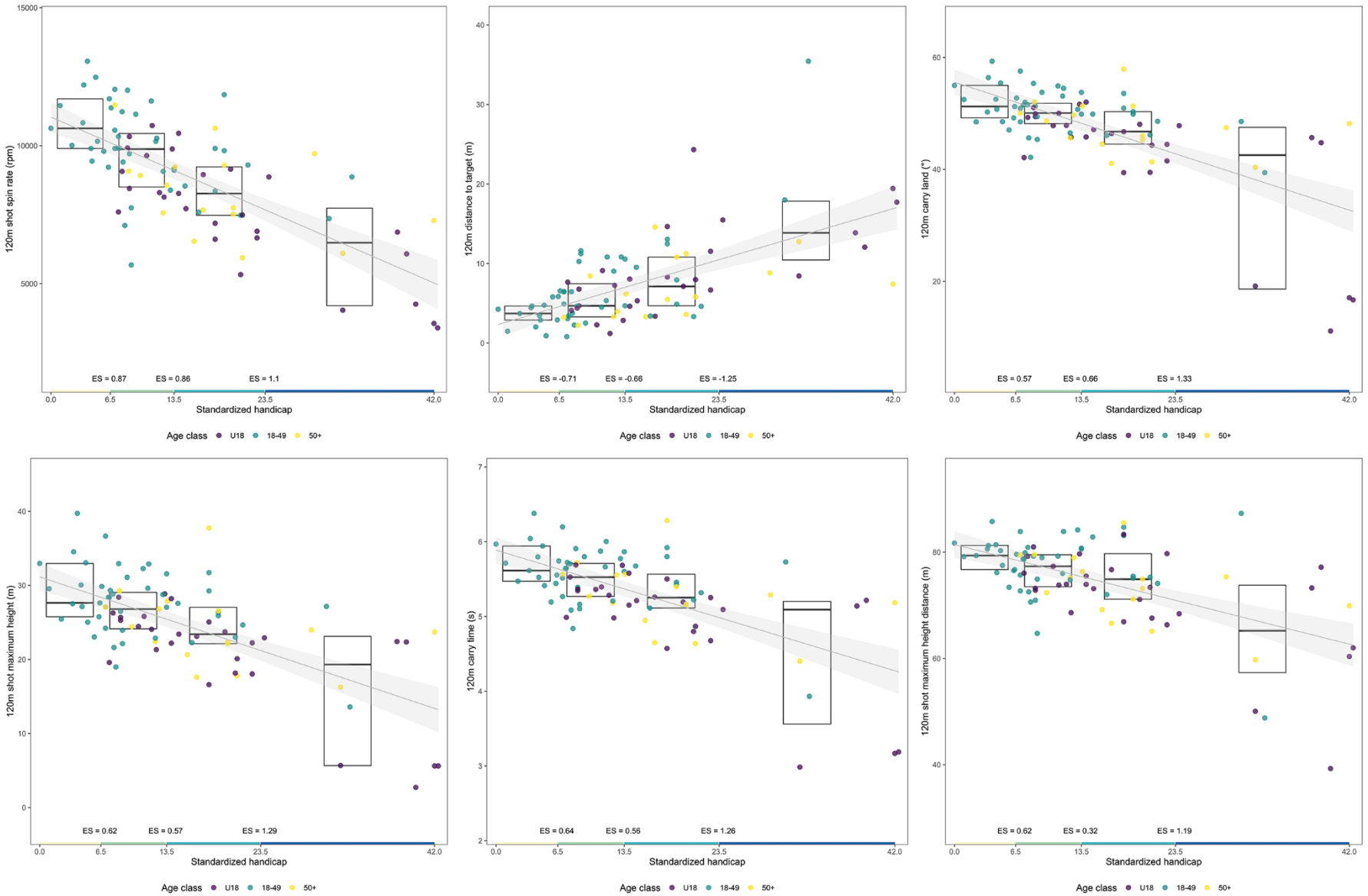


Figure 5.12 (L-R, T-B) a) 120 m shot spin rate, b) 120 m distance to target, c) 120 m carry landing angle, d) 120 m shot maximum height, e) 120 m shot carry time, f) 120 m shot maximum height distance

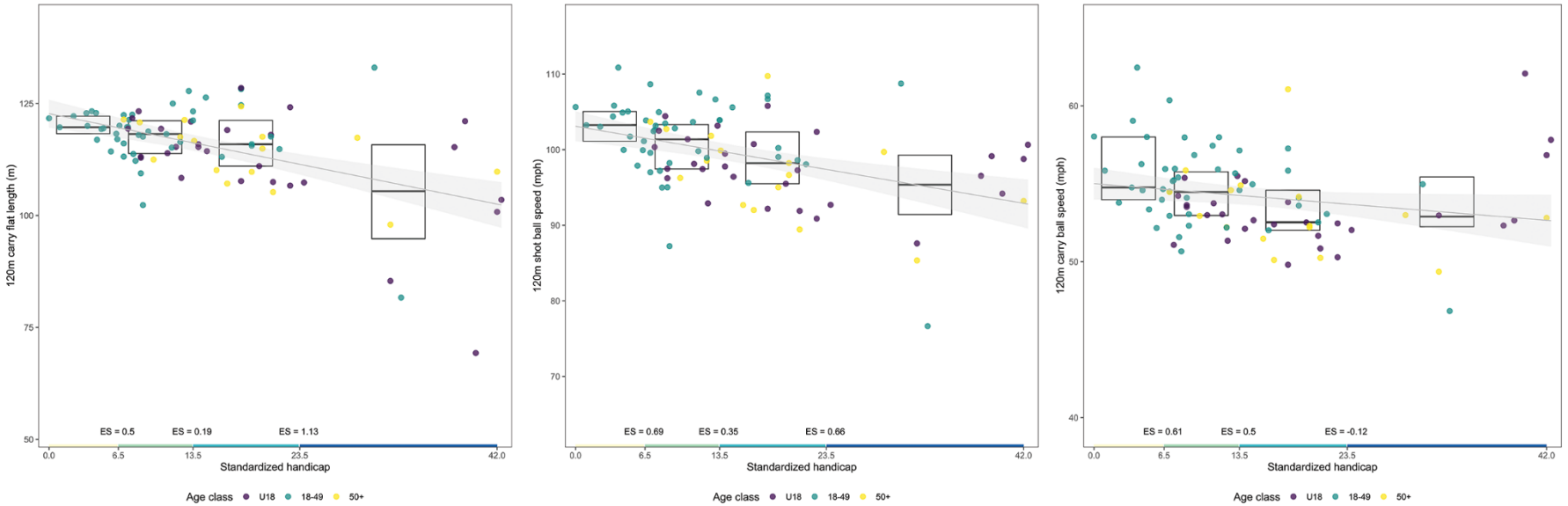


Figure 5.13 (L-R) a) 120 m carry flat length, b) 120 m shot ball speed, c) 120 m shot carry (landing) ball speed

5.4.5 Stage 3 120 m Target Shot: Club kinematics & launch measures

Medium to Large uni-directional ES for 120 m Shot club kinematics were found across all cohort comparisons for Dynamic Loft and CHS (*d* = 0.57 – 1.07). Medium to Large ES were also found between one or more cohort comparisons for 120 m Shot: Launch Angle, Smash Factor, Attack Angle and Low Point. See the forest plot of group difference ES (Figure 5.14) and the bivariate charts (Figure 5.15) for all details.

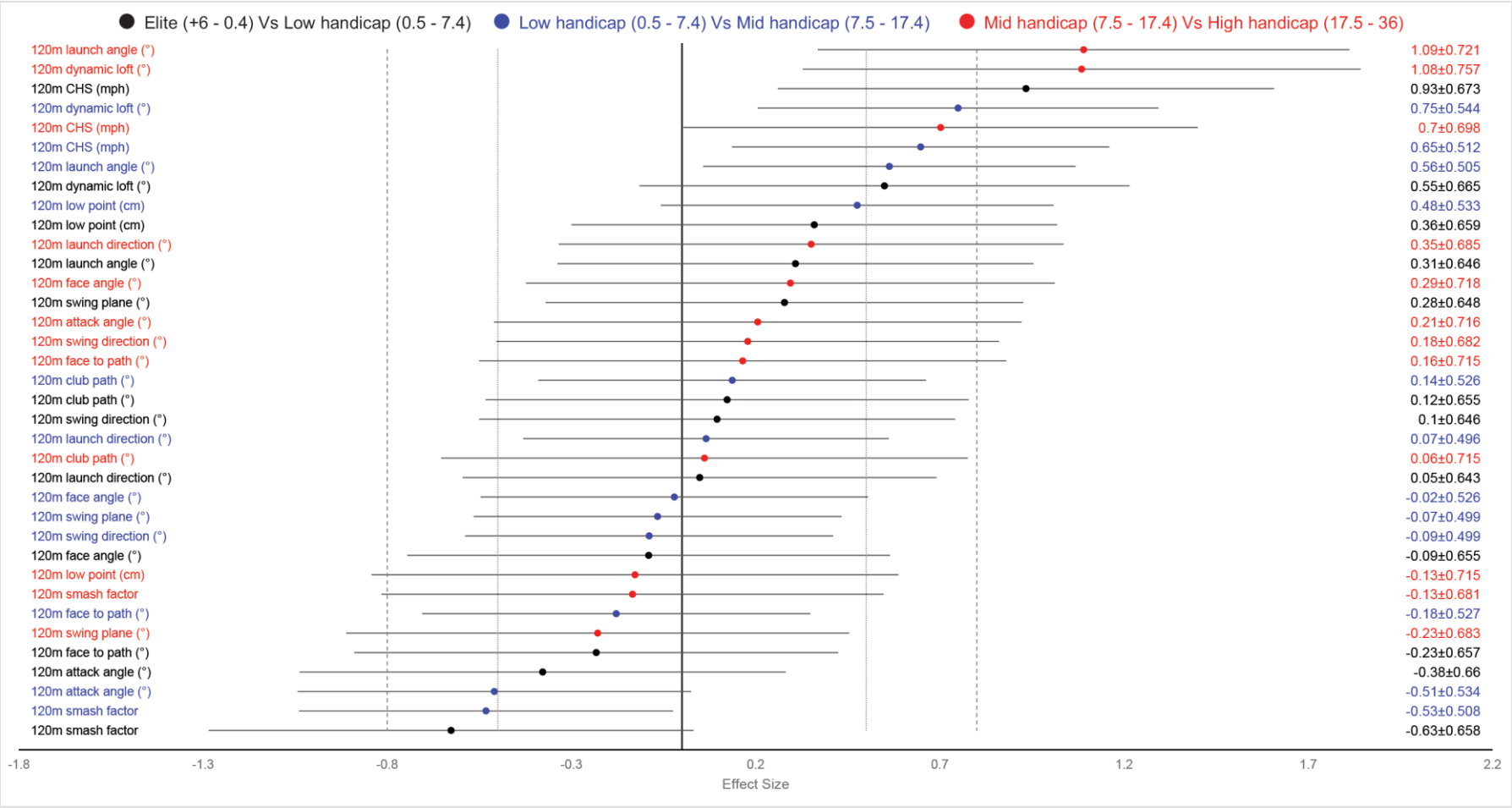


Figure 5.14 Ability cohort differences – club kinematic measures from 120 m Target Shot Test captured by Trackman™

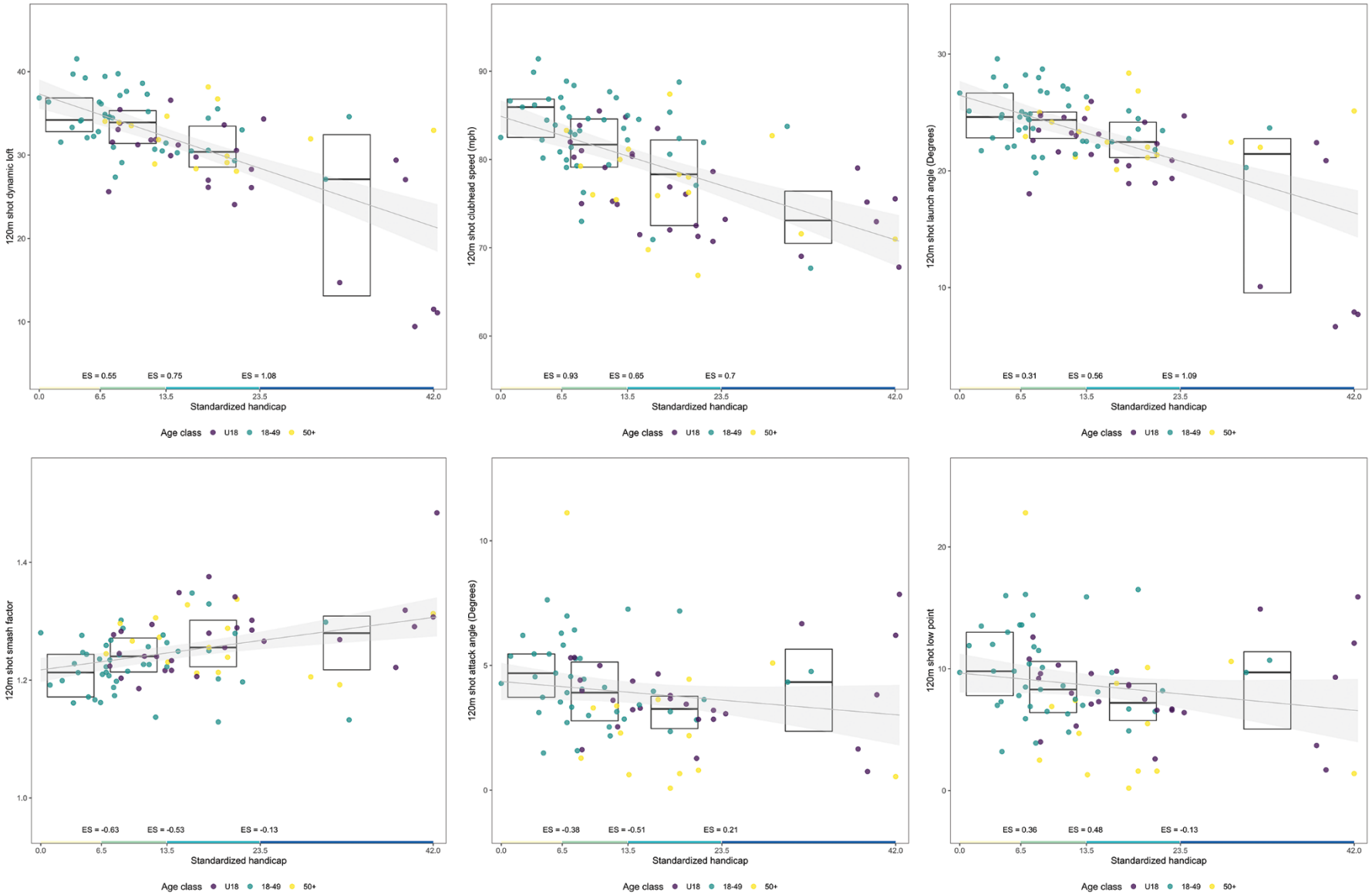


Figure 5.15 (L-R, T-B) a) 120 m shot dynamic loft, b) 120 m shot CHS, c) 120 m shot launch angle, d) 120 m shot smash factor, e) 120 m shot attack angle, f) 120 m shot low point

5.4.6 Stage 2 Maximum Driver Shot: Body kinematics

Medium ES for Max Driver Shot body kinematics were found in two cohort comparisons only for Lead (Angular) Shoulder Speed (d = .20 – .78). The remaining measures presented in bivariate charts below provided a medium ES in only one cohort comparison. Overall, the largest ES in body kinematics were typically found between the Elite and Low-HCP cohorts. See the forest plot of group difference ES (Figure 5.16) and the bivariate charts (Figure 5.17) for all details.

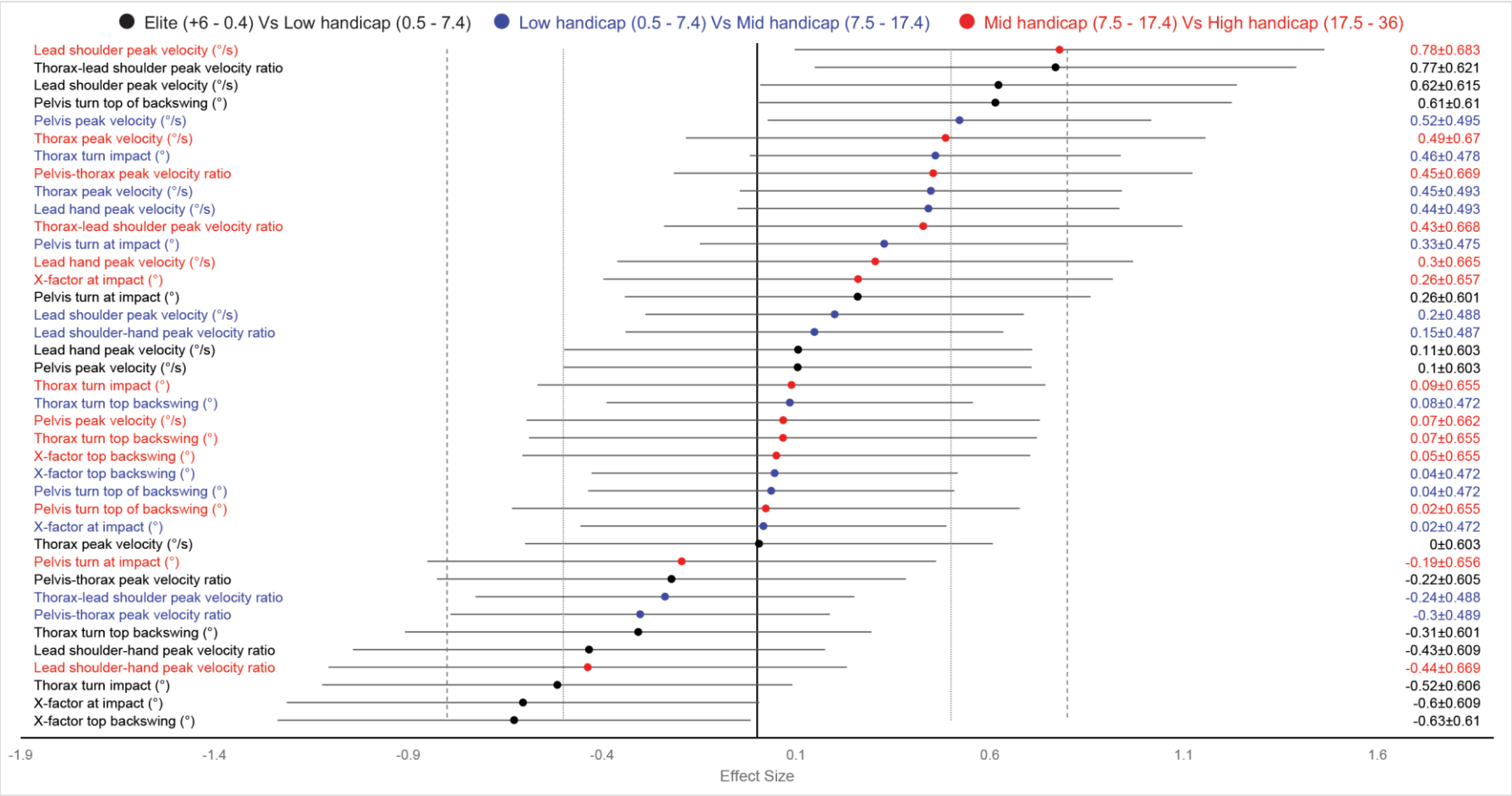


Figure 5.16 Ability cohort differences – 3-Dimensional body kinematic measures from Maximum Driver Distance Test captured by K-Vest™

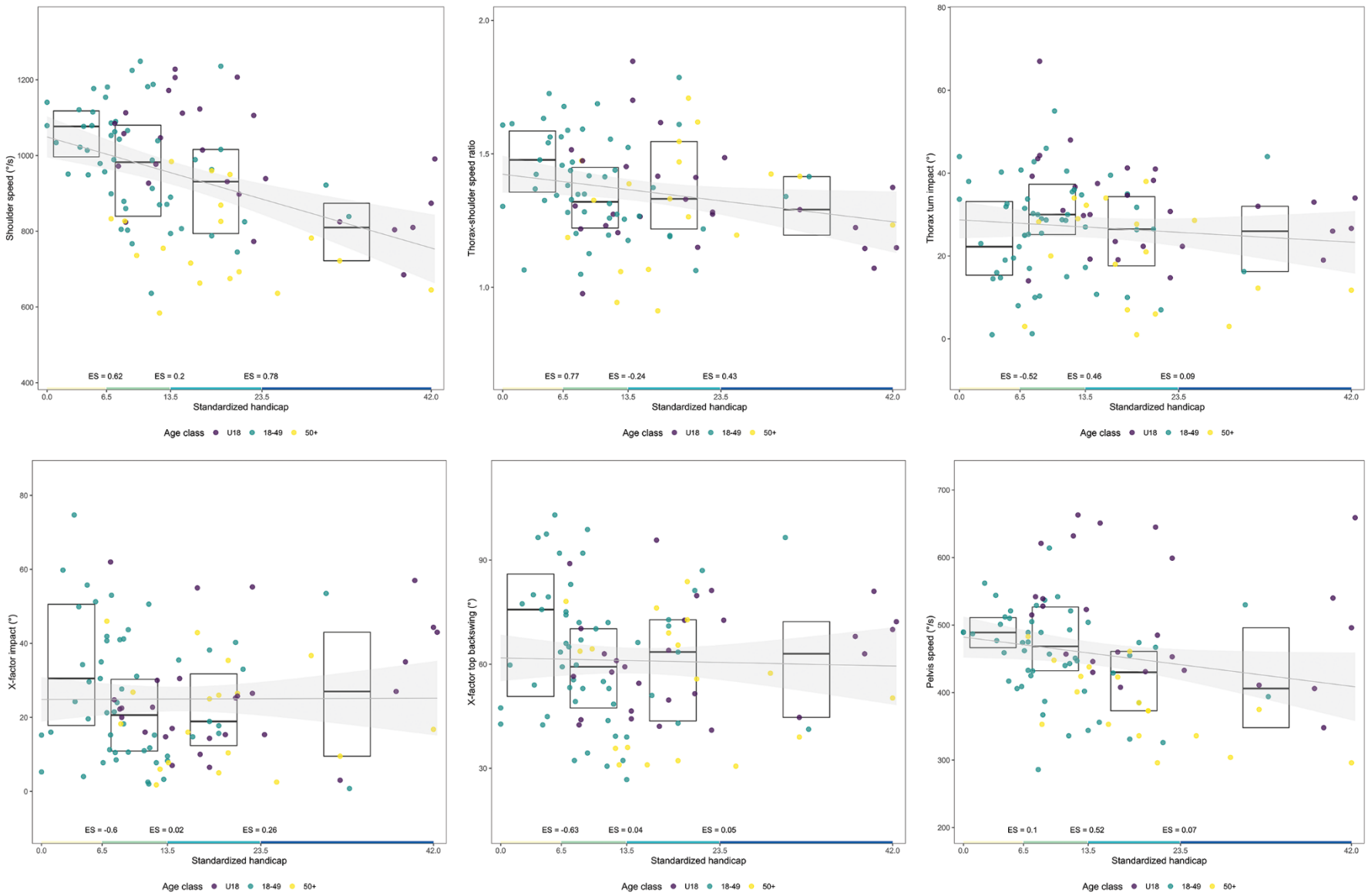


Figure 5.17 (L-R, T-B) a) Lead shoulder peak angular speed, b) Thorax-lead shoulder peak angular speed ratio, c) Thorax turn at impact, d) X-factor at impact, e) X-factor at top of backswing, f) Pelvis peak angular speed

5.4.7 Stage 2 Maximum Driver Shot: Ground reaction forces

Large ES for Max Driver Shot ground reaction forces were found in the Elite and Low-HCP cohort comparison for both Max Fz Rear (*d* = 1.1) and Max Fy Rear (*d* = 1). Medium ES were also seen across all cohorts for Time Between Fy Peaks. The remaining measures presented in bivariate charts below provided a medium ES in one or two cohort comparisons. Overall, the largest ES in GRF were typically found between the Elite and Low-HCP cohorts. See the forest plot of group difference ES (Figure 5.18) and the bivariate charts (Figure 5.19 and Figure 5.20) for all details.

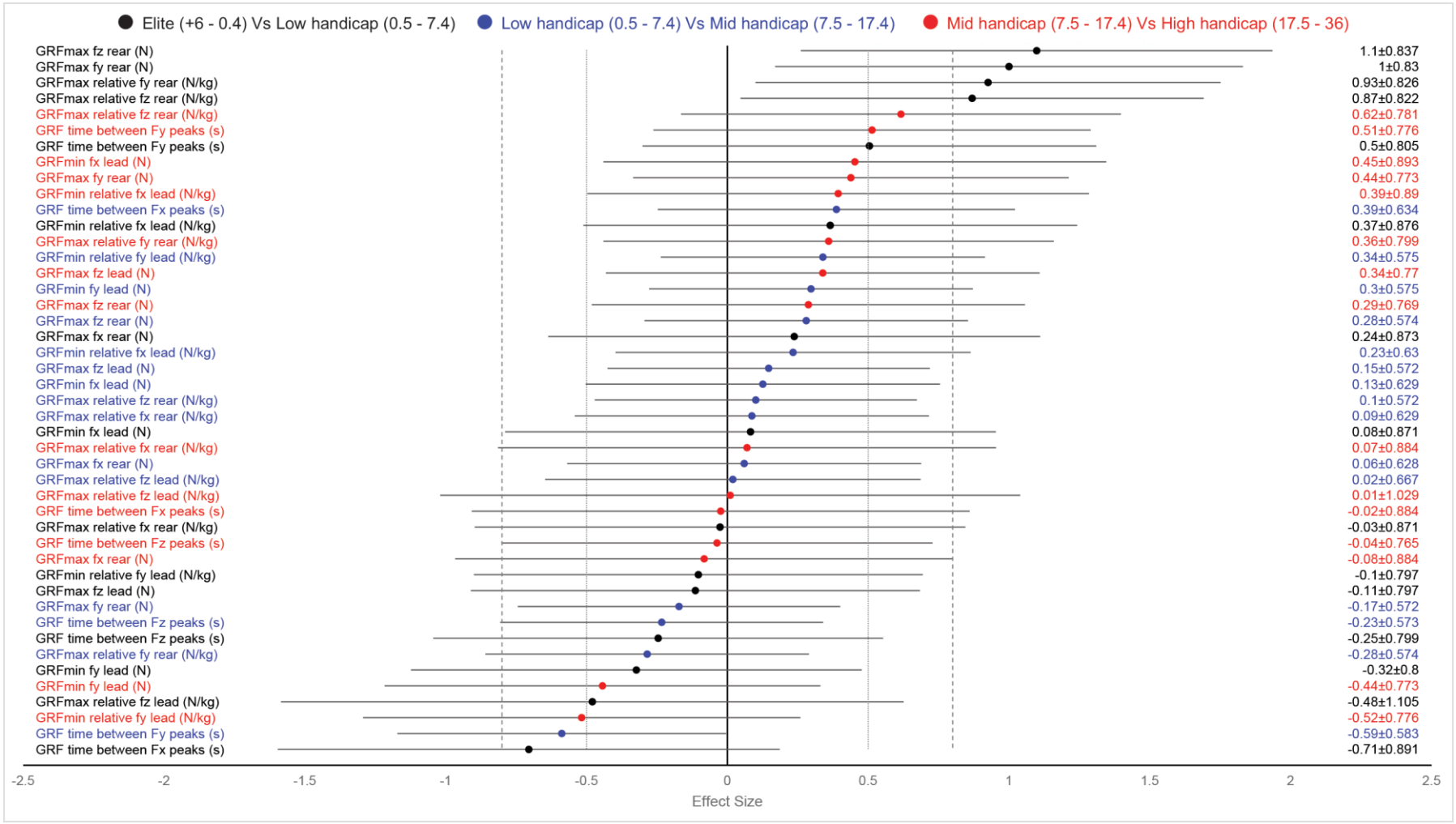


Figure 5.18 Ability cohort differences – 3-Dimensional ground reaction force measures from Maximum Driver Distance Test captured by dual Kistler force plates

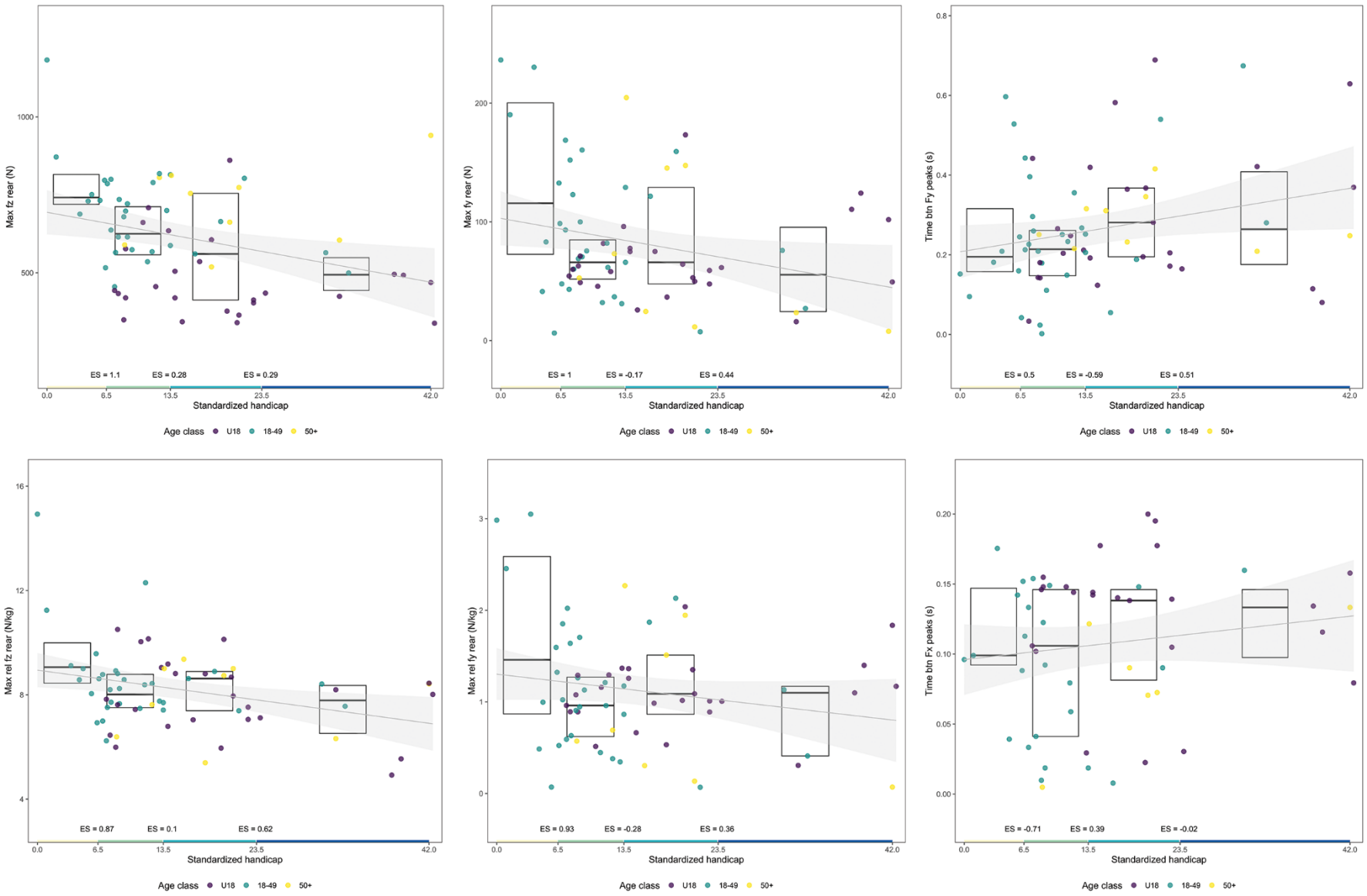


Figure 5.19 (L-R, T-B) a) Maximum Fz rear leg, b) Maximum Fy rear leg, c) Time between rear to lead Fy peaks, d) Maximum relative to bodyweight Fz rear leg, e) Maximum relative to bodyweight Fy rear leg, f) Time between rear and lead leg Fx peaks

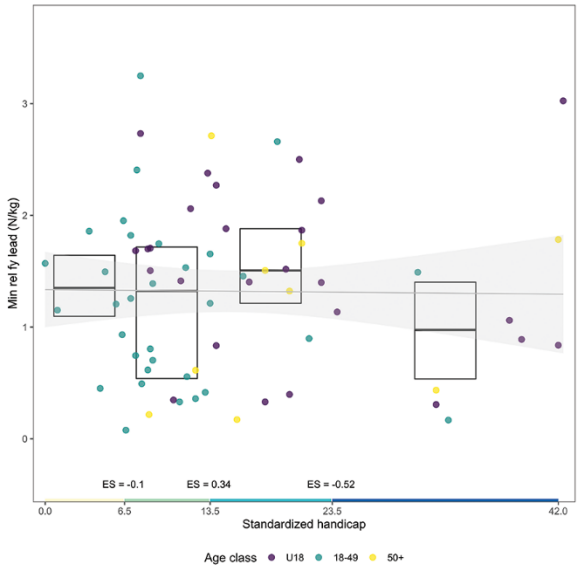


Figure 5.20 Minimum relative to bodyweight Fy lead leg

5.4.8 Stage 1 Physical – Power measures

Medium to Large ES for Physical Power measures were found in the Elite to Low-HCP cohort and the Low-HCP to Mid-HCP comparisons for Lateral Throw 3 kg, Chest Pass 3 kg, Sit Throw 3 kg, Estimated Peak (Leg) Power and Vertical CMJ Reach. A large ES was also found between the Mid-HCP and High-HCP cohorts for CMJ Rel Peak Fz. One Medium ES was also found with the Lateral Jump Lead and Rear tests. Overall, the largest ES in body kinematics were typically found in the comparisons of the top three ability levels. See the forest plot of group difference ES (Figure 5.21) and the bivariate charts (Figure 5.22 and Figure 5.23) for all details.

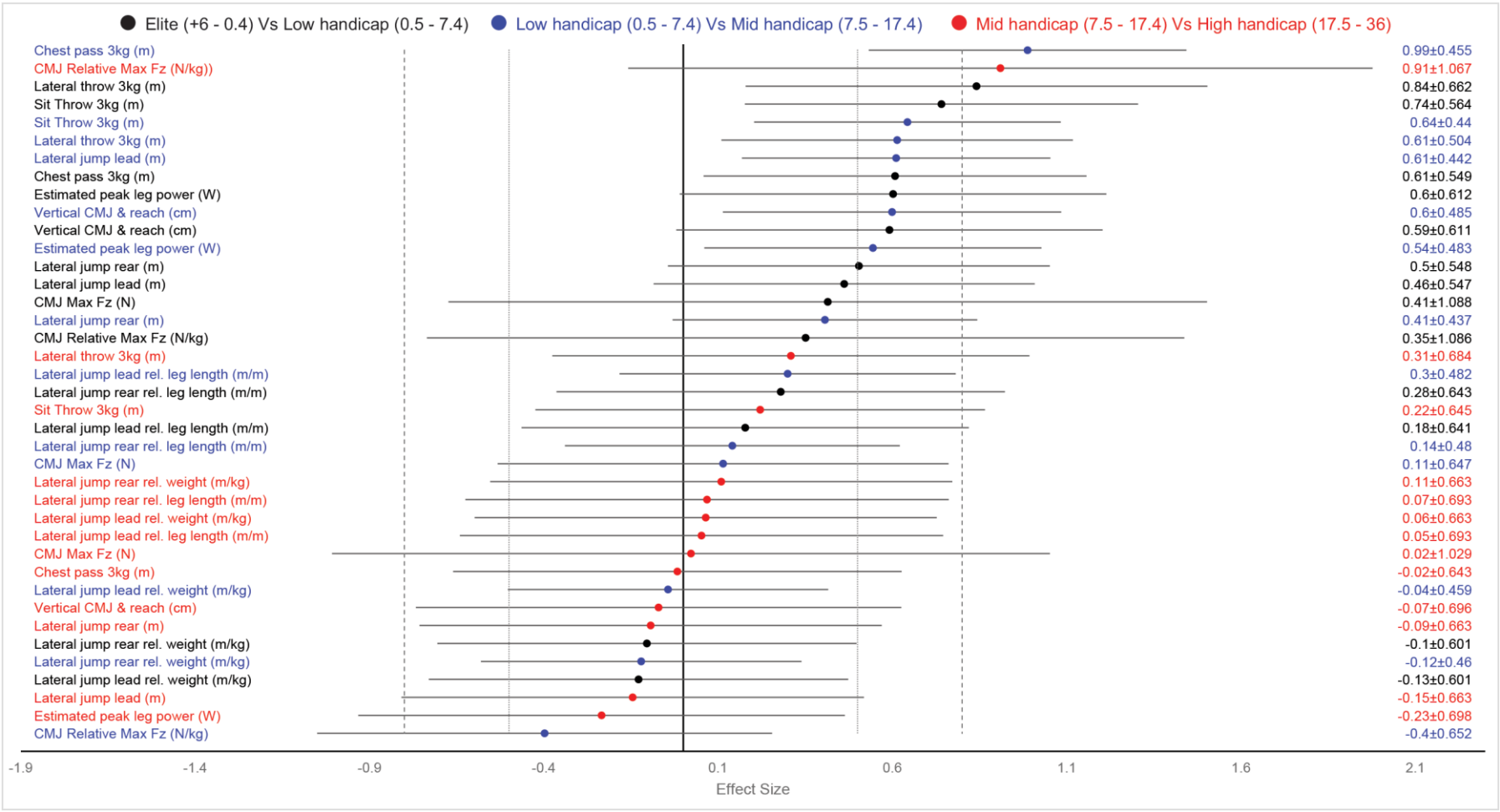


Figure 5.21 Ability cohort differences – power measures from jump and medicine ball throw tests

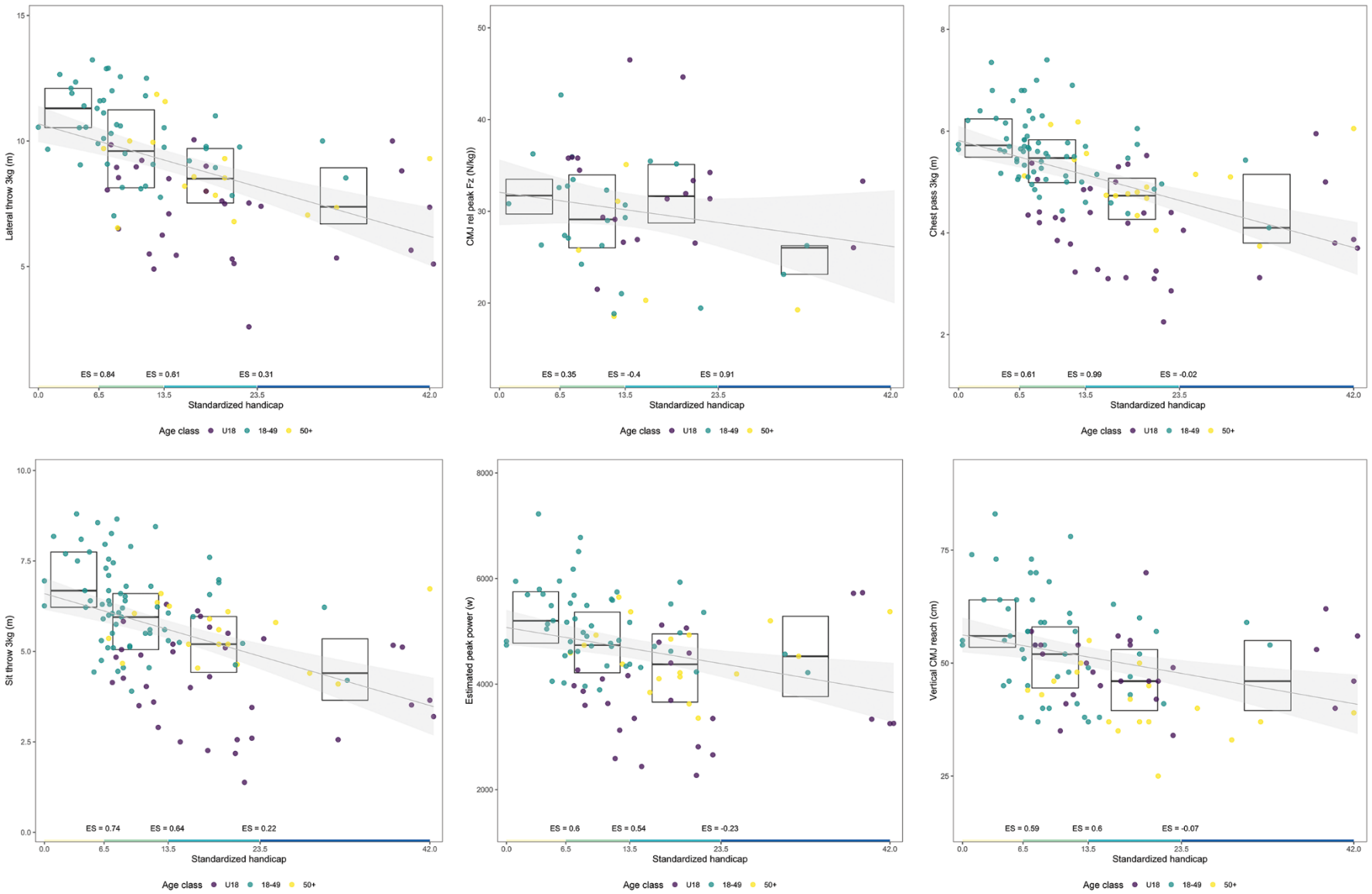


Figure 5.22 (L-R, T-B) a) 3kg medicine ball lateral throw, b) CMJ peak Fz relative to bodyweight, c) 3kg medicine ball chest pass, d) 3kg medicine ball sit throw, e) Estimated peak leg power from CMJ, f) Vertical CMJ and reach

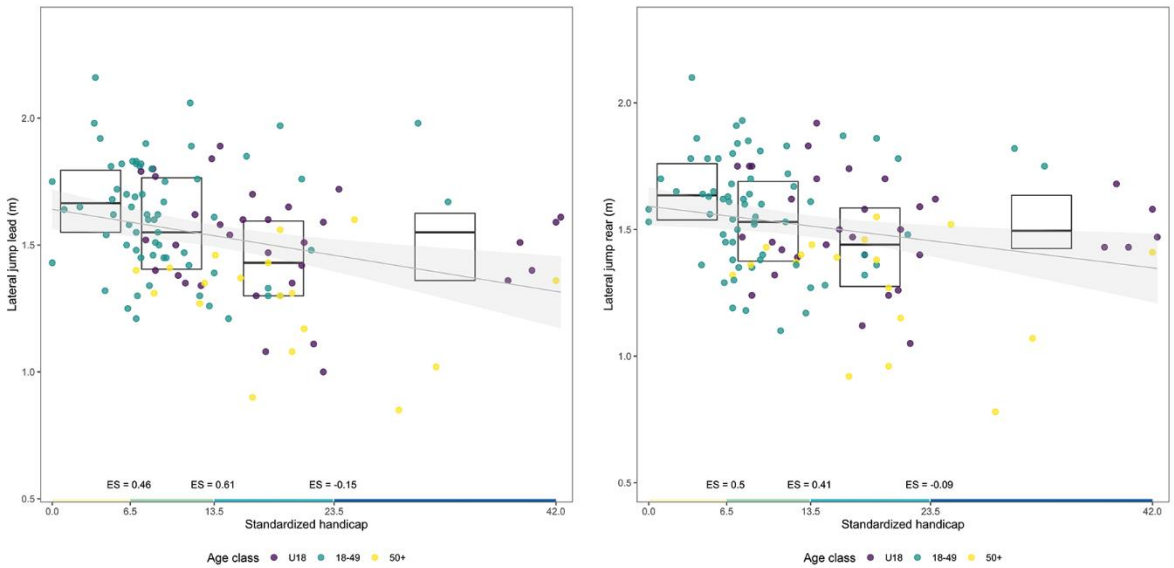


Figure 5.23 (L-R) a) Lateral jump lead leg, b) Lateral jump rear

5.4.9 Stage 1 Physical – Isometric strength measures

Large ES for Absolute (Isometric) Strength measures were only found in the Mid-HCP to High-HCP cohort which may have been affected by low sample size for some tests (High-HCP, *n* = 7). Two medium ES were found between the Low-HCP to Mid-HCP comparisons for Grip Strength Lead and Rear, which also had the largest ES for the Elite to Low-HCP comparison (*d* = 0.42, .43). See the forest plot of group difference ES (Figure 5.24) and the bivariate charts (Figure 5.25 and Figure 5.26) for all details.

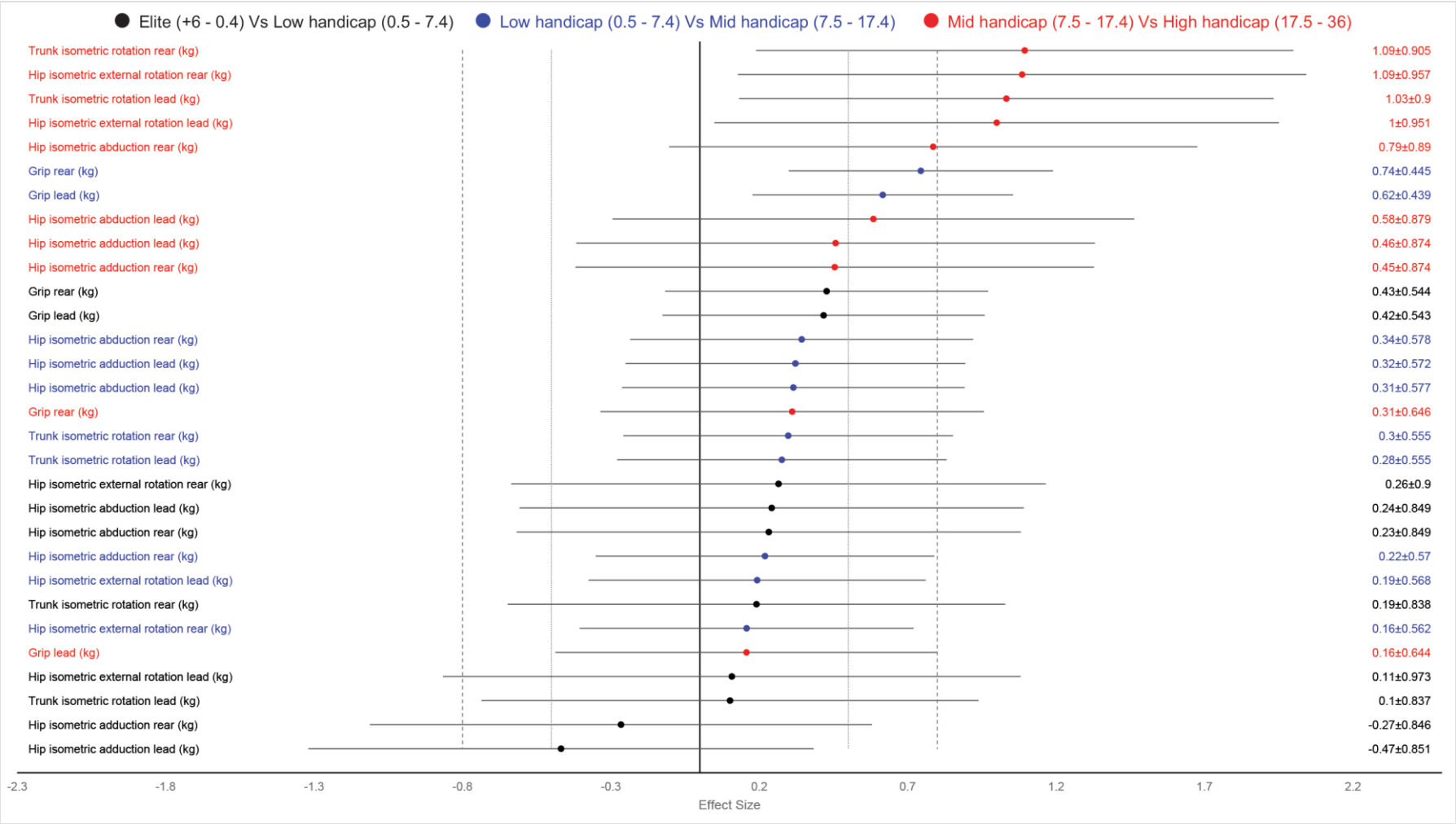


Figure 5.24 Ability cohort differences – absolute force measures from isometric strength measures using Kanga-tech™ electro-dynamometers and manual TTM Original hand grip dynamometer

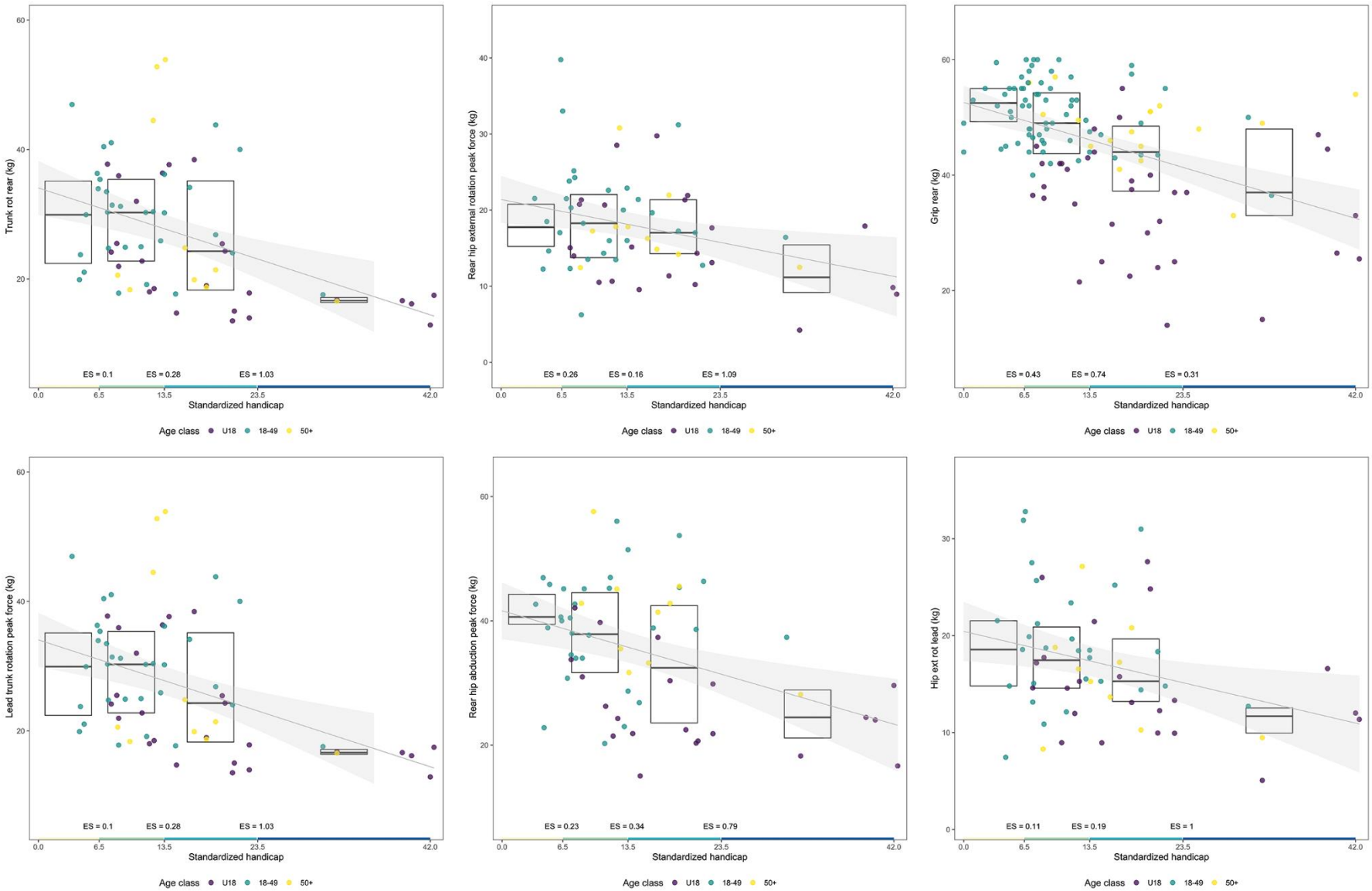


Figure 5.25 (L-R, T-B) Isometric peak force measures: a) Trunk rotation to rear side, b) Rear hip external rotation, c) Rear hand grip, d) Trunk rotation to lead side, e) Rear hip abduction, f) Lead hip external rotation

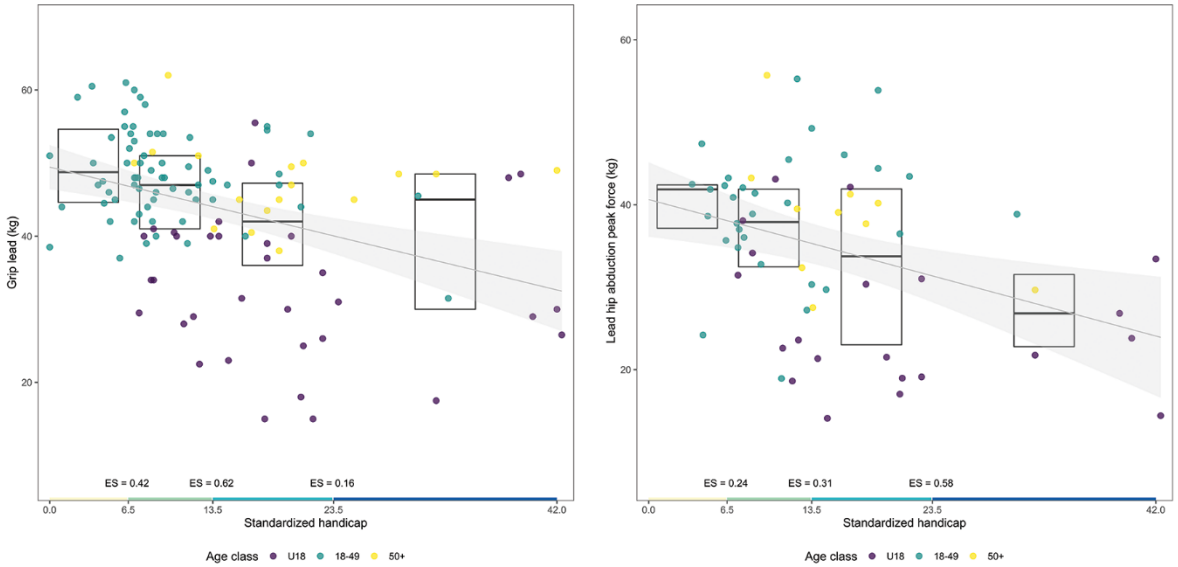


Figure 5.26 (L-R) Isometric peak force measures: a) Lead hand grip, b) Lead hip abduction

5.4.10 Stage 1 Physical – Isometric torque and relative torque measures

Similar results to absolute strength were seen with torque metrics. For all tests, the torque metrics provided larger ES than the relative (to bodyweight) torque metrics, therefore bivariate charts for the latter can be viewed in Appendix B. Large ES for (Isometric) torque and relative torque metrics were only found in the Mid-HCP to High-HCP cohort which also may have been affected by lower sample size for some tests (High-HCP, *n* = 13) – hence the typically larger CI95 widths, although the majority met the expectation of showing significantly positive effect sizes as suggested by the power analysis. Rear and Lead Hip External Rotation Peak Torque provided the largest uni-directional aggregated ES. Lead and Rear Hip Abduction Peak Torque provided the largest ES for the Elite to Low-HCP comparisons (*d* = 0.45 and .44). See the forest plot of group difference ES (Figure 5.27) and the bivariate charts (Figure 5.28) for all details.

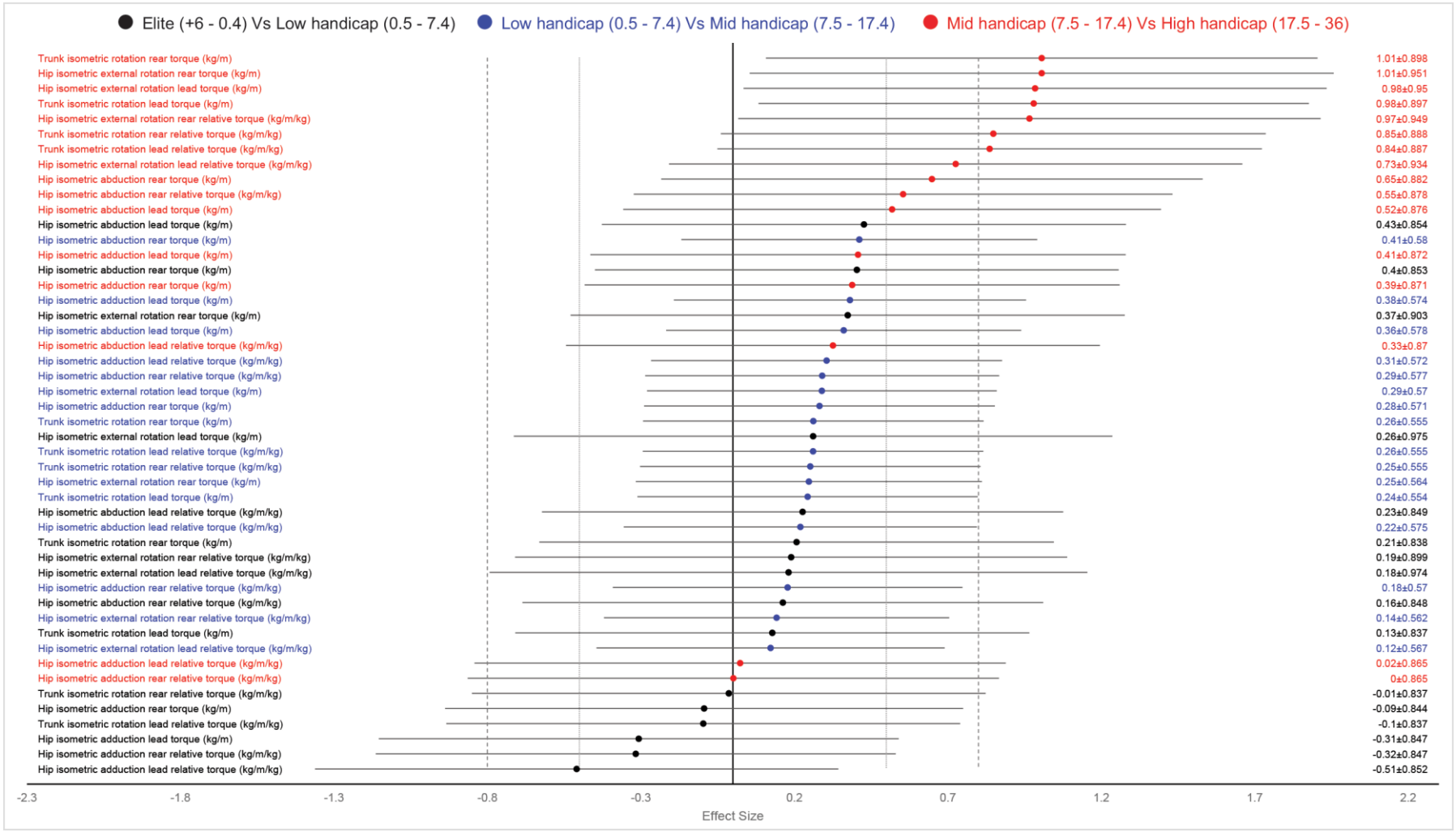


Figure 5.27 Ability cohort differences – isometric torque & relative torque measures from isometric strength measures using Kanga-tech™ electro-dynamometers and hand grip dynamometer

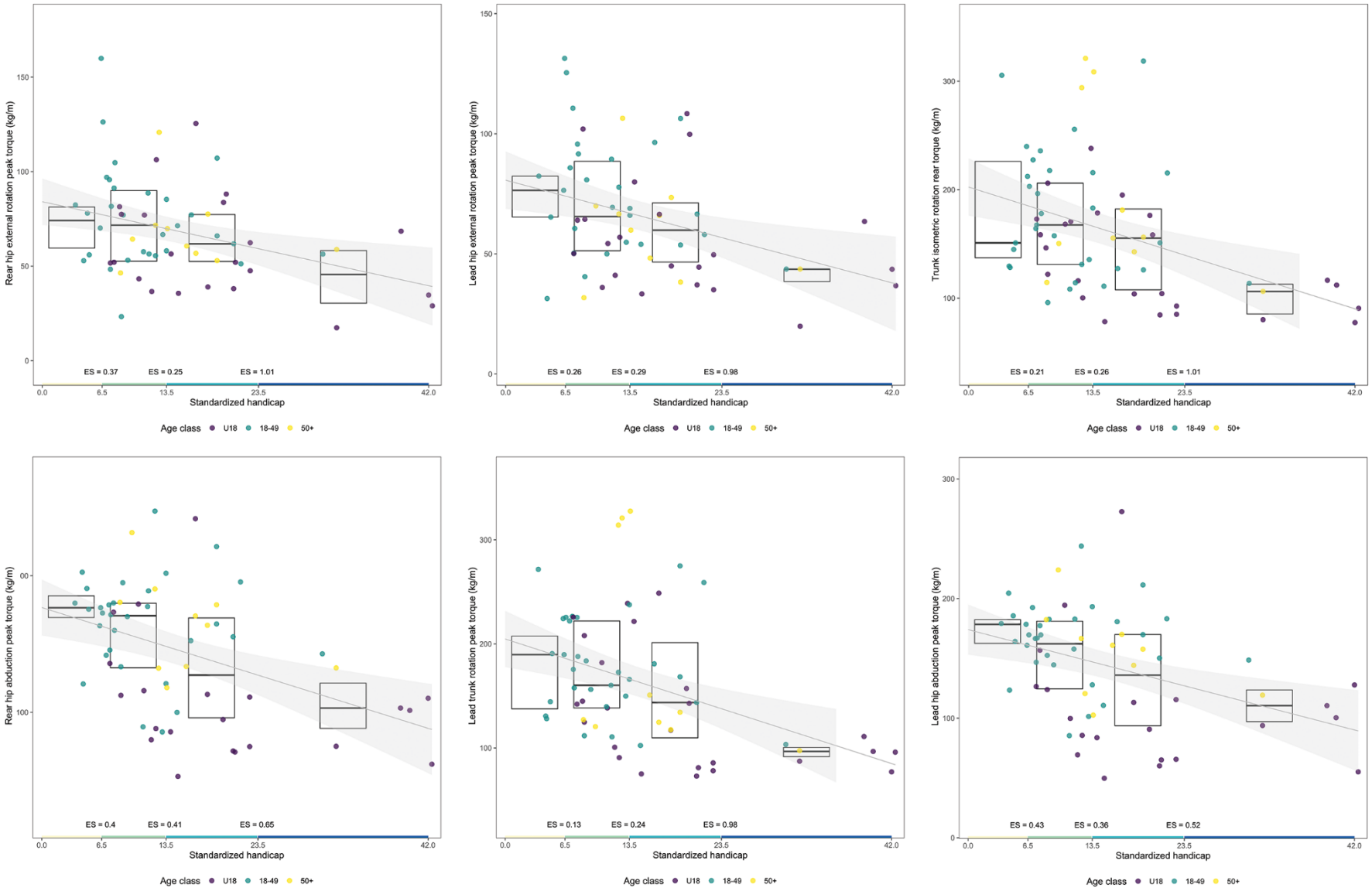


Figure 5.28 (L-R, T-B), Isometric peak torque measures: a) Rear hip external rotation, b) Lead hip external rotation, c) Trunk rotation to rear side, d) Rear hip abduction, e) Trunk rotation to rear side, f) Lead hip abduction

5.4.11 Stage 1 Physical – Balance measures

For all Balance measures, raw scores provided larger ES than the relative (to leg length) metrics, therefore bivariate charts for the latter can be viewed in Appendix B. Small to medium ES for medial, postero-medial and anterio-medial measures for both lead and rear leg were found. ES for Sum Scores for Rear (d = 0.15 – 0.52) and Lead (d = 0.18 – 0.52) were uni-directional across cohorts. See the forest plot (Figure 5.29) and the bivariate charts (Figure 5.30) for all details.

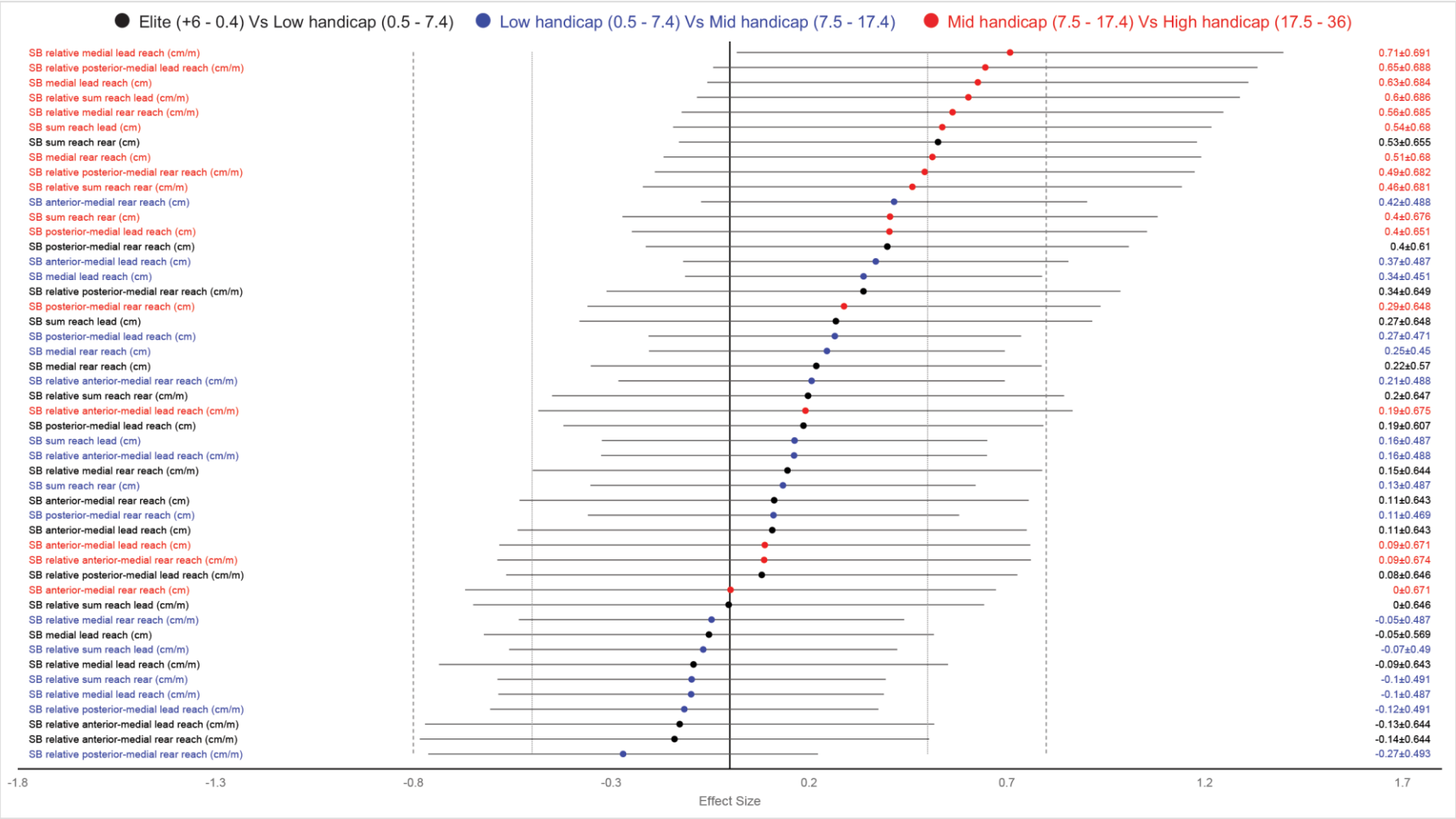


Figure 5.29 Ability cohort differences – absolute and relative to leg-length reach distance measures (antero-medial, medial and postero-medial orientations for rear and lead legs – measure is recorded for standing leg) using Star Balance Mat™

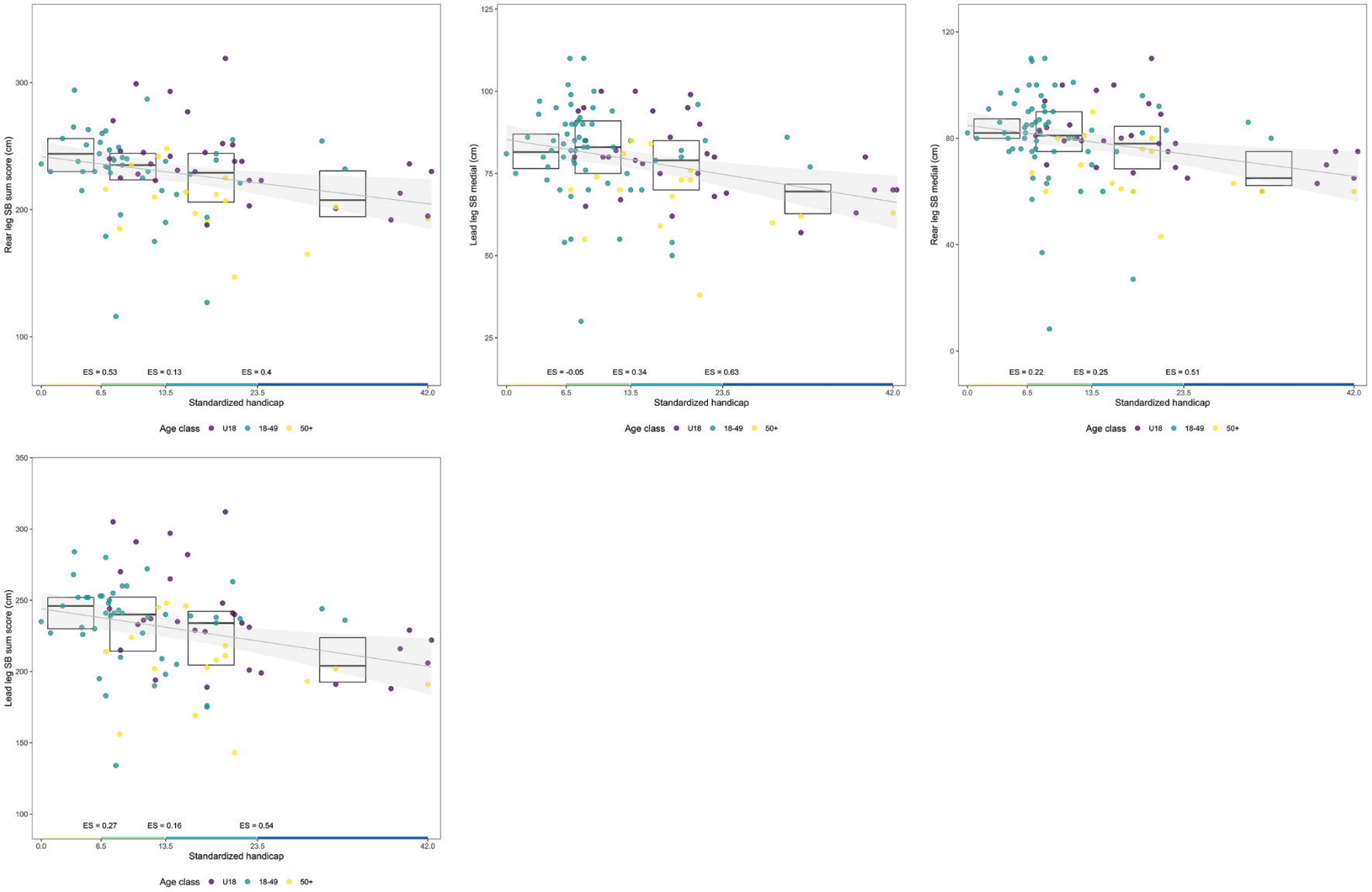


Figure 5.30 (L-R, T-B) a) Rear leg Star Balance sum score, b) Lead leg Star Balance medial, c) Rear leg Star Balance medial, d) Lead leg Star Balance sum score

5.4.12 Stage 1 Physical – Flexibility measures

Positive medium ES for all flexibility measures were found for at least one cohort comparison for Lead Hip Internal Rotation and Hip Extension, Sit & Reach and Thoracic Seated Rotation Lead. Large negative ES were also found for the Mid-HCP to High-HCP cohort comparison for Lead Hip Internal Rotation (d = -1.1) and Hip Extension (d = -0.85). Small to medium uni-directional ES were found across the top three ability levels for Thoracic Seated Rotation Lead (d = 0.32 – 0.52) and Rear (d = 0.25 – 0.49) as well as for Hip Internal Rotation Rear (d = 0.25 – 0.47) and External Rotation Lead (d = 0.23 – 0.46). See the forest plot (Figure 5.31) and the bivariate charts (Figure 5.32 and Figure 5.33) for all details.

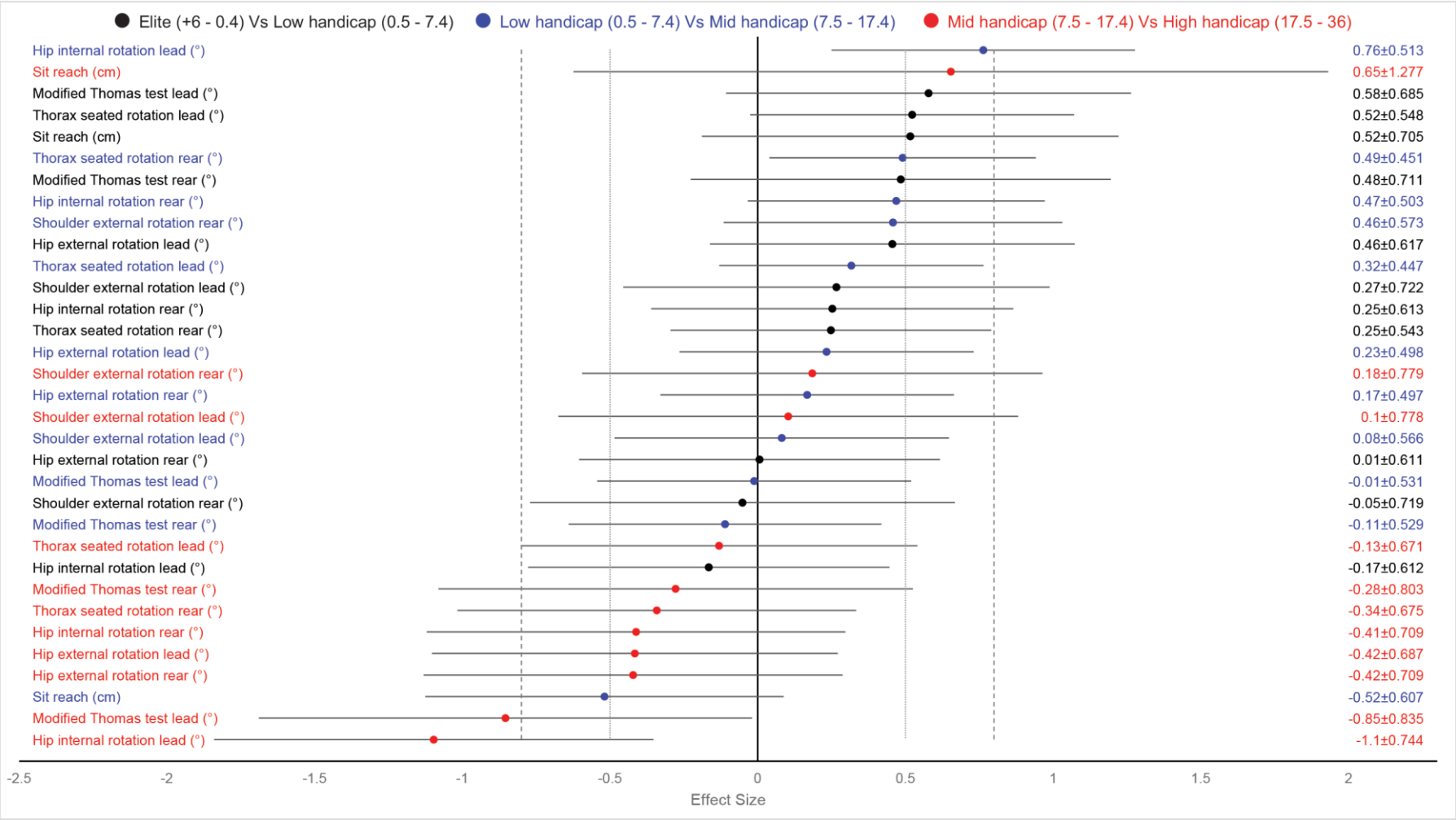


Figure 5.31 Ability cohort differences – flexibility measures. Hip and shoulder measures were passive range of motion, sit and reach test measured active range of motion.

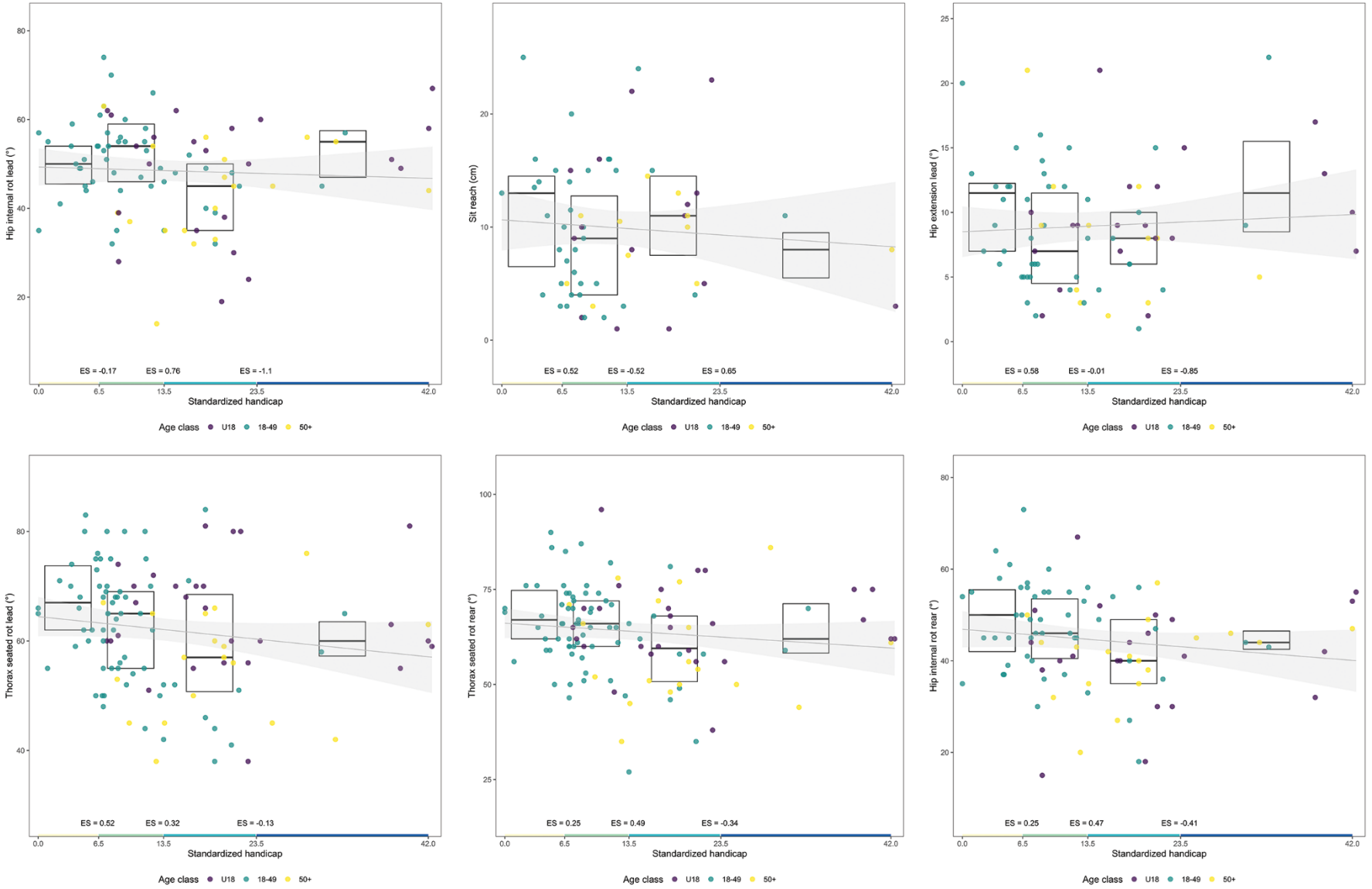


Figure 5.32 (L-R, T-B) a) Lead hip internal rotation, b) Sit and reach, c) Lead hip extension (Modified Thomas test), d) Thorax seated rotation – lead side, e) Thorax seated rotation – rear side, f) Rear hip internal rotation

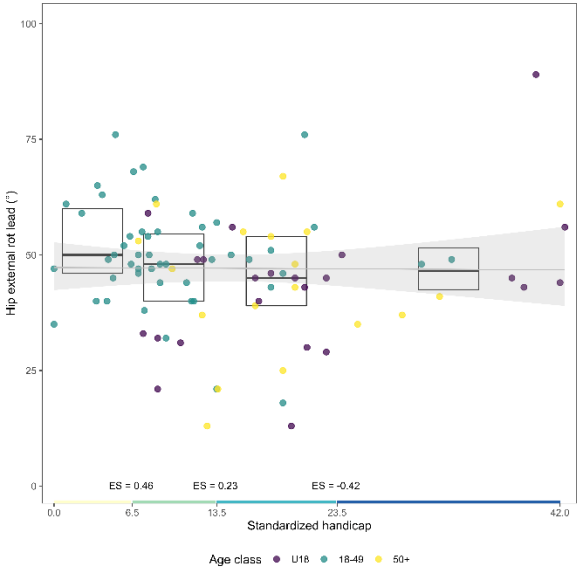


Figure 5.33 Lead hip external rotation

5.5 Discussion

The outputs of comprehensive combines enable the production of physical, technical and competition profiles. Using the measures of central tendency (i.e., mean ± SEE and/or median) provided in this study, practitioners can determine the strengths and weaknesses of the golfer and design interventions accordingly (8, 10, 34). Furthermore, an indication as to the relative importance of measures is highlighted for those that vary unidirectionally with ability level (11, 12). This is the first study that has assessed golfers of all ages, across four ability levels, with parameters that span the P-GPC.

Quantifying the discriminant validity of each measure allows for testers to form simplified combines to target specific golf cohorts. Selecting tests that discriminate between adjacent ability-level cohorts provides a fit-for purpose solution to the tester or multi-disciplinary team – minimising the time required and maximising impact on interventions. For example, if aspiring Low-HCP golfers are the focus, tests could be selected with largest ES between Elite and Low-HCP cohorts for each parameter. Testing and training to improve on these tests may gradually produce the desired Elite physical and technical traits for these golfers. This cohort-specific combine would also consist of fewer tests and be more feasible to administer. The summary forest plots of ES with CI95 intervals in this study provide greater clarity for the utility of each test and measure than statistical significance alone, provided by previous studies (497).

To purpose build combines, there are several factors to consider when interpreting the forest plots and bivariate charts. First, for many measures, the CI95 stretch across the adjacent pre-defined thresholds, commonly expressed as small (0.2), medium (0.5) and large (0.8) ES. For instance, what is discussed as a large ES may potentially only be a medium ES if another sample of golfers were to be tested (498). Therefore, further analysis is needed for measures where CI95 of the ES stretches between positive and negative, to determine the rightful selection or de-selection of tests into future combines.

Second, the magnitude of ES between cohorts in this study can be considered either as a single value (i.e., the magnitude of ES from one comparison of two cohorts) or an aggregated total of the three ES from the three comparisons between the four cohorts. In the example above, the tester would interpret a single specific ES between two cohorts instead (e.g., elite vs low handicap golfers for an elite development program). However, if testing a heterogenous sample (ability-wise), uni-directional ES (e.g., all positive such as 120m Spin Rate, Figure 5.12) across ability all 3 cohort comparisons may be a better indicator of discriminant validity for that purpose. Occasionally, bi-directional effects

across cohorts may even suggest a sweet spot for a measure (i.e., optimal is not too high or too low, e.g., Face Angle, Figure 5.10). This is more likely for technical measures due to the inter-individual golf swing differences for body kinematics and ground reaction forces, independent of ability – especially due to the many factors that dictate HCP, over and above the golf swing (84, 86). Bi-directional ES could also be due to sample bias from different physical characteristics across cohorts, or that the measure is simply ambiguous to performance.

Third, for many measures there is a discrepancy between the estimated mean of the sample and the median of each of the four cohorts. This is an important realisation when using group data sets to determine whether an individual's test score represents a strength or weakness relative to their cohort of golfers. To detect a player's weakness, the median is arguably the preferred central reference as it negates the effect of extreme values within the cohort sample. Additionally, the upper limit of the standardised error of the estimated mean (grey shaded portion on bivariate chart) may also need to be considered for measures, to be confident an individual is indeed above average. Therefore, from a practical perspective, an 'individual's test score that sits below both the median and the upper error of the estimated mean could be considered a weakness that should be addressed with a training intervention. This approach is, of course, based on the assumption that the measure is mechanistically important to the golfer.

Finally, it is arguable that traits that distinguish between Low-HCP and Elite golfers are more generalisable to all golfers as these groups are more homogenous in their skill and characteristics. They also tended to have fewer discriminating measures. Those that were medium or large ES are likely to be important to GP in general. Therefore, the discussion is weighted more highly towards these findings.

5.5.1 P-GPC Stage 3 & 4 Driver Shot Determinants of Ability

Large ES were found for 17 of the 39 measures across all three comparisons of ability level for Driver Ball Kinematic measures – drawn from the best of 4 trials for each golfer from the Maximum Distance Driver Shot Test (Figure 5.5). Driver Ball Speed, Total Length (Distance), Carry, and Maximum Height Distance all had large ES (d = 0.89 – 1.56) for all three comparisons – which is not surprising given that they are all related measures. This importance of the technical process measure, Ball Speed, has been previously shown to discriminate between ability levels (47, 288) and can be used as a proxy measurement of driving or GP (54). Conversely, Total Length and Carry are Stage 4 technical outcome measures (i.e., a direct test of a skill that can be used in

competition). Therefore, these measures are best used to ensure that physical or technical interventions have indeed transferred to improved skill execution. Carry Time, Maximum Height, Carry Ball Speed and Spin Rate also showed some differences across ability levels, although are more likely to be addressed on a tactical basis with individual golfers.

Driver Club Kinematics and Launch Parameters provided fewer large ES (8 of 45) across cohorts, suggesting that greater inter-individual differences or movement variability exist in this parameter category (87, 88, 299) (Figure 5.6). Only Driver CHS exhibited large ES across all three ability levels (d = 0.88 – 1.12), and this raw measure typically provided larger ES than CHS relative to anthropometry (i.e., height, arm span, weight). The utility of Driver CHS as an inter-mediatory measure of performance has been established in the literature with very strong correlations with HCP (226) and significant differences across four ability levels (288). Smash Factor provided the largest ES between Mid and Low-HCP golfers (d = 1.57) but only showed small ES between the other cohorts (d = 0.25 – 0.43). This suggests potentially diminishing returns for this technical process measure once a player reaches Low-HCP level.

Although the largest ES were derived from measures relating to Driver Distance, from a content validity and individual coaching perspective, many remaining ball and club kinematics still warrant further investigation. For example, club head presentation measures such as Attack Angle, Low Point, Face Angle and Launch Direction obviously play a role in ball flight and shot result. However, due to the large variation of successful strategies employed to produce an effective golf shot (299), some of these club and ball measures exhibited only small or trivial ES across cohorts. Therefore, the golf coach is still expected to employ any of these or other given club or ball measures, as needed, with an individual golfer.

5.5.2 P-GPC Stage 3 & 4 – 120m Shot Determinants of Ability

Large ES were found for multiple ball measures across all three comparisons of ability level for the 120 m Target Shot (9 of 42) Figure 5.11. Furthermore, these seem to mechanistically contribute to the performance of golfers on the Stage four measure of accuracy, 120 m Shot Distance to Target. The outcome of this test appears a valid assessment of approach shot skill across golf ability levels' Carry Time (d = 0.56 – 1.26). However, Spin Rate was the only measure with large effects across all three comparisons of ability (d = 0.86 – 1.1), suggesting there may have been various shot types (e.g., wedges, irons, rescue/hybrid clubs) used across our sample in this test. For

this reason, future research may benefit from standardising the shot type with an homogenous sample – if greater understanding of these club and ball measures are sought. Despite this, Spin Rate, Carry Landing Angle (*d* = 0.57 – 1.33), Maximum Height (*d* = 0.57 – 1.29), Carry Time (*d* = 0.56 – 1.26), Maximum Height Distance (*d* = 0.32 – 1.19), Ball Speed (*d* = 0.35 – 0.69), and Carry Length (*d* = 0.19 – 1.13) all increase uni-directionally with ability level. This indicates a higher shot that stops quickly is preferred by better players (as opposed to a lower shot that bounces and rolls up to the target) – which may not have been a shot option within the skill set of the higher-HCP golfers in this study.

The Club Kinematics related to this type of 120 m shot making include those that also exhibit large ES across ability levels in 3 of 36 measures analysed, and many medium ES (Figure 5.14). Dynamic Loft (*d* = 0.57 – 1.07), CHS (*d* = 0.89 – 1.08), and Launch Angle (*d* = 0.33 – 1.08) provide the mechanistic logic for this shot-making. A novel finding from this parameter category was that despite the likelihood of a shorter club being used for the 120 m Shot test, better players also had a longer distance after ball impact to their Low Point. Despite having yet to be reported in the peer-reviewed literature, this aligns with previous findings that suggest more of an ellipse-shaped golf swing for highly skilled golfers than the more circular swing of the club golfer (342, 345). This has been described in computer models (344) and anecdotally described as a ‘3-dimensional flat spot’ through the impact zone of the golf swing, which is presumed to create more time for a 'squaring contact'. Expectedly, Smash Factor and Attack Angle for 120 m Shot provided mostly negative ES across cohorts, where they had been typically positive for Driver, given the differences in impact conditions. All of these factors relate in some way to better players generating higher Spin Rate with a greater ‘friction of the clubface and the ball (499{Tuxen, 2009 #822)}.

The discrepancy generally lower ES for club measures (than ball measures) is likely to be explained by two factors. First, ball measures have greater sequential proximity to the result of the executed shot than club measures, lending some initial support to the construct validity of the P-GPC. Second, greater inter-individual differences and movement variability exist with club kinematics than ball kinematics (87, 88, 299).

5.5.3 P-GPC Stage 2 Determinants of Ability

Body Kinematics

No large ES were found for Stage two body kinematic measures (Figure 5.16), providing further evidence of inter-individual differences in the biomechanics of golfer's swings (86). However, lead shoulder peak velocity (Shoulder Speed) showed small to medium unidirectional ES (d = 0.2 – 0.78) across ability levels. Furthermore, Thorax-shoulder speed ratio exhibited the largest ES between elite and Low-HCP golfers (d = 0.77). Given this phenomena of peak lead shoulder speed occurs in the acceleration phase of the downswing (304, 500), it could be assumed that better players achieve this biomechanical feat with a good power capacity and good dynamic balance (324, 328) – meaning better golfers perform well on tests of power (47) but also a lower normalised COM–COP inclination angular jerk during the downswing as described by Choi (2016). Therefore, despite many individualities of the golf swing, lead shoulder speed offers potential as a desirable intermediatory technical-process body measure. Upper torso rotation velocity was identified as the strongest predictor (β = 0.429) in a regression model that accounted for 66.0% of Driver Ball Speed in a study of 308 golfers by Chu (2010). Therefore, Peak Lead Shoulder Angular Velocity (Lead Shoulder Speed) should be investigated as a proxy for training transfer between physical measures and CHS.

Pelvis peak velocity (Pelvis Speed) was the only other uni-directional measure. This aligns with previous findings where pelvis angular velocity could discriminate between High and Low-HCP golfers and was identified concurrently with superior gluteus maximus and medius strength (122). Therefore, this measure is also a valid test to measure the transfer of strength interventions relating to the pelvis.

X-factor and body segment rotational positions at top of backswing and impact showed smaller bi-directional ES, aligning with previous research that suggest a myriad of different effective golf swing kinematic strategies, independent of ability (86). Differences in measurement techniques for body kinematics across studies also should not be ignored (263, 300). Therefore, consistency in measurement methods and an individualised approach to the golfer is recommended to the golf practitioner in relation to the testing and training relating to body kinematics.

Ground Reaction Forces

The largest ES for Max Driver Shot ground reaction forces was found in the Elite and Low-HCP cohort comparison for both Max Fz Rear which was also uni-directional across

all cohorts (*d* = 0.28 – 1.1) (Figure 5.18). Max Fy Rear was also large (*d* = 1) between the top ability levels as well as the ES for Fz and Fy relative to bodyweight (illustrating that the better players were not simply heavier, but actually utlisied more vertical and latero-medial force through their rear foot). Time between Fy and Fx peaks (i.e., between rear and lead foot) were also less for better golfers. Effective loading and weight transfer throughout the golf swing have previously been noted as hallmarks of a the golf swing of highly-skilled golfers (84, 328, 501). These findings are, however, limited by the fact they were not measured at specific swing events, as is commonplace in the biomechanics literature. Therefore measures of peak force on the rear and lead legs can be used as an initial assessment of weight transfer to then guide either further assessment related to swing events or technical interventions on an individualised basis – relative to the player's goals.

5.5.4 P-GPC Stage 1 Determinants of Ability

Power

Only 3 of the 39 cohort power measures and metrics showed medium or large ES between ability levels (Figure 5.21). Interestingly, power was one of the only parameters where typically larger ES were seen between the higher ability levels than the lower. Chest Pass 3 kg showed the largest ES of all power measures (*d* = -0.02 – 0.99) between the Low and Mid-HCP cohorts but was trivial between Mid and High-HCP cohorts. Lateral Throw 3 kg had the largest ES for the Elite-Low-HCP comparison and the largest sum of uni-directional ES for all cohort comparisons (*d* = 0.31 – 84). Sit Throw 3 kg showed a similar pattern to Lateral Throw 3 kg with small to medium uni-directional ES across groups (*d* = 0.22 – 0.74). The four field tests of leg power (Estimated Peak Leg Power, Vertical CMJ & Reach, Lateral jump Lead & Rear) showed similar ES with small to medium ES (*d* = 0.41 – 0.61) across the best three ability level comparisons. The relative metrics for Lateral Jump and CMJ Max Fz measured with force plate measurements were trivial to small (*d* = -0.13 – 0.41) across these same cohorts – despite the former being suggested for change-of-direction sports (502).

The results of this study suggest that MB throw and jump tests are an effective measure of power for golfers as they discriminate across Elite, Low-HCP and Mid-HCP ability levels. These findings align with previous studies that have reported moderate to strong correlation tests with CHS (39, 176) and HCP (47). Furthermore, numerous S&C studies have shown temporal associations between increased CHS and/or Driver distance concurrently with power capacity improvement (234, 236, 237). Leg peak force

measured with a CMJ on a force plate garnered only trivial to small ES across the top three ability cohorts. Therefore, force plate testing of high-level golfers may be best reserved for the assessment of rate of force development (142) or specific phases of force production, such as positive impulse (239), in order to provide a unique contribution to a combine for golf. Given the similarity of ES for the various vertical leg power tests in our combine, Estimated Peak Leg Power provides one important advantage. It avoids the confounding variable of body mass gain over time, that often occurs through maturation or hypertrophy from training (231, 503). Despite smaller effect sizes, lateral jumps also warrant further investigation as they purportedly measure the different construct of change of direction rather than vertical force (460). It is plausible that the ability to change direction is an important capacity for the golf swing given the importance of medio-lateral COP velocity and range in the golf swing (275, 276).

Strength

Four of the 30 isometric strength and seven of the 48 isometric strength torque measures and metrics across cohorts exhibited large ES (Figure 5.24 and Figure 5.27). The net ES sum scores were largest for Trunk Rotation Rear (d = 0.19 – 1.09) and Hip External Rotation Rear (d = 0.15 – 1.09), all of which were uni-directional. However, this was mostly due to the large ES from comparing the Mid-HCP and Low-HCP cohorts. Conversely, Grip Rear and Lead showed small to medium ES between the three best ability levels (d = 0.42 – 0.74 & .42 – 0.62 respectively). The torque values for core and hip strength were slightly larger than that of absolute strength versions of the measure, which were slightly larger than for relative torque values of the same measure. These findings once again support the importance of grip (176, 258) as well as core and hip strength (11, 251, 488) for golfers. Our findings also support the notion that whilst relative (to bodyweight) power measurements are more meaningful than raw scores, strength measures are not (176). However, this is the first study to suggest that strength torque values have greater discriminant validity than relative (to bodyweight) torque or absolute strength scores and should be favoured in combines.

Balance

Balance measures provided no large ES for any cohort comparisons. Furthermore, seven of the eight measures with medium ES were for the Mid to High-HCP cohort comparison (Figure 5.29). The strongest was SB Relative (to leg length) Medial Lead Reach distance (d = 0.71). The only balance measure with medium ES for Elite to Low-

HCP was SB Sum Reach Rear (*d* = 0.53). Although the Star Balance Excursion Test has been recommended in a review by Read et al 2018 (8), is reliable and sensitive (202) and appears specific to the golf swing, its discriminant validity was the lowest of the physical measures tested in our combine. Furthermore, the absolute reach scores provided larger, uni-directional, ES across the best three golf ability levels than relative measures in this study. It could therefore be argued that whilst balance is inherent to this test, the capacity of strength over ROM is also being tested, highly aided by limb length. Given that height and arm span measures have previously been shown to predict or correlate with GP (47, 66), combines may benefit from a test that assesses the physical capacity of balance (i.e., the neuro-vestibular system) with greater specificity, such as tests that require the eyes to be closed.

Flexibility

Only two large negative ES and five medium ES were present for flexibility measures across cohorts (Figure 5.31). Typically, the largest positive effects sizes for flexibility measures were seen in the comparisons between the top three ability levels. The two large negative ES were both for the lead hip and the comparison of Mid with High-HCP golfers: Modified Thomas Test (*d* = -0.85) and Internal Rotation (*d* = -1.1), both of which appear to be clinically illogical (i.e., it is not clear why High-HCP golfers had larger lead hip extension or internal rotation). This notion is reinforced by the fact that these two measures are also the largest positive ES for the Low to Mid-HCP (*d* = 0.76) comparison and Elite to Low-HCP (*d* = 0.58) comparisons. Therefore, perhaps the most meaningful flexibility measure provides the largest positive uni-directional sum score of ES across cohorts. That measure in this study is Seated Thoracic Rotation Lead (*d* = -0.13 – 0.52) which had small to medium ES between the best three ability levels. The Modified Thomas Test Lead and Sit Reach tests also provided medium ES between Elite and Low-HCP cohorts.

These findings reinforce the role of flexibility in GP. Lead hip ROM has been previously identified as important for preventing low back pain in tour players (189) and allowing ideal lumbo-pelvic mechanics in the golf swing (140, 186). Likewise, rotational trunk flexibility has been stated as important by previous authors (265, 504) and shown to discriminate proficiency level (11). Mechanically, this physical capacity is purported to allow greater X-factor as a force-generating mechanism (312); however, this causal link is yet to be empirically established. Interestingly, thoracic or torso rotation tests have typically only exhibited correlations with CHS for elite players (45), which supports the current findings of ES distributed across our cohorts. This finding also agrees with

previous studies that 'ultra-stable modern swing mechanics', that heavily rely on x-factor for force generation may be more prevalent with the elite golfer (136, 274, 505) – whereas lower-skilled golfers tend to use more side flexion, trunk extension and heel lift, closer to a definition of the 'classic swing' (192, 271). Although these generalisations must be tempered by the notion of swing individuality. Finally, whilst the Sit and Reach test has shown a trivial correlation with CHS in a sample of recreational golfers (181) it appears to discriminate between Elite and Low-HCP golfers in our sample. Whether this is a spurious relationship or an important trait for elite golfers is unclear.

Endurance

The YMCA Step Test was selected for inclusivity and safety given the broad age ranges and physical abilities of participants in this study. The recovery heart rate from this sub-maximal test provided a moderate negative ES between Mid and High-HCP cohorts and only trivial for other cohort comparisons (Figure 5.2). These results align with previous findings of insignificant correlations with Driver and five iron CHS and distance (181) and the reportedly low importance of aerobic fitness, beyond general health, for GP (213, 506).

Limitations

This study provides evidence of the varying traits across ability cohorts quantified by ES. However, more investigation such as regression, longitudinal, efficacy and effectiveness studies are needed before a definitive selection or omission of a test into future combines can occur (51). The power analysis provided sufficient precision for most measures, although it was clear that the smaller sample (n = 13) of the High-HCP golfers provided typically wider confidence intervals than the other cohort comparisons. This typically led to more of CI95 for measures spanning the range of -0.2 – +0.2 – a scenario where it is unclear whether the ES is negative or positive. In these instances, for any cohort comparison, further research with larger samples is required to determine whether these measures are truly trivial. Furthermore, age, limb length, height and varied sample sizes across cohorts are potential confounding variables to this study's results. Although the ES were trivial to small for many of these participant characteristics, in some cases they may have influenced the test scores more than golf ability itself. Therefore, replication of these findings is warranted with characteristic-matched homogenous samples within each ability cohort. Nonetheless, these findings provide insight into the utility of each test across a large heterogenous sample. Finally, these results cannot be assumed to be

generalised to female golfers, who display mechanistically important differences in physical and technical traits (115, 137, 172, 377).

5.5.5 Practical applications

The above findings can be used in several ways in a practical setting (i.e., with an individual or squad of golfers). Comprehensive combines can be constructed to suit an environment and the level of the golfer. Biasing the selection of tests towards those with the largest ES between the ability level of the given squad/player and the adjacent level can increase the discriminant validity of a combine. Combines can be further streamlined for efficiency and effectiveness by selecting the most effective derived metrics from tests. For example, torque values appear to be superior to relative torque or absolute strength values (other than Grip Strength). Star Balance Test raw scores appear superior to relative (to leg length) scores, with sum scores the best of the raw scores. Identifying the 'most important' tests and measures for a given parameter is vital to streamline the testing process for golf development environments that may not have the time, personnel or equipment to undertake testing as comprehensive as this study was.

Furthermore, benchmarks for measures based on the central tendency for an ability cohort can determine whether a player has a weakness to address. The median and mean (including the upper portion of the SEE) are viable options, with the higher of the two selected as the benchmark. This would ensure that a given golfer is highly likely not to be below average on a given test that has been deemed important to that cohort of golfers. The tests where the golfer falls short of this upper measure of average could form the basis of their physical interventions. Technical measures and interventions could be treated in a similar manner, provided the findings and interventions match the individualised performance goals of the golfer.

5.6 Conclusion

ES were presented for the differences across ability levels for each measure analysed from a comprehensive combine designed to assess golfers thoroughly. The findings provide an initial insight into the utility of each test to inform physical and technical interventions and how this may vary with ability levels. Ball kinematic measures for both Driver and 120 m Shot tests typically showed larger ES than club kinematics, which in turn provided larger ES than physical measures. Rather than diminishing the value of physical measures, this provides construct validity to the concept of the P-GPC in

addition to the existing peer-reviewed literature. That is, physical measures would likely provide larger ES with more proximal stages of the P-GPC, such as golf swing body kinematics, than they do for HCP. Physical measures of power and flexibility tended to discriminate better between Elite, Low and Mid-HCP golfers. In contrast, strength and balance measures had larger ES between Mid and High-HCP cohorts. Suggestions were made for greater efficiency and effectiveness for comprehensive combines for specific golf cohorts. Primarily, tests should be selected that showed the largest ES for the specific ability level cohort being tested to and the most adjacent ability level. Using the benchmarks (taking into consideration the mean, error, median and interquartile ranges) provided in the bivariate charts for the adjacent ability level to which the golfer wishes to ascend provides a logical avenue for improvement. Combines should select these tests with the caveat that as many tests with this discriminant validity should be selected from each stage of the P-GPC within the limits of feasibility for the testing environment. Regression modelling from cross-sectional data and linear mixed models from longitudinal data can then be used to weight the importance of the measures derived from these tests – which is addressed in the following Study IV and Study V.

Chapter 6: Study IV – Explaining the mechanisms of golf performance

6.1 Abstract

Regression models that explain the variance in relationships across the Physical-Golf Performance Continuum relationships can quantify specific mechanistic needs of golfers for highly targeted interventions. In this study, a comprehensive combine was utilised to assess the physical, technical and competition proficiency of a large heterogenous sample of Australian male golfers (*n* = 98, Handicap range = +6 – 36.4, Age = 30.7 ± 16.3 years). 12 regression models were built in reverse order of the continuum to establish the best predictors between each stage of the continuum and the preceding stage (i.e., Stage 4-5. Stage 3-5, Stage 3-4 etc). Given the large number of candidate predictor variables considered for each model, multiple steps were taken to avoid multiple collinearity and model adequacy. The strongest predictors for each given Physical-Golf Performance Stage became the dependent variable for the preceding regression model. Two pathways for analyses were created from the Stages 3 and 4 testing combine, one for the 120 m Target Shot and one for the Maximum Driver Shot. The 12 models explained between 13.4% and 95.0% of the variance in the dependent variable. The stage of the P-GPC, dependent variable and strongest standardized predictors (respectively) were: Stage 5) Handicap – Driver Total Distance and Driver CHS, Stage 4) Driver Total Distance – Ball Speed, Club Head Speed and Lead Shoulder Speed, Stage 4) 120 m Distance to Target – Spin Rate, Stage 3) Driver Club Head Speed – Lead Shoulder Speed and Sit Throw 3 kg, Stage 3) 120 m Spin Rate – Sit Throw 3 kg, Stage 2) Driver Lead Shoulder Speed – Lateral Jump Relative to Leg Length. The strongest predictors are discussed with reference to their mechanistic influence on golf performance and should be targeted with testing and multi-disciplinary training interventions. The regression models can refine the needs analysis and athlete profiling of golfers.

6.2 Introduction

The P-GPC (Figure 6.1) addresses recent recommendations in providing a framework to explore and interpret the sequential mechanistic transfer effect of physical and technical measures to competition performance (27, 142). However, more studies are needed to investigate the interplay between these measures, to enhance the multi-disciplinary testing and training of golfers. Regression models provide a suitable analytical tool for this purpose. For example, one study used body kinematic and ground reaction forces (GRF) from 308 male and female golfers to account for 44-74% of variance in Ball Speed (500). Another explained 74% of Stage 3 Driver CHS with two physical power tests in 20 adult male PGA professional golfers (46). Furthermore, 68.7% of variance in HCP was explained by Height, Medicine Ball Throw and Ball Speed in a study of 44 young elite golfers (47). However, more investigation is needed to fully explore all ability levels' parameters to inform golf practitioners and programs.

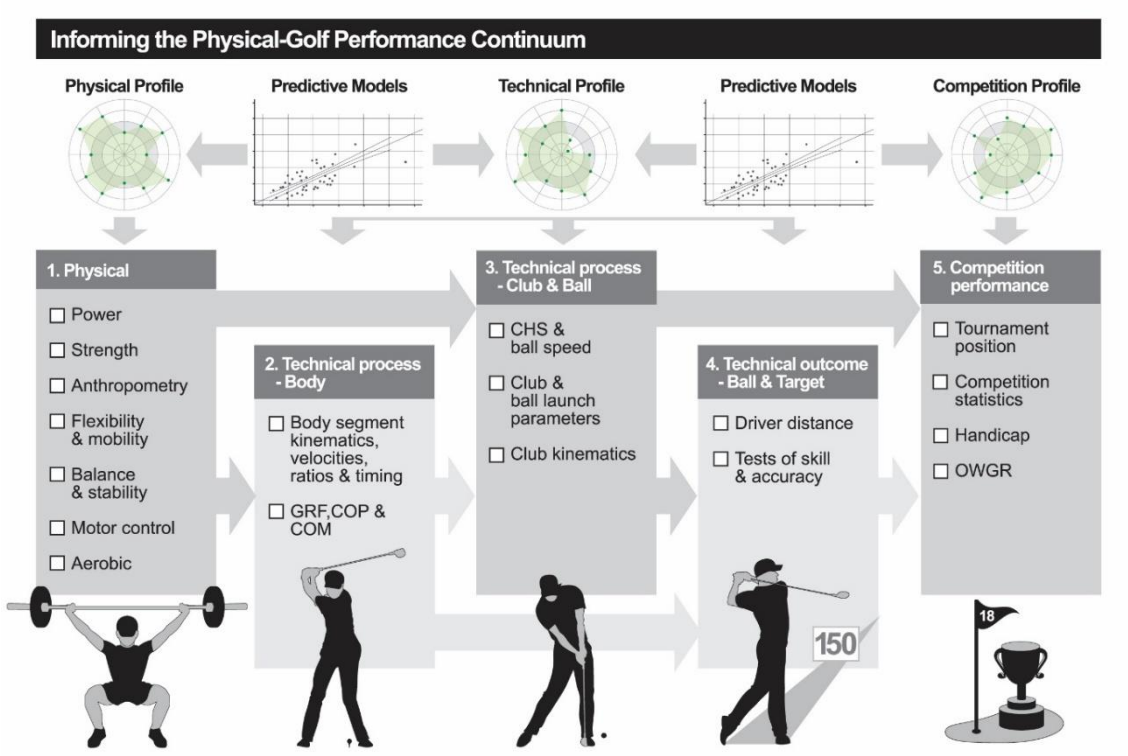


Figure 6.1 Informing the Physical-Golf Performance Continuum (P-GPC) profiles with regression models

With the end-user in sport science settings in mind, studies are needed to guide specific practitioners at intersects of the P-GCP (51). Understanding the mechanisms of training transfer into GP would provide multiple developmental disciplines with stronger evidence to guide practice (27). This knowledge enables athlete profiles for a network of practitioners to assist the golfer by delivering individualised golf-specific interventions (8,

10). Analytical techniques such as regression modelling, allow for the physical and technical determinants of GP to be clearly defined (58, 507). This study aims to extend existing studies by establishing regression models between adjacent stages of the P-GPC.

There is also merit in investigating the relationships between measures and dependent variables from more distal stages of the P-GPC, to see whether the relationships vary to those more proximal. This would explore, for example, whether Stage 3 Driver CHS and Stage 4 Driving Distance have a stronger mechanistic relationship than exists between Stage 4 Driver Distance and Stage 5 HCP – to further assess the construct validity to the P-GPC. Regression models sequentially drawn from technical and physical measures in the P-GPC can indicate the key priorities for the testing and training of golfers. Predictive models from test batteries have shown to reduce talent development costs in other sports and could offer a similar benefit to golf programs (42, 43). To ensure the *content validity* of models, a comprehensive combine (i.e., one that tests a wide range of established GP parameters) was used with a large heterogenous sample of Australian male golfers. These can explain the performance mechanisms of golfers in future research and in the field.

The aim of this study is to use cross-sectional comprehensive combine data to construct regression models that explain the variance of a related dependent variable in the adjacent stage/s of the P-GPC. Combining these models with established benchmarks (in Study III) could allow for a weighted and individualised approach to the testing and training of golfers. This is a vital step forward for the development of golfers given the varied individual responses reported in interventional golf studies (54).

6.3 Methods

6.3.1 Study participants

Participants were active male golfers between the ages of 12 to 71 years. To ensure a representative sample of the entire Australian golf pathway, all participants were required to have completed more than 12 competition rounds and maintained an official GA HCP throughout the previous year and duration of the study. Additionally, participants were recruited from secondary (high) school and the Australian Professional Golfers' Association (PGA) development & trainee programs, local golf clubs and active tour professionals. Unless contraindicated due to injury or pain, each participant completed all assessment protocols on their first visit to a golf test combine session, subject to

equipment availability. A convenience sample of 122 golfers participated in this study. As a minimum, each provided participants characteristics, HCP and an attempt to complete all available tests. The number of participants for each test ranged from 46 to 116. Risk assessments and test completion decisions were made by an attending accredited exercise physiologist, with assistance from the information provided by participants in their adult pre-exercise questionnaire (494).

6.3.2 Combine procedures

The complete combine with previously established reliability, validity, and sensitivity in Chapter 4. Appendix A provides a detailed description of each test including the measures and metrics derived from each test.

6.3.3 Data analysis

Cleaning, outlier detection and missing data

Data was collated into a .csv file from all combine tests using a web-based application purposely for this study. Cases missing more than 25% of test data were removed to avoid sample bias. Twenty-four subjects were removed on this basis, leaving n = 98 remaining for analysis. This data sheet was visually inspected for outliers and data entry errors using a data visualisation software created in the *R* environment (*Inzight version 3.3.1*). Conditional formatting in Microsoft Excel was used to identify and remove data points further than 1.5 times the interquartile range for each measure. 2.3% of data was removed due to being defined as an outlier (

Table 6.1). The causes of missing data were recorded during test sessions and are summarised in Figure 6.2.

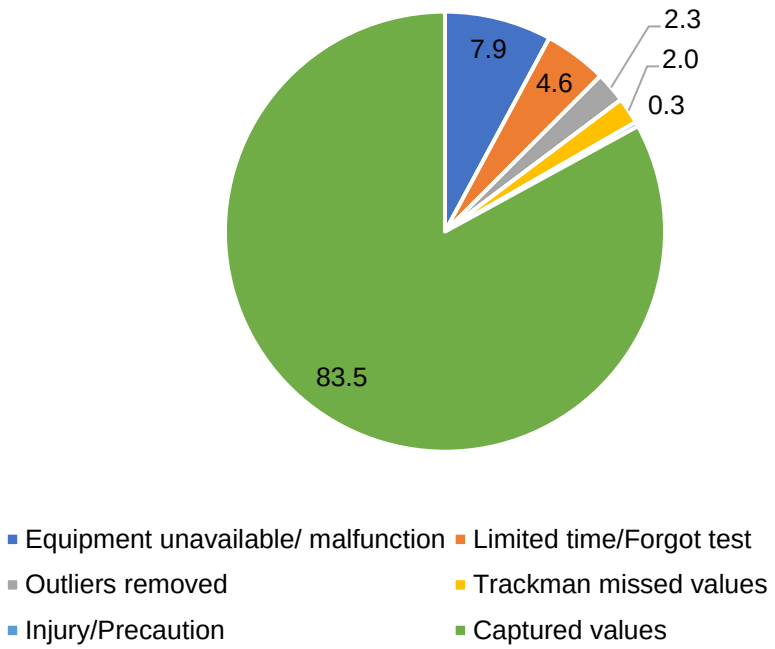


Figure 6.2 Percentage of missing data

Correlation matrices and regression models

Correlation matrices, regression models and visualisations were constructed in SPSS (*IBM, Version 26*) and Microsoft Excel (*Office 365*). Regression models were necessarily constructed in reverse order through the P-GPC (i.e., Stage 4-5, then Stage 3-5, then Stage 3-4 etc.). This allowed the determination of dependent variables (i.e., the strongest mechanistic predictors) for Stage 1, 2 and 3 models, whereas 4 and 5 were pre-determined. The regression models considered all measures from the relevant parameter-category from the preceding adjacent or adjacent plus one stage of the P-GPC. The largest Beta coefficients within a model were selected as the dependent variable for the relevant preceding model in the P-GPC. For example, 120 m Shot Spin Rate had the largest standardised Beta coefficient for Stage 3-4 120 m Shot and was therefore selected as the dependent variable for the Stage 1-3 120 m shot accuracy model. Due to the temporal delineation of club and ball measures (i.e., club measures occur milliseconds prior to ball measures), additional models were created for Stage 3-4 Driver and 120 m Shot club and ball measures. Correlation subsets of the predictors and dependent variables used in models were created subsequent to model formation.

Dimension reduction was required to enable an initial full model fit for all regression models, except the Stage 4-5 model which had only 2 predictors (Figure 6.7). A rule of $n \leq 15$ cases per predictor was used to ensure model adequacy (508). Initial predictor sets ranged between 10 and 67 predictors. The discrepancy between the size of predictor sets was due to the pre-determined output of Trackman™ and K-Vest™ devices and the decision to combine all physical measures, to enhance the content validity of models including Stage 1 of the P-GPC. A multiple-step process was undertaken for measure removal, as measures related to the dependent variable:

1. Removal of weakest correlates to allow initial model fit
    a. Non-significant correlates removed
    b. Weakest correlate of the same measure or derived metric (See Appendix A for derived metrics, page 301)
    c. The weakest of two measures that correlate $r > .90$ with each other, and less correlated with the dependent variable
    d. The weaker of two correlates of same construct and less correlated with the dependent variable (e.g., lead hand and rear hand grip strength – only one was retained in the model)
2. If required, further measures were removed after initial model fit
    a. Collinear measures were removed if variance inflation factor (VIF) > 5
3. If required, further measures were to ensure model adequacy
    a. Measures with the lowest standardized beta coefficient were removed until rule of $n \geq 15$ observations per predictor was met

The removal criteria applied to each model is provided in Appendix D (page 377).

A manual entry method was used for model fit. Residuals were assessed for normality via a visual inspection of histograms, normal *Q-Q* plots and scatterplots of the unstandardised residuals *(508)*. Additionally, a *Shapiro-Wilk's* test showed all but one model to be normally distributed ($p > .05$) (509, 510). The 3-4 Driver Ball model (Shapiro-Wilk, $p = .029$) had n = 71 sample was considered satisfactory as this test is only recommended for $n < 50$ samples (511). Box plots were inspected, and outliers considered for removal. Upon removal of residual outliers (

Table 6.1), *skewness* and *kurtosis z-scores* were within ± 1.96 (512) and all plots appeared to have normal distribution considered satisfactory for linear regression modelling. Normality testing for all regression models are provided in Appendix C (page 340).

Table 6.1 Outliers removed from models

Model	Residual Outliers Removed
3-5 120 m	2
3-4 120 m Ball	2
3-4 120 m Club	3
3-4 Driver Ball	12
3-4 Driver Club	2
1-3 120 m	1

The best available model was deemed where all of the following criteria were met: a) $n \geq 15$ observations per predictor, b) all predictors were significant in the model ($p < .05$), c) collinearity tolerance values were > .2 and *Variance Inflation Factor* (VIF) < 5, d) residual errors were normally distributed based on proximity to the fitted line in Normal P-P Plot, e) residuals homoscedastic based on the distribution of the residuals about the fitted line, f) adequate accuracy of the models was reported by the root mean squared error (RMSE) and SEE of the estimate included on the residual plots, g) the highest adjusted R^2 value was achieved. Once selected the model fits were visualised by plotting the observed values against the dependent values and overlaying the model prediction with 95% confidence intervals.

Analyses were conducted to determine the number of subjects required in this study to ensure the models were adequately powered (495)). Keogh (2009) found that 12 subjects per ability cohort in total would be required for a correlation coefficient of $r = 0.5$ to be significant, with 80% power and a risk of type I error of 5% (12). Therefore, the minimum of 15 golfers per predictor was set as a minimum for this study. Adjusted R^2 is reported for the *coefficient of determination* to describe the explanatory power of each regression model as they relate to our sample, to account for variation in sample size for each model and reduce the chance of overfitting the models. The RMSE is provided as an absolute measure of error for the model in addition to the SEE.

6.4 Results

6.4.1 Participant characteristics

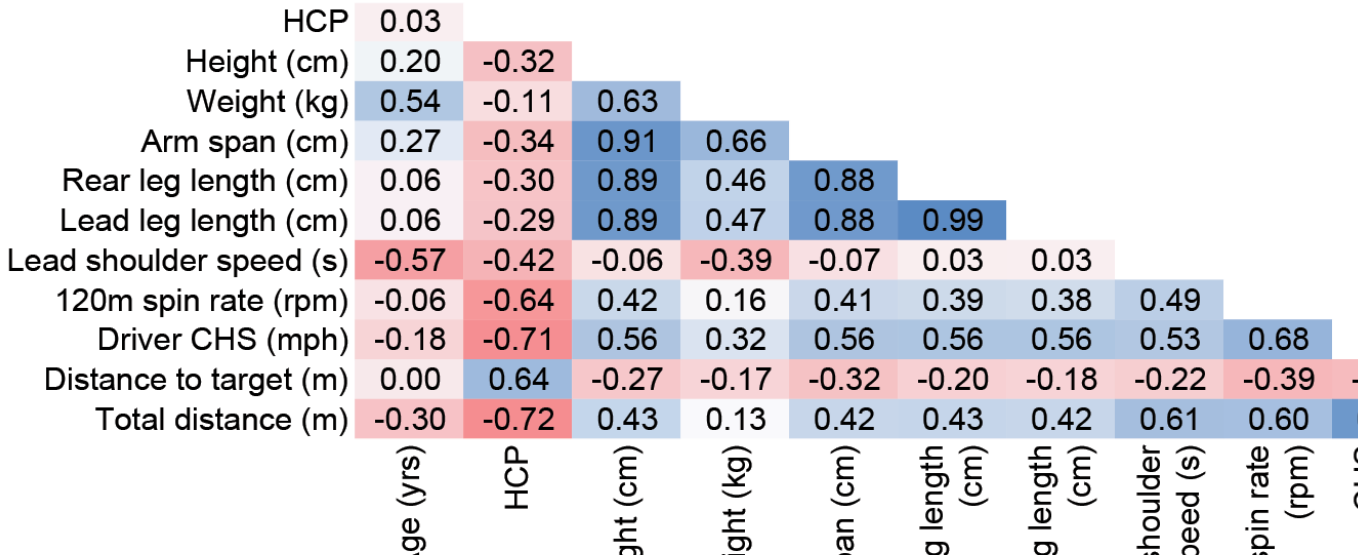
Participant characteristics are provided for the heterogenous sample of 98 Australian male golfers who participated in the study (Table 6.2). Anthropometrics and age were not considered for regression models to avoid the confounding effect of maturation from our adolescent participants.

Table 6.2 Participant characteristics

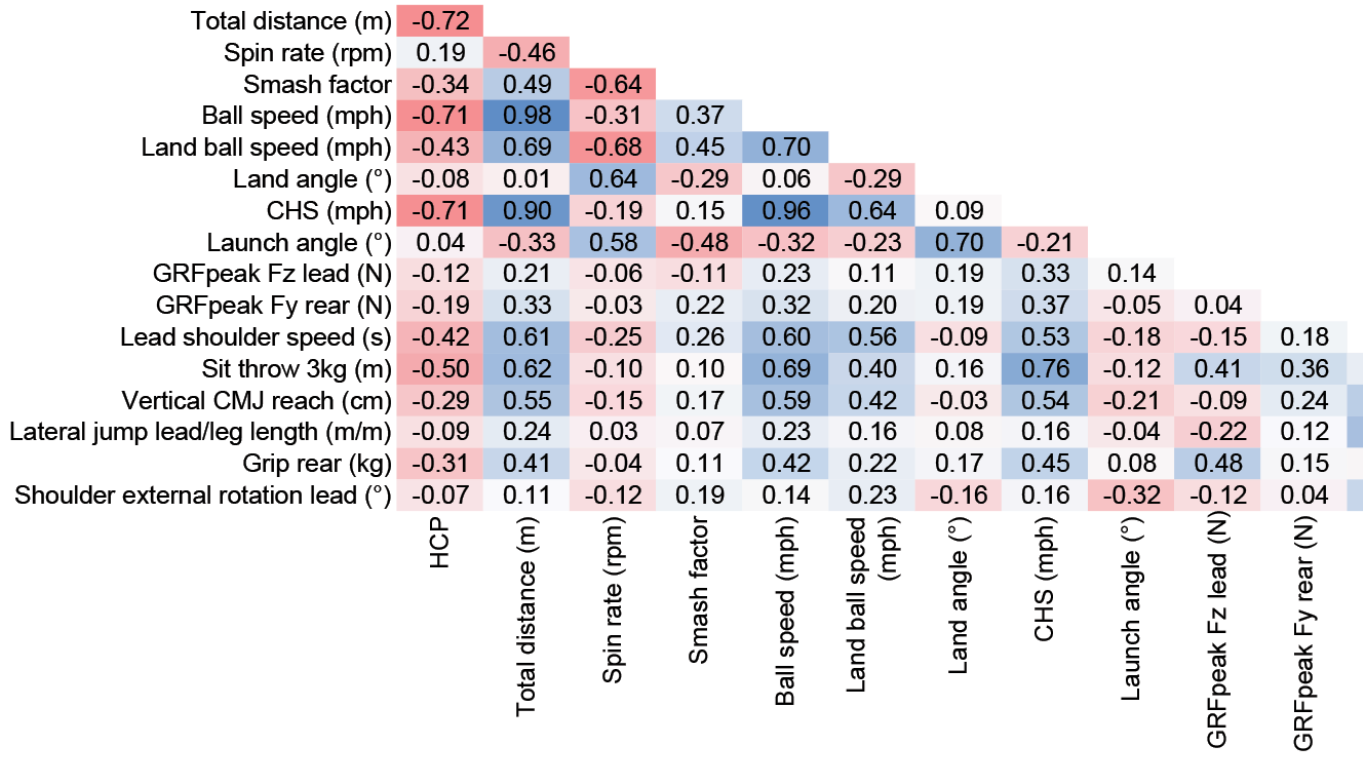
Golfers (*n* =)	HCP Mean ± SD, (Range)	Age (years) Mean ± SD, (Range)	Height (cm) Mean ± SD (Range)	Weight (kg) Mean ± SD (Range)
98	8.6 ± 9.8 (+6 – 36.4)	30.7 ± 16.3 (12.4 – 71.7)	176.1 ± 9.4 (150.5 – 193)	78.6 ± 18.6 (38.9 – 145.4)

6.4.2 Correlation matrices for the regression model variables

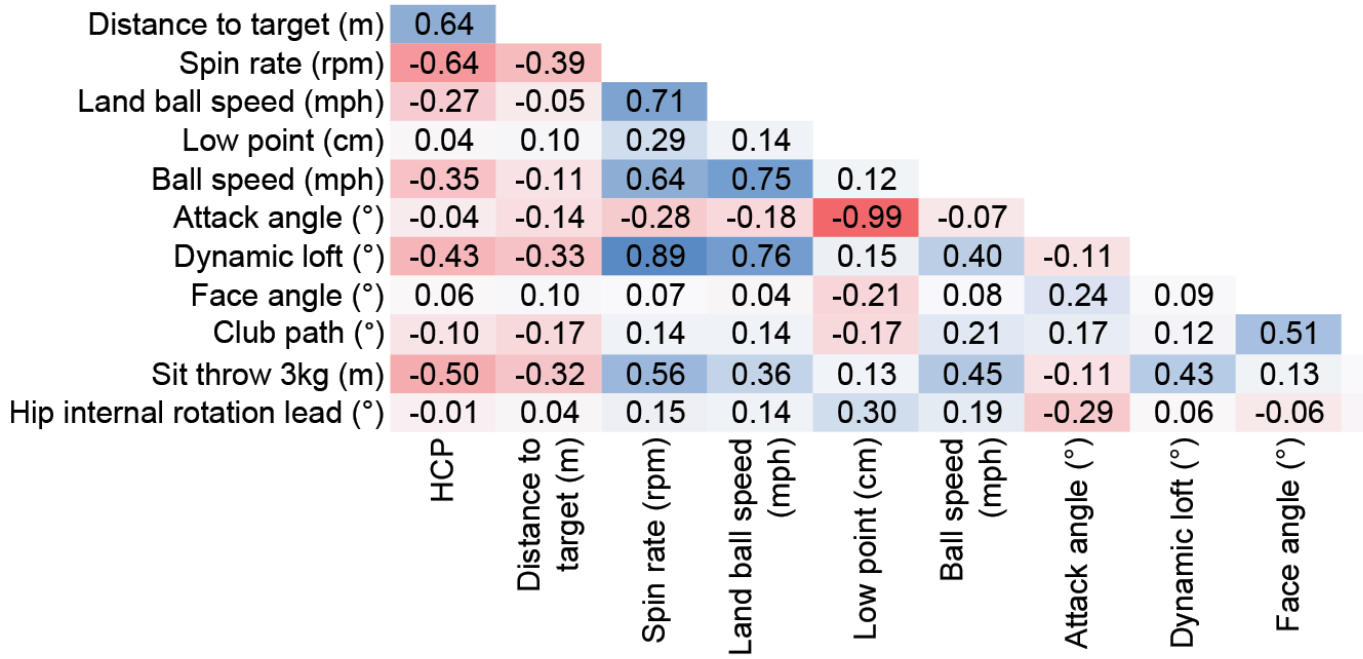
Correlates are provided for all selected predictors and dependent variables in regression models. Correlation matrices are grouped as related to participant characteristics (



), the Maximum Driver Shot test (



) and the 120 m Accuracy Shot test (



). These show associations from the measures from the preceding adjacent or adjacent

plus one stage of the P-GPC and were used in the construction of the subsequent regression models presented below.

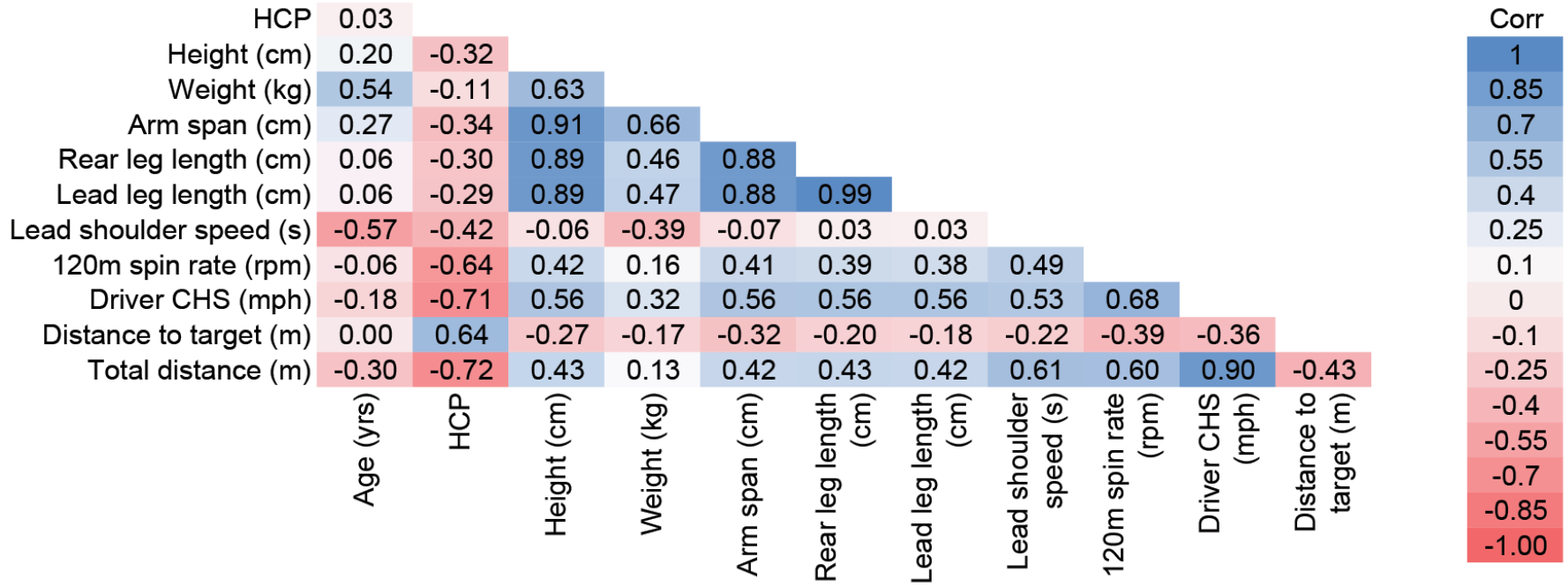


Figure 6.3 Participant characteristics correlates with regression model dependent variables

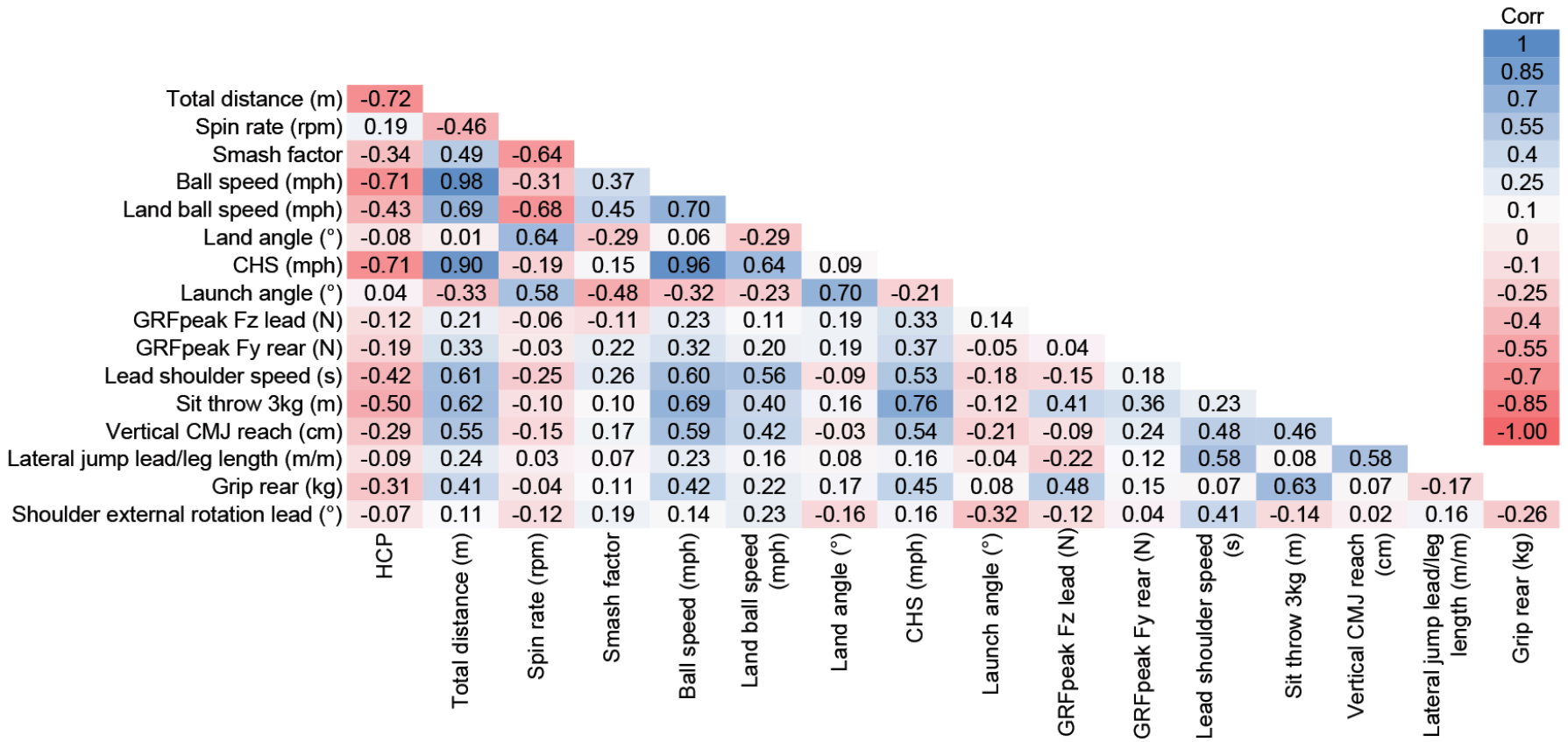


Figure 6.4 Driver Shot predictor correlates with regression model dependent variables

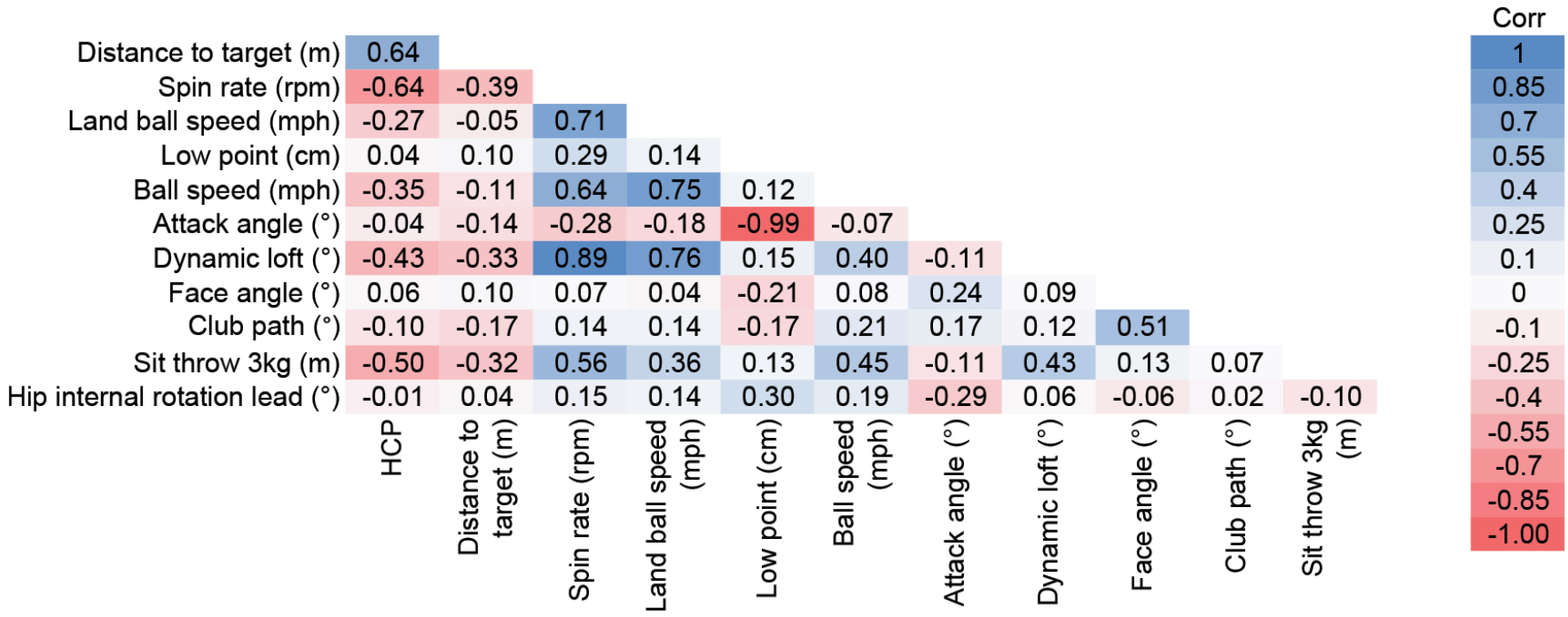


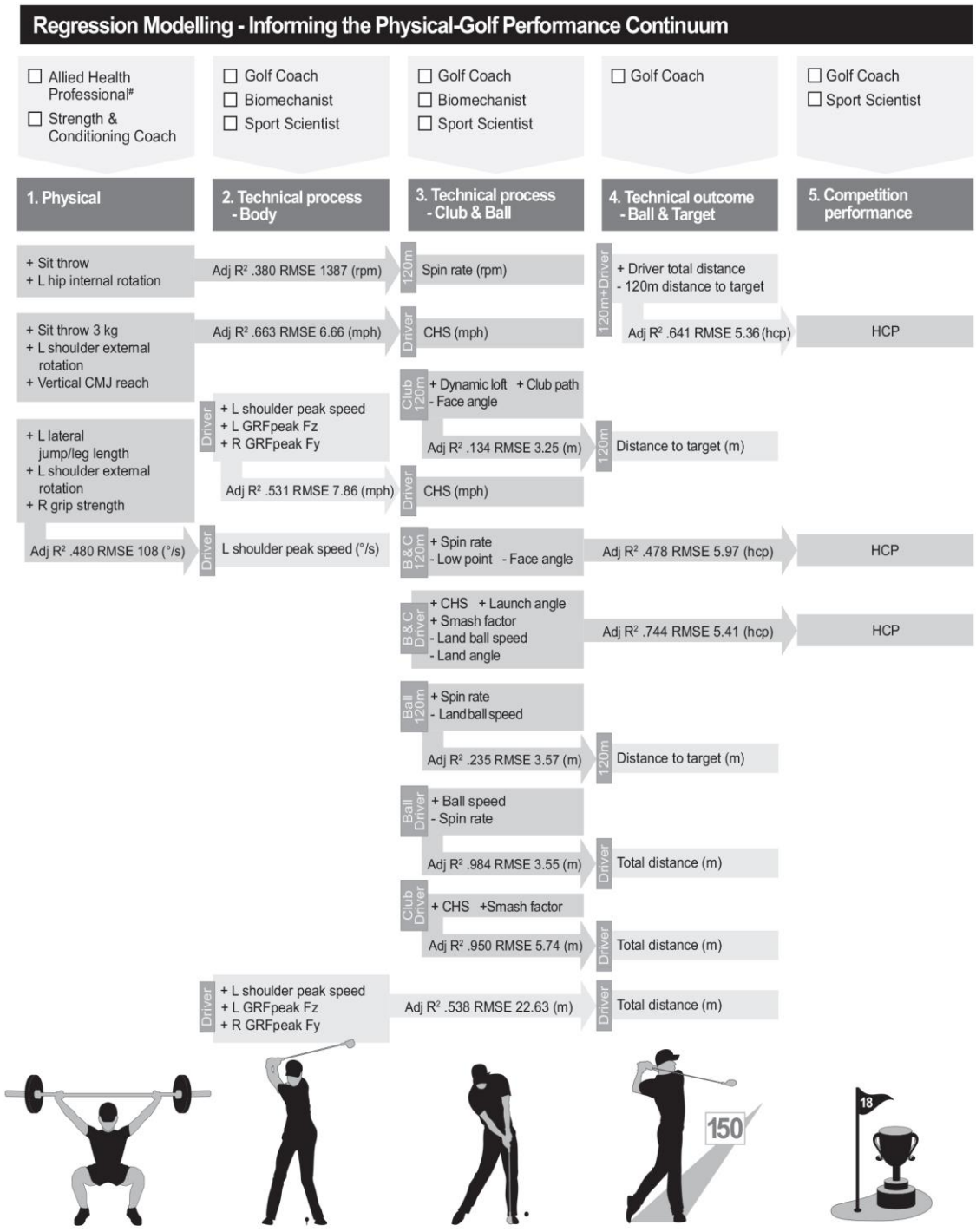
Figure 6.5 120 m Shot predictor correlates with regression model dependent variables

6.4.3 Regression models for the P-GPC

The regression models are presented with residual plots, model summary and coefficients tables. Shortened names for measures are included on correlation matrices and in model equations, where synonyms have been used (e.g., peak velocity = speed, estimated total flat length = total distance, carry flat = land). To enhance interpretability, model equations have been ordered: constant, measures that have a positive relationship with performance, then measures that have negative relationship with performance. If multiple measures were selected that have a positive relationship with performance, these were ordered by importance, based on standardised beta coefficient size.

HCP was selected as the Stage 5 dependent variable in the regression models as it was a feasible measure to collect from all participants within the heterogenous sample of ability levels ranging from tour players to 36-HCP golfers. HCP was standardised relative to the lowest handicap in the data set of minus six (a plus six GA HCP) being treated as zero. Therefore, the constant for each regression model with HCP as the dependent variable was adjusted upwards by six to de-standardise HCP. Therefore, these models can be interpreted relative to HCP in a typical golf setting.

The summary of the 12 regression models constructed across the P-GPC is presented in

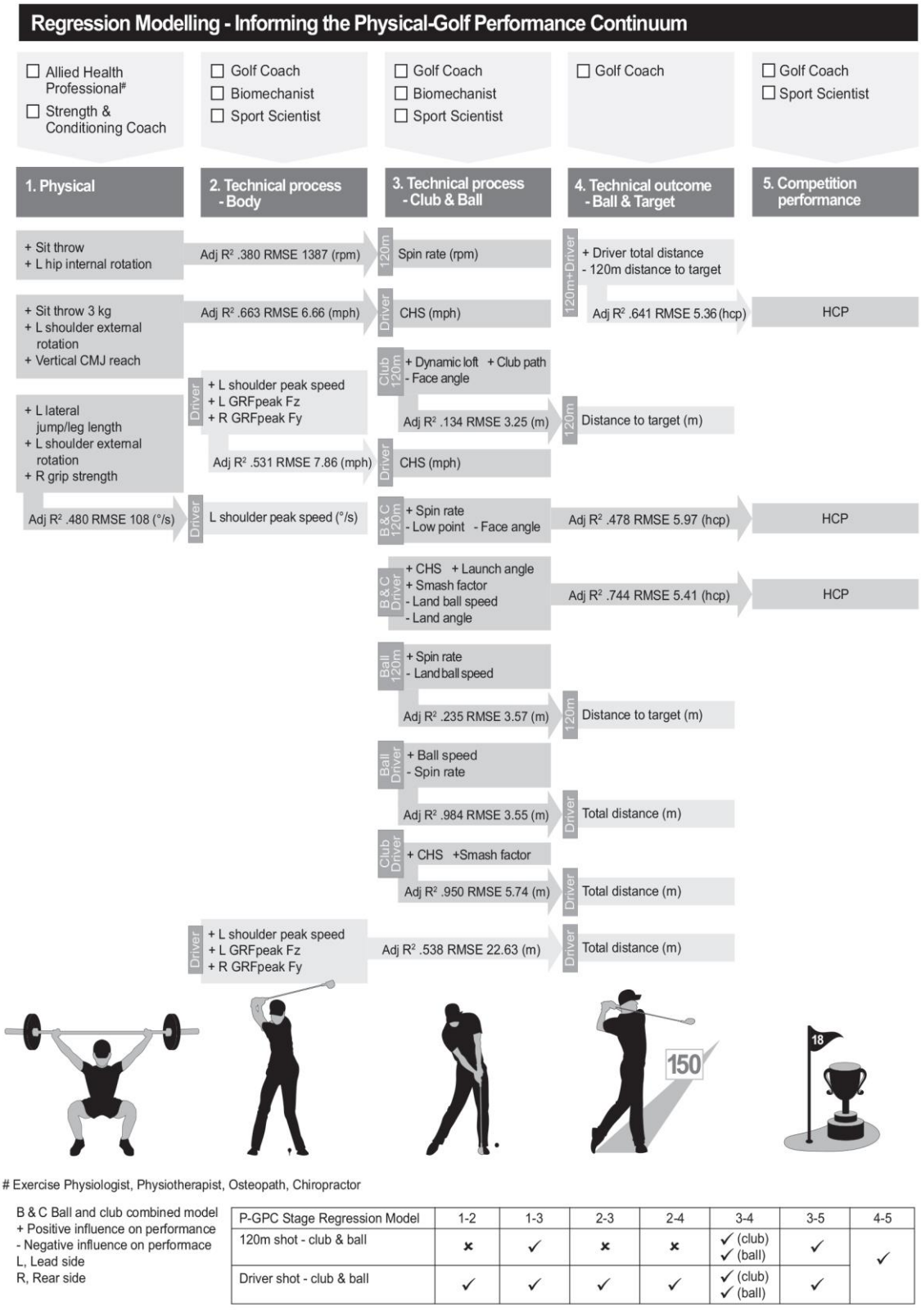


Exercise Physiologist, Physiotherapist, Osteopath, Chiropractor

B & C Ball and club combined model
+ Positive influence on performance
- Negative influence on performace
L, Lead side
R, Rear side

P-GPC Stage Regression Model	1-2	1-3	2-3	2-4	3-4	3-5	4-5
120m shot - club & ball	×	✓	×	×	✓ (club) ✓ (ball)	✓	✓
Driver shot - club & ball	✓	✓	✓	✓	✓ (club) ✓ (ball)	✓	

. This summary diagram illustrates the predictor and dependent measures selected into modes from the adjacent or adjacent plus one stages of the P-GPC. The Adjusted R^2 and RMSE values are shown for each model as well as a summary table of the models that were able to be constructed, constrained by the tests within the combine. The residual plots for each regression model are shown in Figures 6.7-6.17 with the summary of each model's statistics presented in Tables 6.3-6.13.



Exercise Physiologist, Physiotherapist, Osteopath, Chiropractor

B & C Ball and club combined model
+ Positive influence on performance
- Negative influence on performace
L, Lead side
R, Rear side

P-GPC Stage Regression Model	1-2	1-3	2-3	2-4	3-4	3-5	4-5
120m shot - club & ball	×	✓	×	×	✓ (club) ✓ (ball)	✓	✓
Driver shot - club & ball	✓	✓	✓	✓	✓ (club) ✓ (ball)	✓	

Figure 6.6 Summary of regression models across the P-GPC

6.4.4 Stage 4-5 P-GPC Relationships: Driver distance & 120 m Accuracy – HCP

When driver total distance and approach shot accuracy are combined in a regression model they explain 64.1% of the variance in HCP in the sample, via the equation (Six was subtracted from the constant to de-standardise HCP):

HCP = (*39.1 ± 5.8)* – (*Driver distance x 0.154 ± 0.021)* + (*120 m shot distance to target x 0.948 ± 0.177)*

The residual plot is shown in Figure 6.7 and model summary in Table 6.3.

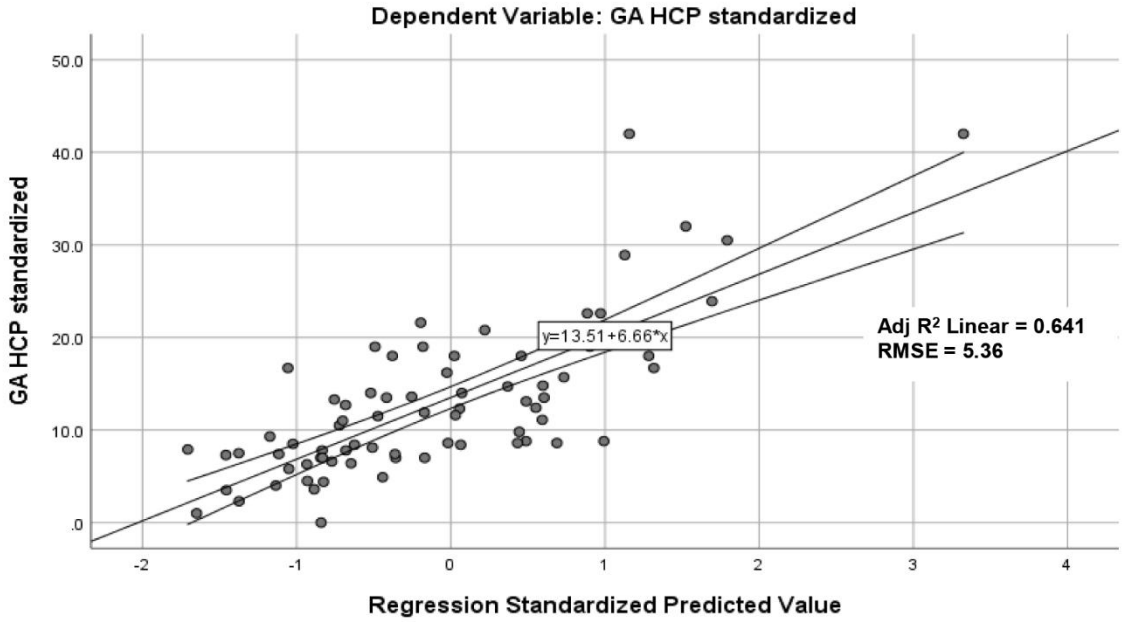


Figure 6.7 Stage 4-5 Driver Distance & 120 m Accuracy predictors for Handicap. Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.3 Stage 4-5 Driver Distance & 120 m Accuracy – HCP linear regression model summary

n	R	Adjusted R^2			SEE	
78	0.807	0.641			5.844	
Coefficients[a]						
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	45.089	5.831		7.733	<0.001		
Driver total distance m	-0.154	0.021	-0.543	-7.164	<0.001	0.812	1.231
120 m distance to target m	0.948	0.177	0.406	5.361	<0.001	0.812	1.231
a. Dependent Variable: GA HCP standardized							

(Note – these are repeated for the remaining tables in this chapter) SEE, Standard error of estimate. B, Unstandardised beta coefficient. SE, Standard error. B, Standardised beta coefficient. Tol., tolerance. VIF, variance inflation factor.

6.4.5 Stage 3-5 P-GPC Relationships: Driver Ball & Club Kinematics – HCP

The following driver club and ball measures, combined in a regression model, explained 74.4% of the variance in the sample's HCP, via the equation (HCP is de-standardised):

HCP = (291.5 ± 29.2) – (Driver CHS mph x 1.142 ± 0.095) – (Driver launch angle ° x 3.153 ± 0.436) – (Driver smash factor x 186.235 ± 22.520) + (Driver land ball speed mph x 1.760 ± 0.292) + (Driver carry land angle ° x 1.010 ± 0.183)

The residual plot is shown in Figure 6.8 and model summary in Table 6.4.

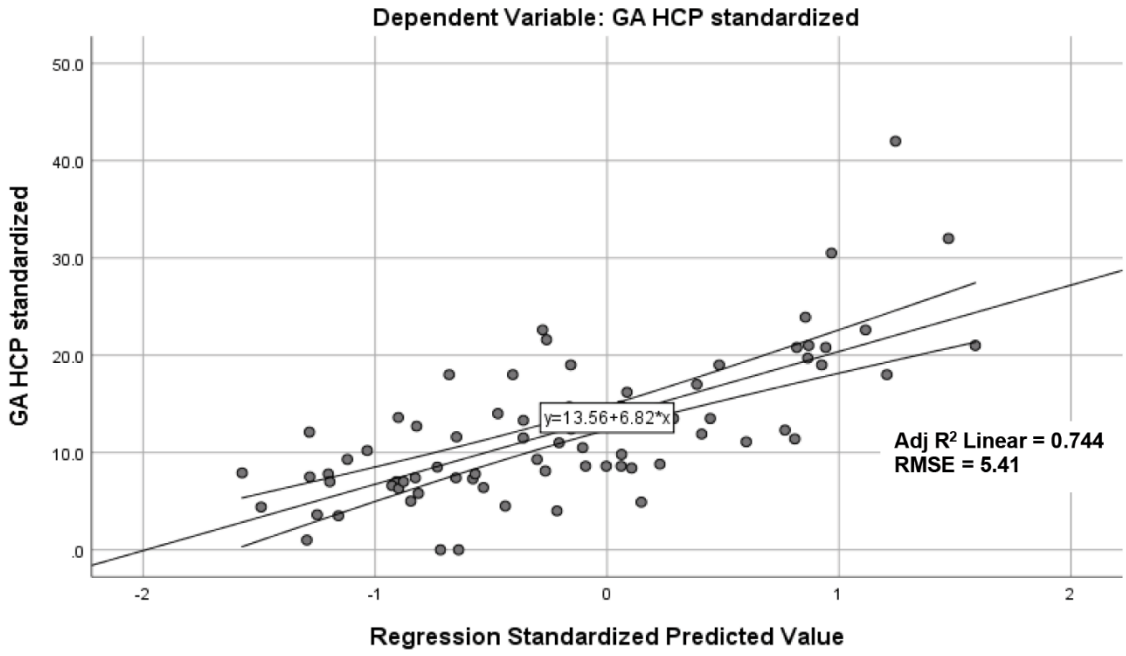


Figure 6.8 Stage 3-5 Driver Ball & Club measure predictors for Handicap (HCP). Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.4 Stage 3-5 Driver Ball & Club – HCP linear regression model summary

n	R	Adjusted R^2		SEE		
75	0.873	0.744		4.932		
Coefficients[a]						
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	291.515	29.241		9.970	<0.001		
CHS mph	-1.142	0.095	-1.271	-12.032	<0.001	0.301	3.321
Smash factor	-186.235	22.520	-0.682	-8.270	<0.001	0.495	2.021
Carry land angle°	1.010	0.183	0.618	5.509	<0.001	0.267	3.744
Land ball speed mph	1.760	0.292	0.673	6.036	<0.001	0.270	3.703
Launch angle°	-3.153	0.436	-0.832	-7.231	<0.001	0.254	3.942
a. Dependent Variable: GA HCP standardized							

6.4.6 Stage 3-5 P-GPC Relationships: 120m Shot Ball & Club Kinematics – HCP

120 m shot ball and club kinematics were considered for the regression model that explained 47.8% of the variance in the sample's HCP, via the equation (Six was subtracted from the constant to de-standardise HCP):

HCP = (*42.2 ± 4.3)* – (*120 m spin rate rpm x 0.0039 ± 0.0005)* – (*120 m low point cm x 0.832 ± 0.259)* + (*120 m face angle° x 0.686 ± 0.353)*

The residual plot is shown in Figure 6.9 and the model summary in Table 6.5.

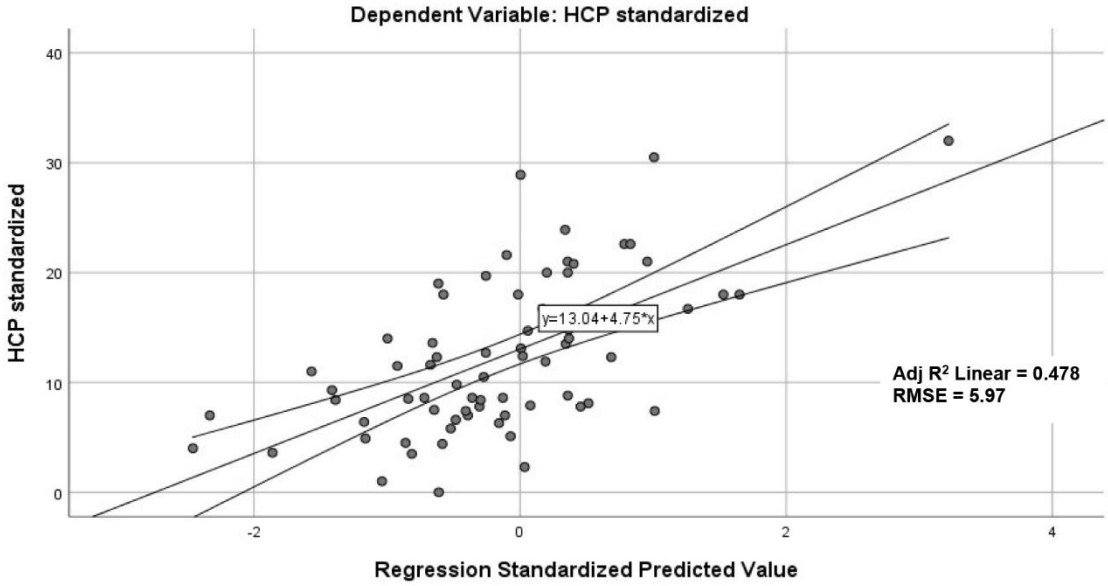


Figure 6.9 Stage 3-5 120 m Ball & Club measure predictors for Handicap (HCP). Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.5 Stage 3-5 120 m Ball & Club Measures – HCP linear regression model summary

n	R	Adjusted R^2			SEE		
70	0.707	0.478			7.050		
Coefficients[a]							
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	42.163	4.251		9.918	<0.001		
120 m spin rate rpm	-0.004	0.0005	-0.741	-8.185	<0.001	0.897	1.115
120 m low point cm	0.832	0.259	0.297	3.211	0.002	0.862	1.160
120 m face angle°	0.686	0.353	0.172	1.945	0.049	0.940	1.064
a. Dependent Variable: GA HCP standardized							

6.4.7 Stage 3-4 P-GPC Relationships: Ball Kinematics – Driver Total Distance

The following ball measures, combined in a regression model explain 98.4% of the variance in the sample's Driver Total Distance, via the equation:

Total Driver Distance m = (*51.3 ± 5.4)* + (*Driver ball speed mph x 1.704 ± 0.029)* – (*Driver spin rate rpm x -0.02219 ± 0.00080)*

The residual plot is shown in Figure 6.10 and model summary in Table 6.6.

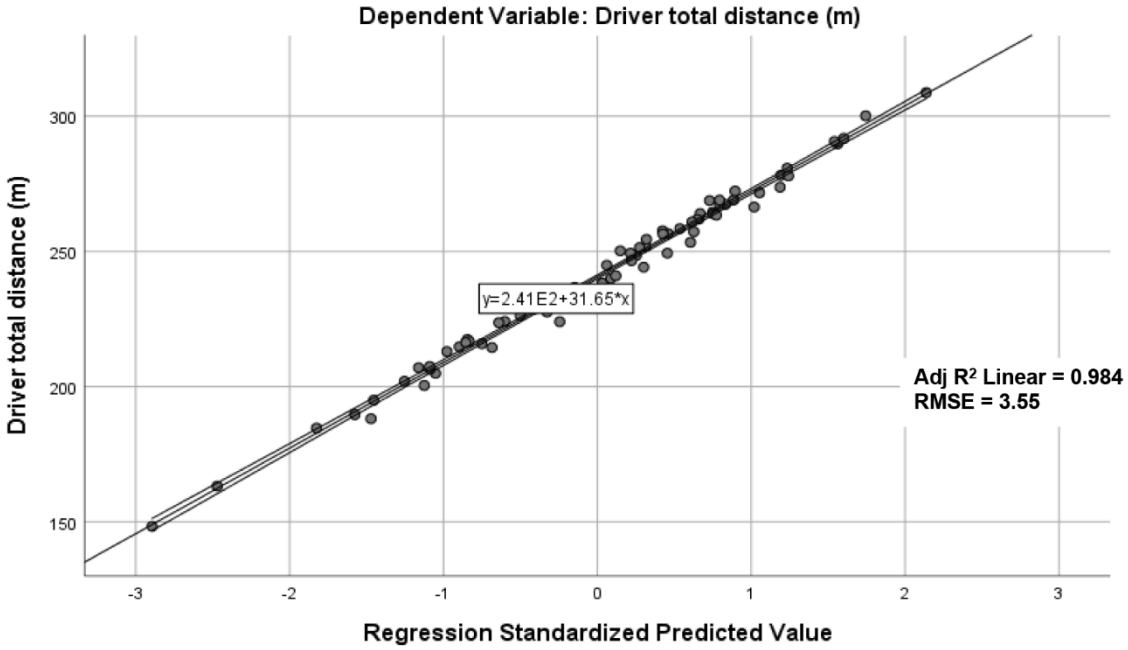


Figure 6.10 Stage 3-4 Ball Measure predictors for Driver Distance. Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.6 Stage 3-4 Ball Measures – Driver Distance linear regression model summary

n	R	Adjusted R^2			SEE	
71	0.992	0.984			4.333	
Coefficients[a]						
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	51.328	5.364		-2.135	<0.001		
Driver ball speed mph	1.704	0.029	0.840	64.732	<0.001	0.836	1.197
Driver spin rate rpm	-0.022	0.001	-0.340	-12.168	<0.001	0.836	1.197
a. Dependent Variable: Driver total distance m							

6.4.8 Stage 3-4 P-GPC Relationships: Club Kinematics – Driver Total Distance

The following club measures, combined in a regression model, explain 95.0% of the variance in the sample's Driver Total Distance, via the equation:

Driver Total Distance m = (-549.5 ± 35.3) + (Driver CHS mph x 2.703 ± 0.081) + (Driver smash factor x 355.123 ± 24.547)

The residual plot is shown in Figure 6.11 and model summary is shown in Table 6.7.

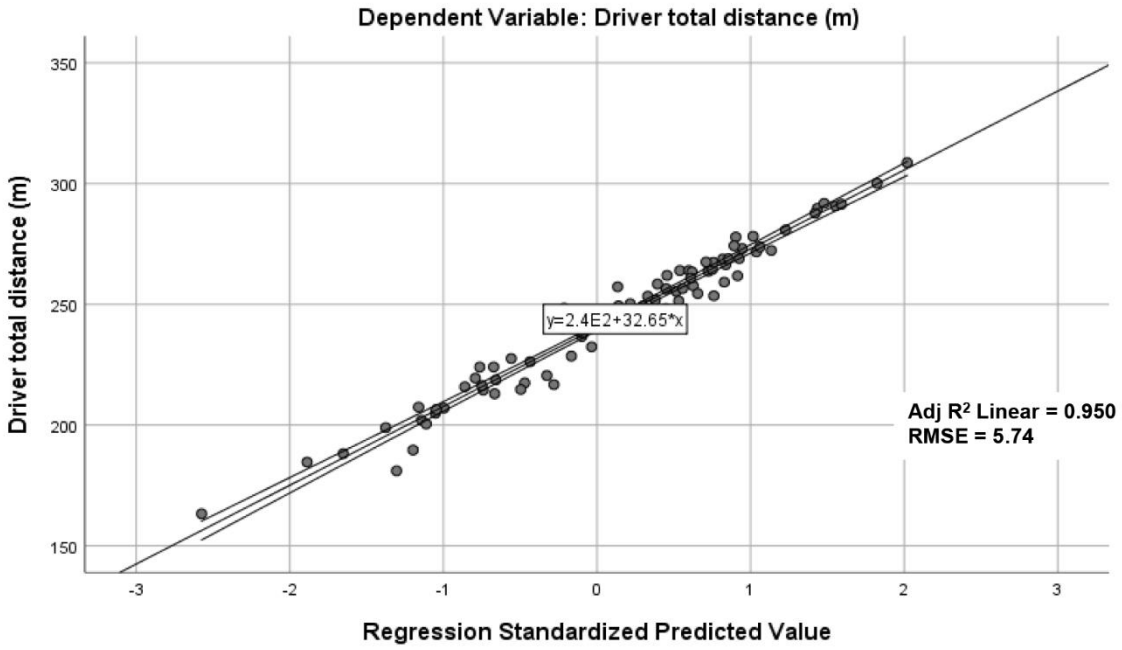


Figure 6.11 Stage 3-4 Club Measure predictors for Driver Distance. Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.7 Stage 3-4 Club Measures – Driver Distance linear regression model summary

n	R	Adjusted R^2			SEE	
81	0.975	0.950			7.774	
Coefficients[a]						
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	-549.481	35.316		-15.559	<0.001		
Driver CHS mph	2.703	0.081	0.846	33.401	<0.001	0.974	1.027
Driver smash factor	355.123	24.547	0.367	14.467	<0.001	0.974	1.027
a. Dependent Variable: Driver total distance m							

6.4.9 Stage 3-4 P-GPC Relationships: 120 m Shot Ball Kinematics – 120 m Accuracy

Both ball and club kinematics were considered as predictors of 120 m Shot Distance to Target. The following club and ball kinematics, combined in a regression model, explain 23.5% of the variance in the sample's 120 m accuracy, via the equation:

Distance to 120 m target m = (*-23.828 ± 11.852)* – (*spin rate rpm x 0.0016 ± .0003)* + (*120 m carry ball speed mph x 0.8347 ± 0.2528)*

The residual plot is shown Figure 6.12 and model summary in Table 6.8.

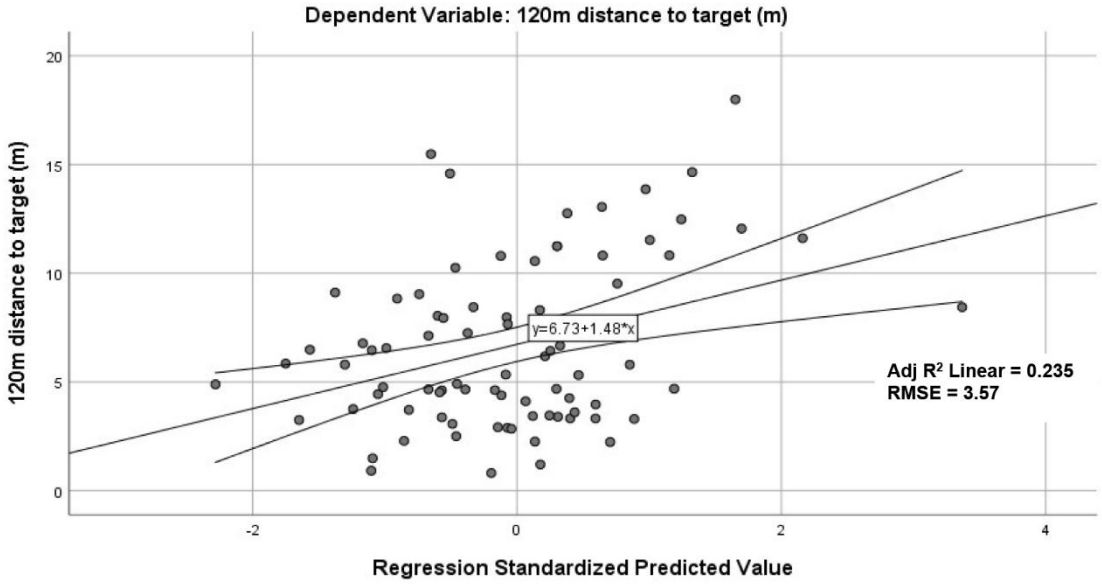


Figure 6.12 Stage 3-4 120 m Shot Ball measure predictors for Target Accuracy. Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.8 Stage 3-4 120 m Shot Ball Measures – Accuracy linear regression model summary

n	R	Adjusted R2		SEE		
82	.504a	0.235		3.654		
Coefficients[a]						
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	-23.828	11.852		-2.010	0.048		
120m spin rate rpm	-0.002	0.000	-0.711	-5.191	<0.001	0.497	2.011
120 m carry ball speed mph	0.835	0.253	0.452	3.302	0.001	0.497	2.011
a. Dependent Variable: 120m distance to target (m)							

6.4.10 Stage 3-4 P-GPC Relationships: 120 m Shot Club Kinematics – 120 m Accuracy

Both ball and club kinematics were considered as predictors of 120 m Shot Distance to Target. The following club and ball kinematics, combined in a regression model, explain 13.4% of the variance in the sample's 120 m accuracy, via the equation:

Distance to 120 m target m = (*16.671 ± 3.895) - (120 m dynamic loft° x 0.302 ± 0.118) -* (*120 m club path° x 0.401 ± 0.172) +* (*120 m face angle° x 0.476 ± 0.210)*

The residual plot is shown in Figure 6.13 and model summary in Table 6.9.

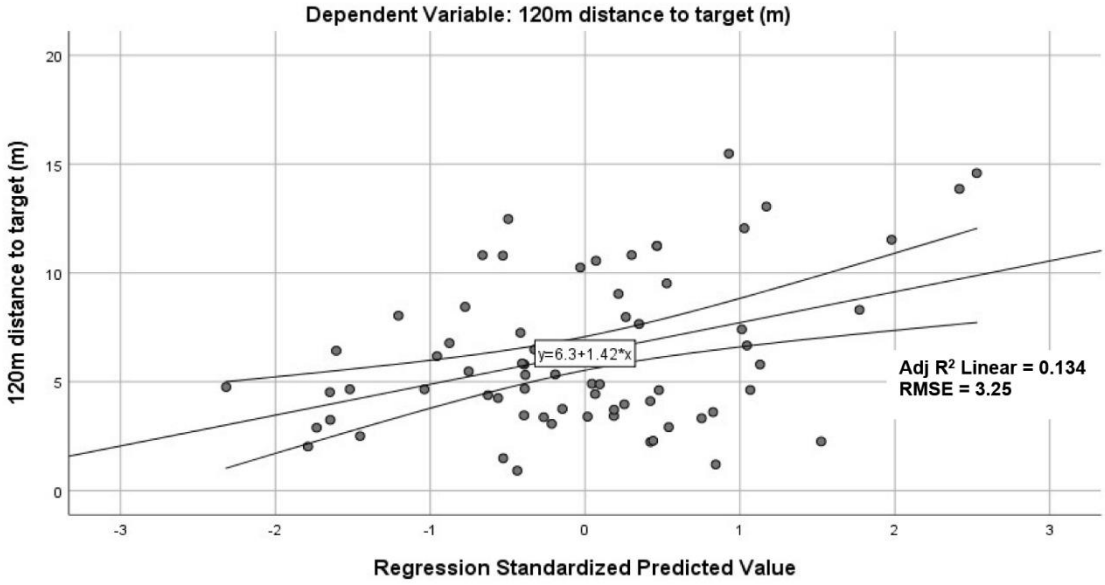


Figure 6.13 Stage 3-4 120 m Shot Club measure predictors for Target Accuracy. Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.9 Stage 3-4 120 m Shot Club Measures – Accuracy linear regression model summary

n	R	Adjusted R^2		SEE		
70	0.412	0.134		3.743		
Coefficients[a]						
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	16.671	3.895		4.280	<0.001		
120 m dynamic loft °	-0.302	0.118	-0.282	-2.554	0.013	0.985	1.015
120 m face angle°	0.476	0.210	0.289	2.264	0.027	0.736	1.359
120 m club path°	-0.401	0.172	-0.300	-2.336	0.022	0.731	1.368
a. Dependent Variable: 120m distance to target (m)							

6.4.11 Stage 2-4 P-GPC Relationships: Body Kinematics & GRF – Driver Total Distance

The following body kinematic and ground reaction force measures, combined in a regression model, explain 53.4% of the variance in the sample's Driver Total Distance, via the equation:

Total Driver Distance m = (*70.0 ± 23.3)* + (*Lead shoulder peak velocity°/s x 0.126 ± 0.019)* + (*GRFpeak Fz lead N x 0.041 ± 0.013)* + (*GRFpeak Fy rear N x 0.195 ± 0. 067)*

The residual plot is shown in Figure 6.14 and model summary in Table 6.10.

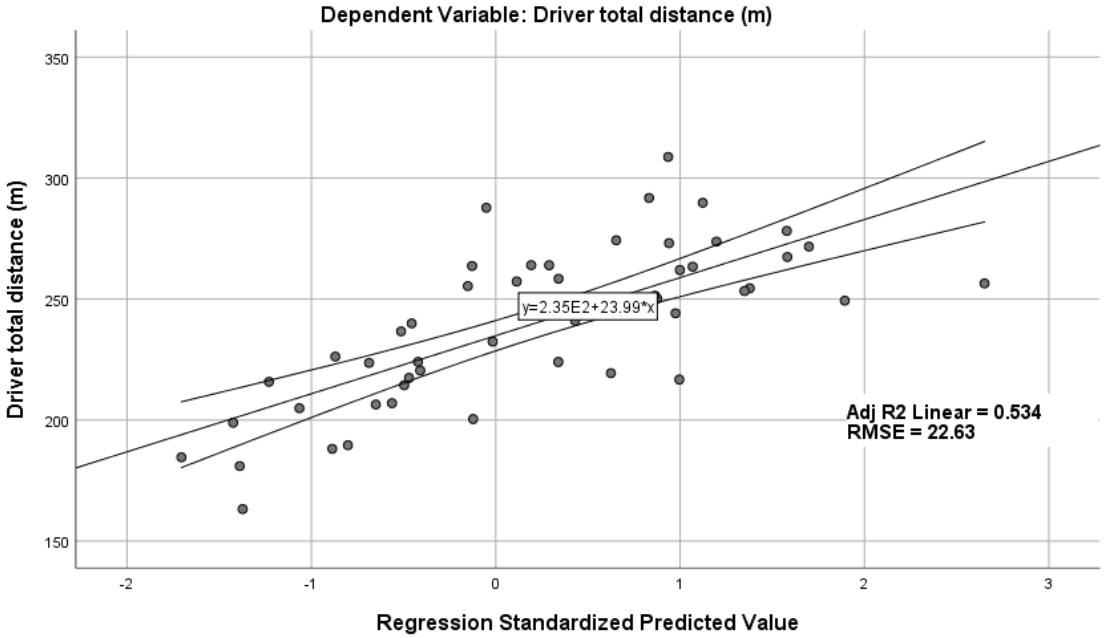


Figure 6.14 Stage 2-4 Body & GRF measure predictors for Driver Distance. Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.10 Stage 2-4 Body & GRF – Driver Distance linear regression model summary

n	R	Adjusted R^2			SEE	
52	0.748	0.534			22.638	
Coefficients[a]						
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	70.044	23.303		3.006	0.004		
Lead shoulder speed°/s	0.126	0.019	0.628	8.325	<0.001	0.930	1.076
GRFpeak Fz lead N	0.041	0.013	0.309	3.261	0.002	0.958	1.043
GRFpeak Fy rear N	0.195	0.067	0.275	2.901	0.005	0.963	1.039
a. Dependent Variable: Driver total distance m							

6.4.12 Stage 2-3 P-GPC Relationships: Body Kinematics & GRF – Driver CHS

The following body kinematic and ground reaction force measures, combined in a regression model, explain 53.1% of the variance in the sample's Driver CHS, via the equation:

Driver CHS mph = (*44.8 ± 7.3)* + (*Lead shoulder peak velocity°/s x 0.0370 ± 0.0061)* + (*GRFpeak Fz lead N x 0.0187 ± 0.0040)* + (*GRFpeak Fy rear N x 0.0639 ± 0.0211)*

The residual plot is shown in Figure 6.15 and model summary in Table 6.11.

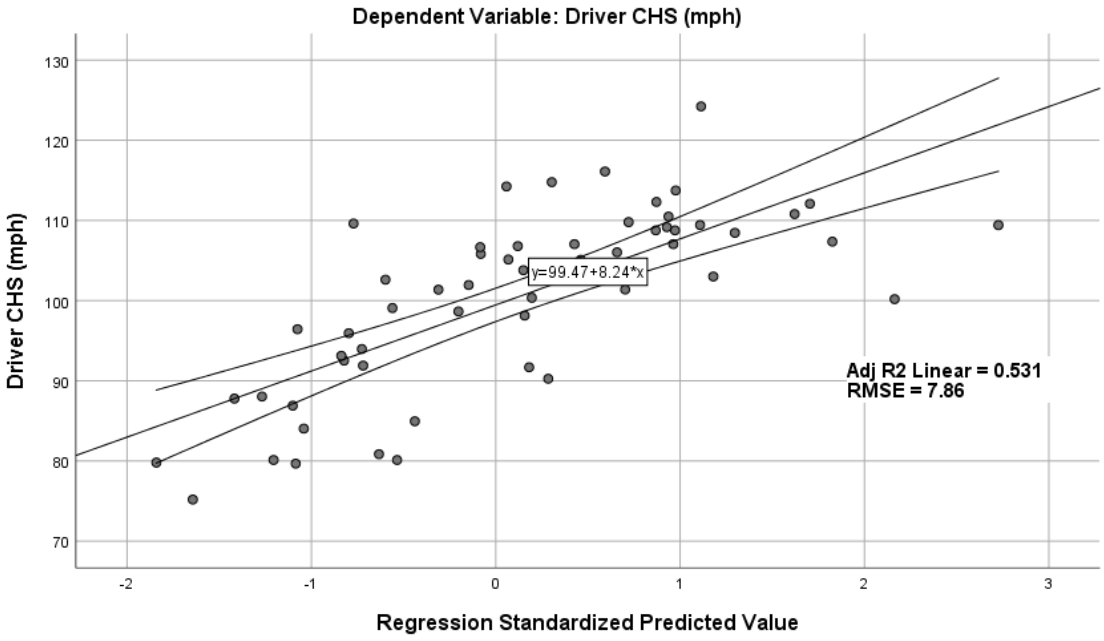


Figure 6.15 Stage 2-3 Body & GRF measure predictors for Driver CHS. Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.11 Stage 2-3 Body & GRF – Driver CHS linear regression model summary

n	R	Adjusted R^2			SEE	
56	0.745	0.531			7.378	
Coefficients[a]						
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	44.784	7.328		6.111	<0.001		
Lead shoulder speed°/s	0.037	0.006	0.565	6.062	<0.001	0.930	1.076
GRFpeak Fz lead N	0.019	0.004	0.432	4.708	<0.001	0.958	1.043
GRFpeak Fy rear N	0.064	0.021	0.277	3.024	0.004	0.963	1.039
a. Dependent Variable: Driver CHS mph							

6.4.13 Stage 1-3 P-GPC Relationships: Physical – Driver CHS

The following physical measures, combined in a regression model, explain 66.3% of the variance in the sample's Driver CHS, via the equation:

Driver CHS mph = (*34.1 ± 9.6)* + (*Sit throw 3kg m x 5.086 ± 0.640)* + (*Shoulder external rotation lead° x 0.3059 ± 0.0932)* + (*Vertical CMJ reach cm x 0.2133 ± 0.0876)*

The residual plot is shown in Figure 6.16 and model summary in Table 6.12.

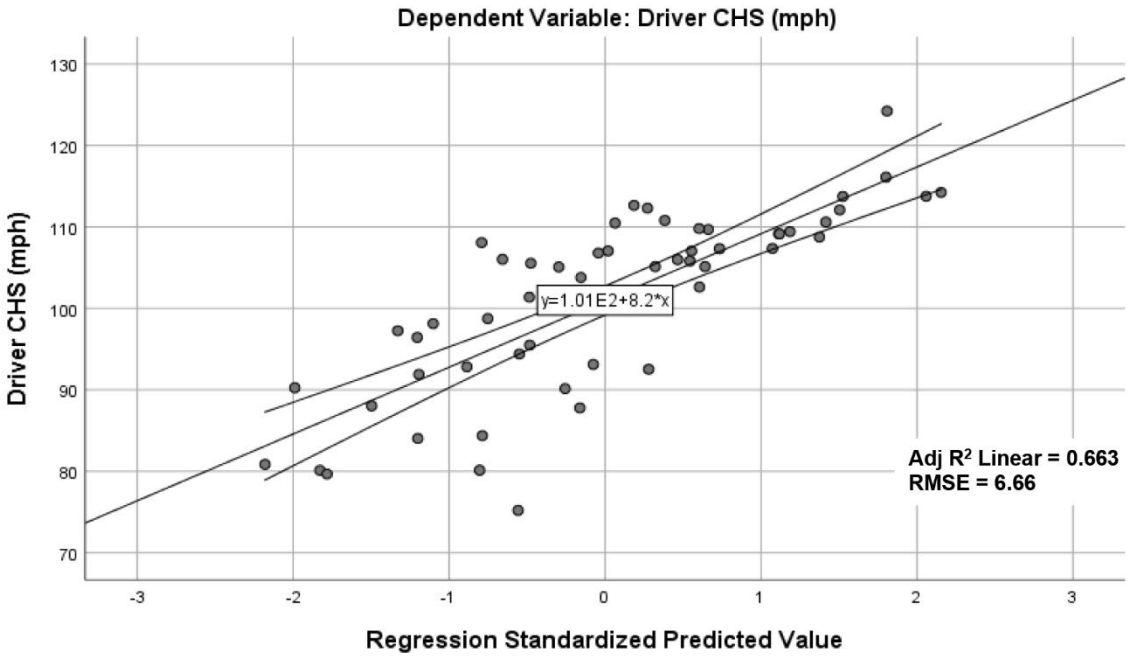


Figure 6.16 Stage 1-3 Physical measure predictors for Driver CHS. Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.12 Stage 1-3 Physical – Driver CHS linear regression model summary

n	R	Adjusted R^2		SEE		
57	0.825	0.663		6.307		
Coefficients[a]						
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	34.123	9.593		3.557	0.001		
Sit throw 3 kg m	5.086	0.640	0.694	7.951	<0.001	0.763	1.311
Shoulder external rotation lead ROM°	0.306	0.093	0.254	3.284	0.002	0.972	1.029
Vertical CMJ reach cm	0.213	0.088	0.210	2.434	0.018	0.777	1.287
a. Dependent Variable: Driver CHS mph							

6.4.14 Stage 1-3 P-GPC Relationships: Physical – 120 m Shot Spin Rate

The following physical measures, combined in a regression model, explain 38.0% of the variance in the sample's 120 m shot spin rate, via the equation:

120 m shot spin rate rpm = (2663 ± 1138) + (Sit throw 3 kg m x 758.493 ± 114.246) + (Hip internal rotation lead° x 42.708 ± 17.398)

The residual plot is shown in Figure 6.17 and model summary in Table 6.13.

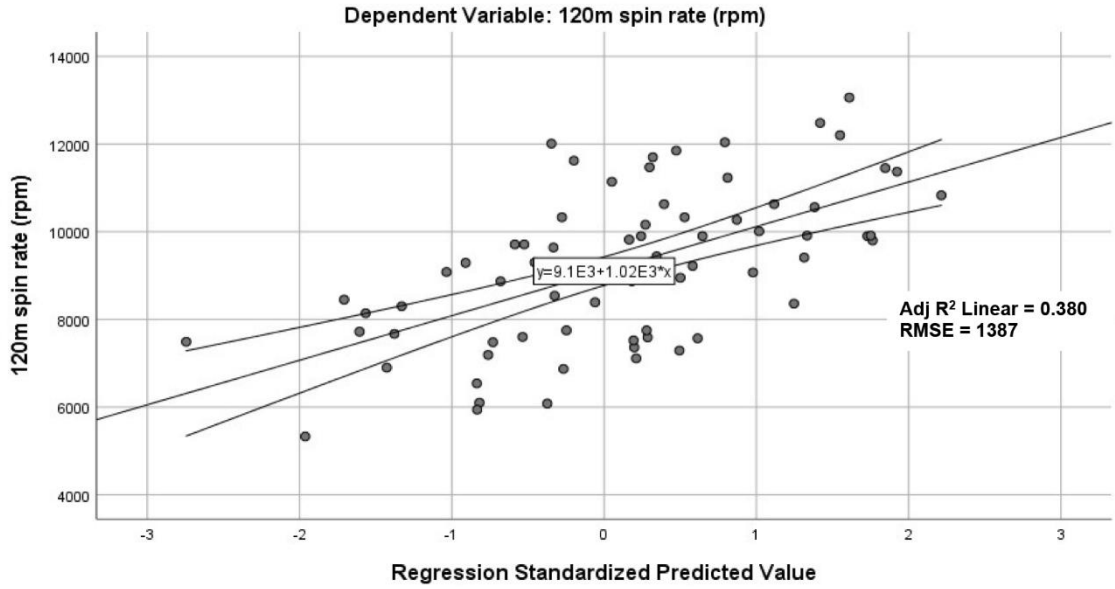


Figure 6.17 Stage 1-3 Physical measure predictors for 120 m Shot Spin Rate. Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.13 Stage 1-3 Physical – 120 m Shot Spin Rate linear regression model summary

n	R	Adjusted R^2			SEE	
74	0.630	0.380			1450.164	
Coefficients[a]						
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	2663.364	1138.391		2.340	0.022		
Sit throw 3 kg m	758.493	114.246	0.610	6.639	<0.001	0.991	1.009
Hip internal rotation lead°	42.708	17.398	0.226	2.455	0.017	0.991	1.009
a. Dependent Variable: 120m spin rate rpm							

6.4.15 Stage 1-2 P-GPC Relationships: Physical – Driver Lead Shoulder Speed

The following physical measures, combined in a regression model, explain 48.0% of the variance in the sample's Lead Shoulder Peak Velocity (°/s), via the equation:

Lead shoulder peak velocity °/s = (*-605 ± 243)* + (*Lateral jump distance relative to leg length lead m/m x 362.619 ± 63.042)* + (*Shoulder external rotation lead° x 7.165 ± 1.823)* + (*Grip strength rear kg x 6.406 ± 2.391)*

The residual plot is shown in Figure 6.18 and model summary in Table 6.14.

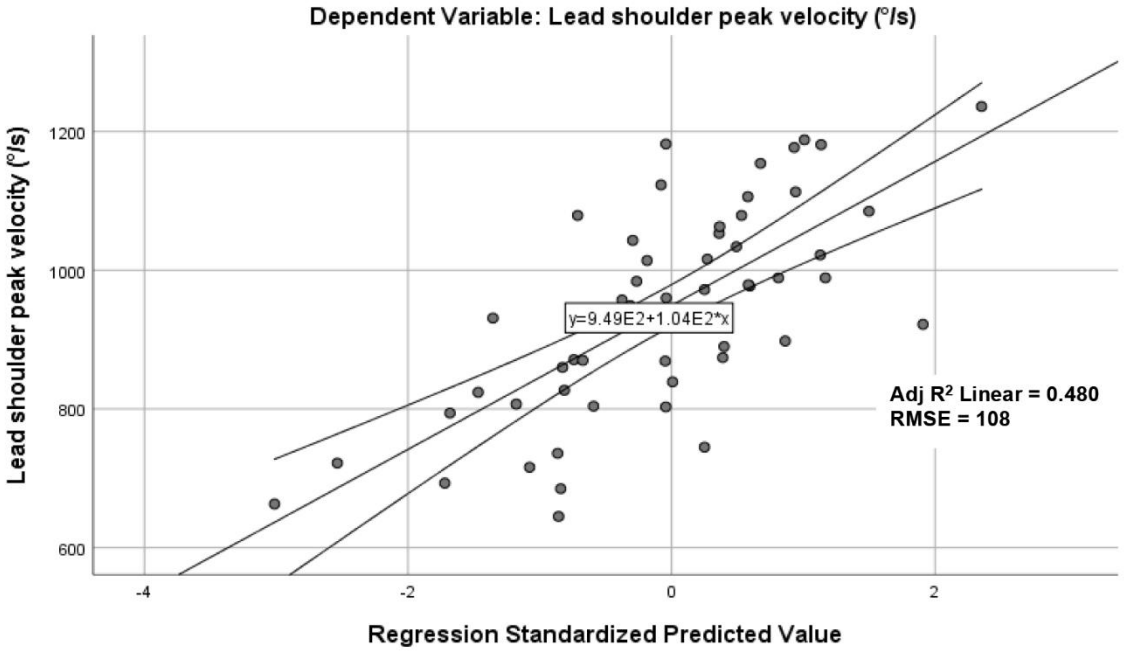


Figure 6.18 Stage 1-2 Physical measure predictors for Driver Lead Shoulder Speed. Linear regression residual plot and standard error of estimate at 95% confidence interval, adjusted R^2 and root mean squared error (RMSE) for linear regression model.

Table 6.14 Stage 1-2 Physical – Driver Lead Shoulder Speed linear regression model summary

n	R	Adjusted R^2			SEE		
53	.713[a]	0.480			118.814		
Coefficients[a]							
Predictors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	SE	β			Tol.	VIF
(Constant)	-605.015	242.664		-2.493	0.016		
Shoulder external rotation lead ROM°	7.165	1.823	0.392	3.930	<0.001	0.916	1.091
Lateral jump distance relative to leg length lead m/m	362.619	63.042	0.562	5.752	<0.001	0.956	1.046
Grip strength rear kg	6.406	2.391	0.267	2.679	0.010	0.915	1.092
a. Dependent Variable: Lead shoulder peak velocity (°/s)							

6.5 Discussion

The use of regression modelling with established physical and technical measures in golfers can provide further insight to guide testing and training. The multiple linear regression models, including predictor measures from a given stage of the P-GPC, explain variance in the dependent variables from the adjacent and adjacent plus one stage. Due to the strength of relationships and proximity within the P-GPC, it is likely that some of these relationships are mechanistically relevant to GP. Several of the models blend unique regression contributions from different parameters for each side of the body. This avoids multiple-collinearity and produces regression models that are effective across a heterogenous sample.

There is also evidence from this study's findings that the measures from parameter-categories that are more proximal within the P-GPC are stronger predictors than those that are more distal (i.e., at a lower or higher stage of the P-GPC). This was also generally true for correlational strength and direction. For example, most driver measures exhibited stronger correlations with Driver Total Distance than HCP. These findings provide construct validity to the P-GPC.

6.5.1 Stage 4-5 P-GPC Relationships: Driver distance & 120m Accuracy – HCP

The two selected Stage 4 tests of skill, Driver Total Distance and 120 m Shot Distance to Target explained 64.1% of variance in HCP (Figure 6.7 and Table 6.3). Importantly, these two measures were selected as they were most representative of the test instructions, (i.e., 'to drive the ball as far as possible with accuracy' and 'as close to the 120 m target as possible') (141). The model provided good accuracy for the heterogenous sample, predicting HCP within ± 5.36. This is in support of previous studies on these two basic golf skills. That is, the ability to drive the ball a long way off the tee (82, 348, 513) and to hit an approach shot as close as possible to the target (347, 355).

6.5.2 Stage 3-5 P-GPC Relationships: Driver Ball & Club Kinematics – HCP

Five driver ball and club measures were selected as predictors in the model that explained 74.4% of variance in HCP within ± 5.41 (Figure 6.8 and Table 6.4). The two club measures of CHS, and Smash Factor have previously shown to align with ability levels (82, 288). CHS has also shown very strong correlation with HCP in a previous large heterogenous sample (226). These measures aid GP via influencing ball speed, with CHS generating the force and smash factor indicating an efficient transfer of energy to the golf ball via optimal club head presentation and club face impact location (288). Launch Angle has previously been shown to been to increase with proficiency and

influence distance (82). The remaining two predictors relate to how the driver shot interacts with the ground as it lands: Driver Carry (Land) Ball Speed and Driver Carry Land Angle. That is, lower landing angle would promote rollout, whilst lower landing speed might represent a more controlled landing of the ball, however this is yet to be examined empirically (514). These two measures within the model may suggest there is a 'sweet spot' for lower HCP golfers between these two somewhat opposing measures – as they both provided positive Beta coefficients in the model that explained HCP in our sample (i.e., the lower the landing angle and the lower the ball speed the lower the HCP would be expected to be). To the author's knowledge, this is the first time that driver landing speed and angle has been included in a regression model for HCP.

6.5.3 Stage 3-5 P-GPC Relationships: 120 m Shot Ball & Club Kinematics – HCP

Three club and ball measures from the 120 m Shot test combined to explain 47.8% of variance in HCP within ± 5.97 accuracy (Figure 6.9 and Table 6.5). A high Spin Rate allows for a climbing ball flight that would increase the chance of the ball stopping near the target in an approach shot (337). A shorter Low Point (the distance between the ball and the low point of the club head at the bottom arc of the swing (489)) shows the importance of a descending strike for shots of this distance range; typically associated with players powerful enough to use a shorter, high lofted club. The negative β for Face Angle suggest a 'less open' face is used by lower HCP players when executing an approach shot. Sweeney et al (2013) found a strong relationship (R^2 = 0.82) between club-head rotation (akin to face angle in this current study) and launch side angle in 21 Low to Mid-HCP golfers (338) as did Betzler et al (2014) across ability cohorts (β = 0.655) (82). Side Angle has also been shown to differentiate across ability levels (82). However, these studies all investigated a driver shot – to the author's knowledge, this is the first study to demonstrate a similar importance of face angle in an approach shot. Based on their negative and positive relationships with HCP, these predictors highlight the differences in effective shot-making to a 120 m target in a sample of golfers of varied ability.

6.5.4 Stage 3-4 P-GPC Relationships: Ball Kinematics – Driver Total Distance

Ball Speed and Spin Rate were selected into the most effective model that explained 98.4% of variance in Driver Total Distance within ± 3.55 m (Figure 6.10 and Table 6.6). In addition to a very strong explanation of variance, the model provided good accuracy, predicting Driver Total Distance. The strength of these relationships between these ball measures and HCP were expected. However, the correlation between Ball Speed and Total Distance was stronger than previously reported (r = 0.66 with carry distance) (515).

This is likely due to the heterogenous sample in this study, as opposed to the smaller homogenous sample used in the previous study. In previous studies, Ball Speed has been shown an effective predictor of ability within regression models (47, 82) and temporal associations with increases in Total Distance following S&C interventions (92, 254, 258). There is also a similar magnitude of effect of ball temperature on Ball Speed and Distance, providing further evidence of an obvious intrinsic link (337). Spin Rate negatively influenced Total Distance. Considerably high back spin can reduce the carry distance, owing to a higher trajectory than is optimal and a reduction caused by the Spin Rate's negative impact on the drag force against the air (499). Therefore, Ball Speed is a monitorable measure that provides valuable insights to the golfer and multiple service providers (47). Whereas appropriate Spin Rate speeds can allow a golfer to optimise their Driving Distance – highlighting the importance of optimising swing mechanics and club-fitting.

6.5.5 Stage 3-4 P-GPC Relationships: Club Kinematics – Driver Total Distance

Driver CHS and Smash Factor explained 95.0% of the variance in Driver Total Distance within ± 5.74 m (Figure 6.11 and Table 6.7). These relationships are logical, well established (82, 288) and align well with HCP, as mentioned earlier in this chapter. CHS can provide important intermediate goals for the S&C coach to assess the training transfer of physical interventions for the golfer (8, 34, 54, 225). Although not as prevalent in the literature, Smash Factor also has a potential role alongside CHS to ensure training transfer and is correlated with ability level (295). Smash factor can ensure that accuracy of club head presentation, for an efficient ball strike, is maintained as power capacity increases through training (82, 288). This is in support of previous findings that good distance from the tee requires both generating high Driver CHS and a centred club face strike typically associated with high Smash Factor, which are typically more prevalent in lower HCP golfers (82, 288, 516).

6.5.6 Stage 3-4 P-GPC Relationships: Ball Kinematics – 120m Distance to Target

Spin Rate and Land Ball Speed explained 23.5% of the variance in 120 m Shot Distance to Target ± 3.57 m (Figure 6.12 and Table 6.8). These predictors denote the importance of a climbing ball flight and stopping ability of the golf ball due to higher spin rate and lower ball speed when it lands. These findings are similar to that of previous studies on approach shot accuracy (14, 247, 355).

6.5.7 Stage 3-4 P-GPC Relationships: Club Kinematics – 120m Distance to Target

Club Path, Face Angle and Dynamic Loft explained 13.4% of the variance in 120 m Shot Distance to Target ± 3.25 m (Figure 6.13 and Table 6.9) A larger Dynamic Loft angle is synonymous with a shorter, higher lofted, club, which would be the club of choice for the more powerful athletes. Although not assessed, this is likely to be associated with Spin Rate from the previous model. The two opposing influences of Club Path (negative β) and Face Angle (positive β) on approach shot accuracy suggest a tendency away from an 'out-to-in' club path with an open clubface (i.e., avoiding a 'pull slice shot' as described by Tuxen (2009) – ball flight that starts left of the target line and then curves to the right (517)). The lower explanatory power of this and the previous approach shot model, relative to the driver distance models, is likely explained by the large heterogenous sample used. The sample included a portion of shorter hitters (older and early teens) who used longer clubs with a lower shot to still attain reasonable accuracy for the approach shot test. This may have slightly diluted the benefit of the high shot typically executed with a wedge for the Low-HCP and Elite adult golfers. In other words, there is a greater variety of effective shot options to a 120 m target than to execute a long driver shot – warranting further investigation of the approach shot within more distinct shot classifications.

6.5.8 Stage 2-4 P-GPC Relationships: Body Kinematics & GRF – Driver Distance

Lead Shoulder Speed (peak angular velocity), GRFpeak Fz Lead Leg and GRFpeak Fy Rear Leg explained 53.4% of the variance in Driver Total Distance ± 22.63 m (Figure 6.14 and Table 6.10). Creating segmental angular velocity with the shoulders in the golf swing has previously been shown as necessary to achieve good driver distance, supporting the findings on Lead Shoulder Speed in this study (247, 304, 342). In relation to GRF, Han et al (2019) also found strong correlations between GRFpeak Fz Lead Leg and CHS in highly skilled (HCP ≤ 3) golfers, in support of GRFpeak Fz Lead Leg in this model. In order to achieve this effective lead foot maximal loading, which tends to occur in the downswing (276), an effective weight transfer strategy from the rear foot is required (84, 324, 328) supporting the inclusion of GRFpeak Fy Rear Leg (rear foot to lead foot direction) in this model. Given the similarity of these three predictors to the findings from previous studies and the importance of GRF to power the proximal to distal sequence, it is plausible that these simple (in that they are not linked to specific swing events) peak GRF measures are important contributors to Driver Total Distance. These GRF measures combined with Lead Shoulder Speed GRFpeak Fy Rear Leg also fit the general motor pattern description of the golf swing provided by Han et al (2019) of 'shift-rotate-shift-rotate' motion pattern (336). Interestingly, GRFpeak Fz Lead Leg and

GRFpeak Fy Rear Leg had no correlation with each other – hinting at the prevalent inter-individual differences in golf swing technique (276, 290). In summary, these three measures are worthy of testing to provide some solutions to how the golfer may aim improve their driving distance.

6.5.9 Stage 2-3 P-GPC Relationships: Body Kinematics & GRF – Driver CHS

Lead Shoulder Speed, GRFpeak Fz Lead and GRFpeak Fy Rear explained 53.1% of the variance in Driver CHS with ± 7.86 mph accuracy (Figure 6.15 and Table 6.11). Containing the same predictors as the stage 2-4 driver distance model, these measures are likely to agree with the concepts of 'swinging in balance' with an effective weight transfer to generate angular shoulder acceleration to ultimately generate CHS (304, 324, 328, 518). This Stage 2-3 model also confirms the mechanism of performance transfer from the similar predictors contained in the Stage 2-4 model. That is, these body kinematic and GRF measures generate Driver Total Distance, at least in part, by generating Driver CHS.

6.5.10 Stage 1-3 P-GPC Relationships: Physical – Driver CHS

Sit Throw 3 kg (MB), Shoulder External Rotation Lead and Vertical CMJ Reach explained 66.3% of the variance in Driver CHS ± 6.66 mph (Figure 6.16 and Table 6.12). Core power (measured by Sit Throw 3 kg in our study) has been previously identified as an important physical parameter for GP in cross-sectional (193), experimental (254, 488, 519) and literature reviews (251). Tests of power using MB throws have also shown strong correlation with Driver CHS (39). However, this is the first study that has included the MB sit throw test in a model to explain variance in Driver CHS.

The importance of vertical leg power for generating CHS is well supported in the golf literature (235, 238-240). To this end, Vertical CMJ Reach is a convenient, valid and commonly used field test of leg power for golfers (39). However, this measure can conflate jump ability with leg power and does not favour an increase in bodyweight over time, which can occur with maturation or resistance training. Therefore, power estimates or positive impulse calculations, calculated from jump height and mass should also be considered for models used to inform training longitudinally (176).

Less is known about the role of lead shoulder external rotation in GP. One large-sampled study showed that rear shoulder external rotation was significantly different across proficiency levels. In contrast lead shoulder was only approaching significance (11). It is possible that higher levels of lead shoulder external rotation are a general sign of joint health and integrity – allowing the golfer to withstand better the high levels of force

experienced by the lead shoulder whilst generating driver CHS (192, 211) – although this notion requires further research. Nonetheless, this is the first study to include this flexibility measure as a predictor of Driver CHS, in combination with two other measures.

6.5.11 Stage 1-3 P-GPC Relationships: Physical – 120 m Shot Spin Rate

Sit Throw 3 kg (MB) and Lead Hip Internal Rotation ROM explained 38.0% of variance in Spin Rate ± 1387 rpm (Figure 6.17 and Table 6.13). These findings suggest that both core power and lead hip ROM contribute to the golfer's ability to produce higher spin rates in an approach shot, which golfers use to create a climbing ball flight and a landing where the ball either stops suddenly or spins backwards (337{Penner, 2002 #3087)}. The principle of specificity would suggest that the rapid shoulder extension in the Sit Throw 3 kg test bears similarity with the accelerating descending blow that allows the maintenance of wrist-cock angle required to create back spin with a short iron shot (241, 499{Verkhoshansky, 2011 #2758)}. Previous correlational studies have similarly shown the importance of abdominal strength and power with chipping and putting accuracy (66, 91). However, attempts to use these measures with approach shot accuracy, such as in Torres-Ronda et al (2014), have been unsuccessful until this study (47).

If limited, lead hip internal rotation ROM has been shown to interfere with the efficient transmission of kinetic energy from the lower extremities to the lumbopelvic kinetic chain, thereby causing excessive compensatory lumbar rotational stress during the golf swing – increasing the chance of lower back pain in high-level golfers (186, 189). Different methods of assessment for hip internal ROM have shown varied predictive validity to related golf swing attributes (36), therefore the seated hip internal rotation method used in this study appears to be useful. Good ROM in the lead hip is likely to be a sign of a functioning hip, free of muscular or capsular restrictions and neuro-inhibitiion, allowing better pelvic mechanics in the golf swing (140, 186). This is the first study to combine a golf-specific power and flexibility measure into a regression model to explain a portion of variance in an important technical measure for an approach shot. However, body kinematics were not assessed in the 120 m Shot test. Hence, further research is needed to confirm the mechanism for these physical attributes enabling golfers to generate higher spin rates in an approach shot or whether these are just spurious rleationships. Factors such as swing styles and club selection are also pertinent in approach iron shots and should be considered in furture research (85).

6.5.12 Stage 1-2 P-GPC Relationships: Physical – Driver Lead Shoulder Speed

Lateral Jump Distance Relative to Leg Length Lead, Shoulder External Rotation Lead and Grip Strength Rear explained 48.0% of variance in Lead Shoulder Speed ± 108 °/s

(Figure 6.18 and Table 6.14). The benefits of shoulder flexibility and leg power in general to the golfer were discussed in the previous model. However, varying from the other highly reported tests of vertical leg power, the lateral jump test purportedly measures the different construct of change of direction (460). This is logical given the importance of medio-lateral COP velocity and range in the golf swing (275, 276). Furthermore, lateral power capacity in the lead leg would be utilised when decelerating the pelvis during the downswing to transfer kinetic energy to generate thorax and lead shoulder angular velocity (304, 309). The relativity to leg length ensures this test is appropriate for heterogenous samples in terms of leg lengths.

Whilst grip strength has previously been shown important for Driver CHS (176, 258, 383), this is the first time its relationship with a body-kinematic measure that can explain how this physical capacity is transferred. It is plausible that grip strength would be important for handling the mass and inertia of the driver to enable high angular speeds of the lead shoulder. These three measures provide a varied blend of physical traits to explain the important golf swing body kinematic trait, Lead Shoulder Speed.

6.5.13 Limitations

A delimitation of this study was our approach for dependent variable selection for our regression models. Only selecting the highest standardised Beta coefficient for the relevant model in the next stage of the P-GPC meant that many potentially important relationships were not investigated. Although it would lead to a plethora of models, all Beta coefficients in each model of the P-GPC arguably warrant being investigated as a dependent variable and is a recommendation for future research. Furthermore, previous research has also suggested that regression models that include technical process measures (e.g., Launch Angle) are strengthened by the inclusion of face impact location (82). However, this may currently only be feasible with bespoke research-grade equipment. Furthermore, data for these models is of a cross-sectional nature. Longitudinal data would present the opportunity to further validate the predictive validity of the predictors presented in these models, as would the cross-validation of models.

There were several instances where the same parameter-category predictors explained less variance in the dependent variable of the adjacent stage of the P-GPC than they did the adjacent plus one stage. An example of this was the Stage 1 physical measures being able to explain greater variance in Stage 3 Driver CHS (Adjusted $R^2 = 0.663$) than Stage 2 Lead Shoulder Speed (Adjusted $R^2 = 0.480$). These instances likely reflect the shortcomings of the selected tests or the inherent variance in golfers golf swing styles (84, 86, 276) rather than the legitimacy of the P-GPC. Therefore, future studies could overcome this shortcoming by selecting temporally based body-related golf swing

measures and potentially divide and analyse golfers based on pre-defined swing styles. Furthermore, the lack of concurrently recording the temporal swing events limits the interpretability of the GRF data in this study – although basic GRF measures may provide an easy-to-measure indicator of weight transfer.

6.5.14 Practical applications

These mechanistic relationships presented in this study are often logical and/or align with previous studies. These regression models demonstrate the benefits of utilising a comprehensive combine that measures multiple physical parameters. Some of the previously reported predictors have now been shown to explain variance in different GP measures in more proximal stages of the P-GPC. Thus, this study extends on previous findings by explaining performance mechanisms in greater depth. Understanding how and why a trainable capacity is transferred to create GP, informs practitioners at specific intersects of the P-GPC. This knowledge fosters an integrated multi-disciplinary approach (8, 15).

The strongest predictors identified within these regression models can be used as benchmarks, by the relevant practitioners within a multi-disciplinary team, to monitor training transfer. Monitoring these selected predictors for individual athletes against their relative cohort (e.g., via a radar plot) allows the practitioner to address the weakest physical or technical capacities of the golfer. To provide a simple example, a golfer would undergo the three tests for the identified physical predictors (i.e., Sit Throw 3 kg, Lead Shoulder External Rotation and Vertical Jump and Reach) of Driver CHS in this study. If the regression model predicts a higher value in Driver CHS for this individual than their actual score, this golfer may have the physical capacity for greater Driver CHS than what they currently exhibit. In this scenario, this golfer is not transferring this capacity well enough to their swing and may require either greater specificity of training or a focus on swing technique to improve training transfer – if indeed increased Driver CHS was desirable for this golfer. The reverse interpretation would apply if the model predicted a lower value in the dependent variable than the golfer's actual score. The only caveat on this approach is to be aware of the proportion of variance that is unaccounted for (e.g., if 66.3% of Driver CHS is explained by three physical tests, 33.7% is accounted for by unknown factors). Profiling in this manner represents an important progression from current practice where practitioners may otherwise give each parameter equal or general attention. This approach builds on earlier works to create benchmarks of physical and technical measures, including those presented in Chapter 5, that can now be *weighted* and *individualised* to a given golfer (8, 10, 40).

Profiling in this manner could also be advantageous in talent identification. The young, highly skilled but physically under-trained or developed golfer represents a great opportunity to golf development programs. This type of player appears to be more common in elite amateur ranks of golf than other sports (216, 520). It is plausible that the regression model example provided above would predict a lower Driver CHS than the talented golfer's actual Driver CHS – due to their highly developed skill of swinging the golf club, relative to their physical capacities (although the prevalence of this across the sample was not investigated in this study). This typical aspiring player would therefore be characterised as undertrained and well-transferred in Stage 1–3 model. In this example, initiating a regular golf-specific S&C program could prevent a future performance plateau by increasing the physical capacity of the golfer. Aligning talent identification to the predicted improvement multi-disciplinary development programs can provide could be a pivotal strategy to maximise program outcomes and future research should seek to quantify the effectiveness of such an approach.

A large heterogenous sample of golfers is the most effective way to demonstrate generalisability and application of findings for these models with golfers. Many golfers are attempting to progress from their current ability-level towards a lowered HCP or elite performance. Conversely, differences in findings and different levels of model accuracy would be expected with more homogenous samples of golfers. Many of the measures used have been shown to vary with age (117) and ability (11, 12, 82). Therefore, there is merit in future investigations utilising a similar comprehensive combine on large homogenous samples of golfers, or a sample that is heterogenous in ability, yet homogenous in all other participant characteristics. This would determine which of our results are replicated and which may vary.

6.6 Conclusion

Regression models can quantify the explanation of variance by mechanistically relevant predictors across the P-GPC. Understanding the mechanisms of performance transfer, from one trait to another, can inform the various practitioners that act within a multi-disciplinary team to optimise GP. Benchmarks can be derived from the measures of central tendency presented in Study III and the contribution of measures weighted from regression models in this study. This allows for a proportionate and individualised approach to the testing and training of golfers. That is, combines and training can be reduced to the most important assessable physical and technical traits. This knowledge can guide an informed approach for perpetual holistic player development.

Chapter 7: Study V – Explaining the mechanisms of golf performance longitudinally

7.1 Abstract

Analysing longitudinal repeat measures from across the physical-golf performance continuum is the optimal method for identifying talent and assessing the impact of interventions aimed at enhancing golf performance. A comprehensive golf combine assessed the physical, technical (including driver and approach shot) and competition proficiency of a large heterogenous sample (*n* = 122, Handicap range = +6 – 36.4, Age = 29.5 ± 15.2 years) of Australian male golfers. Linear mixed models were built with each individual golfer considered as a random effect to establish the best predictors between each stage of the continuum and the preceding two stages (i.e., Stage 4–5, Stage 3–5, Stage 3–4, Stage 2–4 etc.). The 12 models explained between 1.6% and 95.0% of variance in the dependent variables. The stage of the P-GPC, dependent variable and strongest standardized predictors (respectively) were: Stage 5) Handicap – Driver Total Distance and Driver CHS, Stage 4) Driver Total Distance – Ball Speed, Club Head Speed and Lead Shoulder Speed, Stage 4) 120 m Distance to Target – Spin Rate and Dynamic Loft, Stage 3) Driver Club Head Speed – Ground Reaction Force Peak Fz Lead Foot and Sit Throw 3 kg, Stage 3) 120 m Spin Rate – Sit Throw 3 kg, Stage 2) Driver Lead Shoulder Speed – Vertical Jump and Reach. These predictors can be used as isolated tests or integrated into bespoke combines to create athlete profiles. These linear mixed models have validity for longitudinal applications such as identifying talent and quantifying the training transfer of physical and technical interventions over time.

7.2 Introduction

A fundamental reason for the repeated testing athletes over time is to gauge their progress in response to a training program and how this transfers to competition performance (89, 90). The longitudinal data that is gained from repeated testing can be used to develop predictive models that have utility in talent identification and development of any level of golfer. Measures can be assessed for their stability as valid quantifiers of training transfer. Targeted combines can then inform the multi-disciplinary team with valid feedback loops to ensure perpetual improvement for the golfer (8, 10, 15).

Few studies have investigated the relationships between physical, technical and competition measures in a longitudinal manner. A recent systematic review identified 17 high quality (quality rating of $\geq$ 15/20) golf S&C interventional studies (54). The most common dependent variables selected in these studies were CHS, Ball Speed, Carry Distance and Total Distance in order to measure the effect of the S&C programs. These are valid measures for this purpose. Several of the studies measured change in swing kinematics or HCP, however only temporal associations between physical change and these measures were reported. All 17 studies used samples n ≥ 30. Furthermore, only two of these studies used repeat measures – both with small treatment samples (n = 5 - 9) (129, 237). Whilst these are not necessarily methodological limitations for the purpose of these studies, they do limit the inferences that can be gained for the mechanistic relationships between these physical and technical measures (27). Therefore, analytical techniques that explicitly demonstrate these relationships are needed to explain trainable mechanisms of performance transfer and provide rationale for differences in individual training responses seen in all golf S&C interventional studies (54). This knowledge can inform integrated, individualised interventions for research and the field.

Linear mixed (effects) models (LMM), also known as hierarchical linear models are commonly used to understand sports performance over time (521). LMM are suited to this purpose as they can a) account for dependence of observations, b) maximise the use of unbalanced or incomplete datasets and, c) account for the random effects of confounding variables (522). To date however, there have been no large-sampled studies using longitudinal repeated measures in golf. Therefore, the aim of this study is to use longitudinal repeated analysis of physical, technical and competition measures to identify important relationships for GP in a large heterogenous sample of Australian male golfers. Furthermore, these results of this approach will be compared to the regression models from cross-sectional data from Study IV, to provide further predictive validity to the tests within the combine used for the studies in this thesis. Given the predictors

included in LMM are drawn from longitudinal data, they have utility for assessing the effectiveness of training interventions over time.

7.3 Methods

7.3.1 Participants

Participants were the same 122 active male golfers between the ages of 12 to 71 years described in Chapter 6 (page 226). Participants were encouraged to return to be re-tested up to four times over a 12-month period, with a total of 13 test days made available to participants. For the 64 participants who returned to be tested at least twice, the mean duration between first and last tests for participants was 134 ± SD 126 days. The sample gained for each test day visit is shown in Table 7.1.

Table 7.1 Participants for repeated test sessions

Test Visits	1	2	3	4
Participant *n*	122	64	28	15

7.3.2 Combine procedures

A comprehensive golf combine was utilised addressing measures at each stage of the P-GPC. The same test protocols were utilized as described in Chapter 4 (page 149) and Appendix A (page 301). Unless contraindicated due to injury or pain, each participant completed all assessment protocols each visit, subject to equipment availability. The combine scores provided 156 measures and metrics to be considered in the construction of 12 LMM that span the P-GPC.

7.3.3 Data

The predictor variables were centred by subtracting the mean of each variable from each observation and then scaled by dividing by one standard deviation of the variable. Scaling allowed for easier interpretation of each predictors effect on the marginal outcome of the predicted values. The scaled beta coefficients can be interpreted as the effect on the dependent variable for a one standard deviation change of the predictor variable, with all other predictor variables held constant. Scaling the predictor variables also allows some direct comparison between the relative effect of each predictor variable on the outcome. However due to the complexity of LMM's and the consideration of conditional random effects, a complete direct comparison cannot be made (523).

7.3.4 Statistical modelling

Dimension reduction was required to allow an initial full fit of each model, except the Stage 4-5 model which had only 2 predictors (Figure 7.1). The process used in Study IV was replicated for this study (see page 227). The full list of criteria applied to each removed measure is provided in Appendix D (page 377).

An LMM statistical framework was implemented in *R* (524). The models were constructed and fitted to the data using the *lmer* function from the *lme4* package (525). Each model assumed a normal distribution for the residual errors. An individual subject (i.e., each individual participant) was specified as a random intercept in the model. According to Bates et al (2015), one interpretation of this model structure is that the random intercepts of a subject provide an estimate of the standard deviation of the fixed effects (525).

7.3.5 Model diagnostics and performance

The residuals of each model were assessed for normality by plotting them as histograms and scatterplots, and then assessing their distributions: median, quantiles, minimum and maximum values. If the residuals did not appear to be normally distributed, the data was log-transformed, models re-fit and the distribution of residuals were re-assessed. The residuals of the selected model were plotted with the fixed effects parameter estimates and their 95% confidence intervals for each model using *ggplot2* (526). The estimated the proportion of the variance explained by the fixed effects, and random effects in each model, were determined using a method developed by Nakagawa et al (2017) (527) using the *performance* package (528). The estimated RMSE of the residuals for each model were calculated using the same package.

7.4 Results

Identical dependent variables and predictor sets were used for the 12 LMM that span the P-GPC as were used for the multiple linear regression models presented in Study IV. The summary outputs for each model are shown with a forest plot of standardized beta coefficients in Figure 7.1 to Figure 7.12 and a summary Table 7.2 to Table 7.13. The figures show the relative (standardized) strength of the relationship of each predictor with the dependent variable. The summary table provides an indication of the proportion variance explained by fixed effects (the predictors) with the R^2 *– conditional* value. The accuracy of the model prediction was quantified with RMSE, which has the same units as the dependent variable for each model. The Akaike Information Criterion (AIC) was used for model selection within each predictor set (529, 530). Sigma represents the

standard deviation of the residual within each model. R^2 conditional is the coefficient of determination that explains the variance from the predictors in each model. The implications for GP are provided in the discussion on a model-by-model basis.

7.4.1 Stage 4-5 P-GPC Relationships: Driver distance & 120 m Accuracy – HCP

Maximum Driver Shot test Driver Total Distance and 120 m Target Shot test Distance to Target were combined in a LMM to explain the variance in HCP. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.1. The dependent variable is in the boxed section at the top of the plot. Selected predictors for the LMM are on the vertical axis. Coefficients to the left of the dashed zero line of the forest plot are negative, those to the right are positive. A change of a predictor in a positive direction (to the right) would increase the score of the dependent variable in the positive direction also. For example, in Figure 7.1, either a decrease of Driver Total Distance or an increase of 120 m Distance to Target would predict an increase in the dependent variable HCP also.

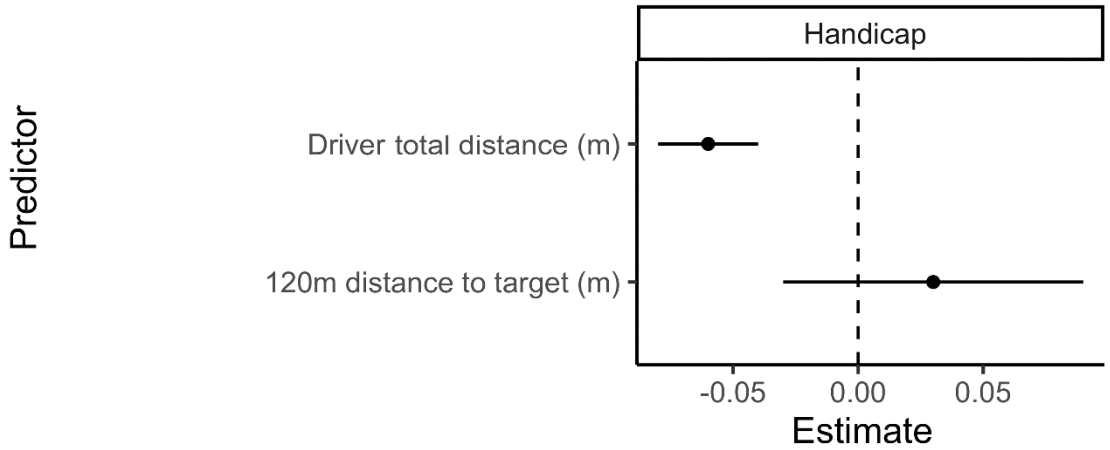


Figure 7.1 Stage 4-5 Driver Distance & 120 m Accuracy predictors for Handicap. Linear mixed model forest plot.

These predictors explain 11.8% of the variance in HCP ± 0.88 (RMSE) in the sample (Table 7.2).

Table 7.2 Stage 4-5 Driver Distance & 120 m Accuracy – HCP linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
1.18	657.14	125	0.118	0.88

7.4.2 Stage 3-5 P-GPC Relationships: Driver Ball & Club Kinematics – HCP

Longitudinal Maximum Driver Shot test club and ball measures were combined in a LMM to explain the variance in HCP. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.2.

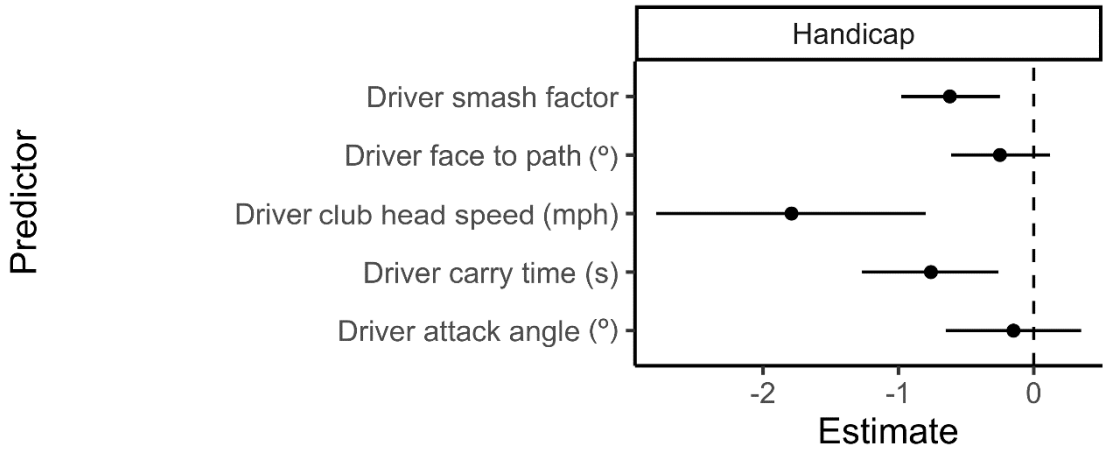


Figure 7.2 Stage 3-5 Driver Ball & Club measure predictors for Handicap. Linear mixed model forest plot.

These predictors explain 16.3% of the variance in HCP ± 0.93 (RMSE) in the sample (Table 7.3).

Table 7.3 Stage 3-5 Driver Ball & Club – HCP linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
1.23	710.19	135	0.163	0.93

7.4.3 Stage 3-5 P-GPC Relationships: 120m Shot Ball & Club Kinematics – HCP

Longitudinal 120 m Target Shot test club and ball measures were combined in a LMM to explain the variance in HCP. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.3.

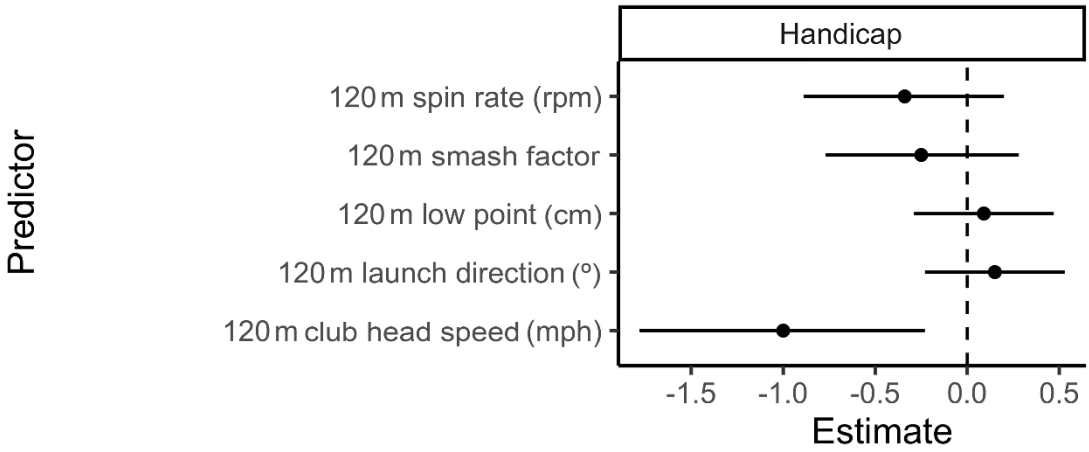


Figure 7.3 Stage 3-5 120 m Ball & Club measure predictors for Handicap. Linear mixed model forest plot.

These predictors explain 1.6% of the variance in HCP ± 0.87 (RMSE) in the sample (Table 7.4).

Table 7.4 Stage 3-5 120 m Ball & Club Measures – HCP linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
1.19	695.29	123	0.016	0.87

7.4.4 Stage 3-4 P-GPC Relationships: Ball Kinematics – Driver Total Distance

Longitudinal Maximum Driver Shot test ball measures were combined in a LMM to explain the variance in Driver Total Distance. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot (Figure 7.4).

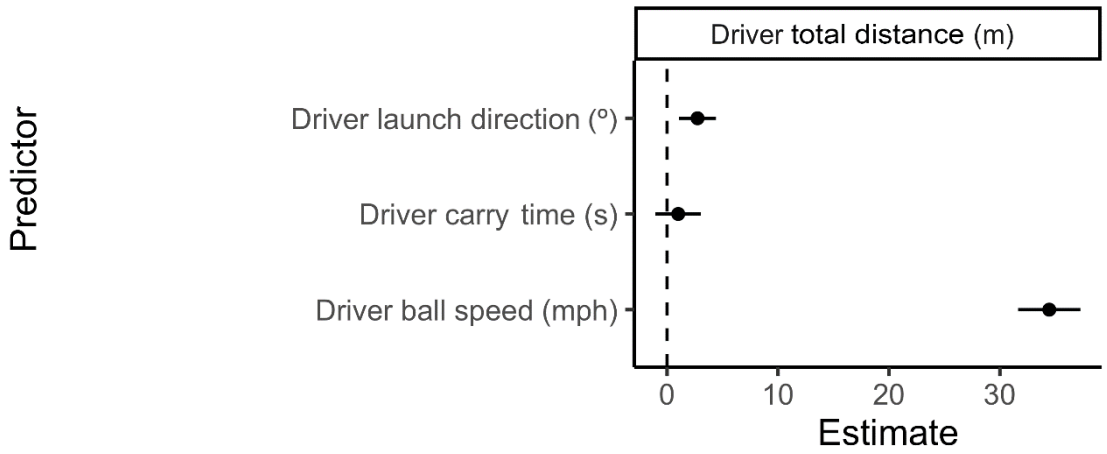


Figure 7.4 Stage 3-4 Ball measure predictors for Driver Distance. Linear mixed model forest plot.

These predictors explain 88.4% of the variance in Driver Total Distance ± 4.79 m (RMSE) in the sample (Table 7.5).

Table 7.5 Stage 3-4 Ball measure predictors for Driver Distance linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
6.04	1055.72	138	0.884	4.79

7.4.5 Stage 3-4 P-GPC Relationships: Club Kinematics – Driver Total Distance

Longitudinal Maximum Driver Shot test club measures were combined in a LMM to explain the variance in Driver Total Distance. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.5.

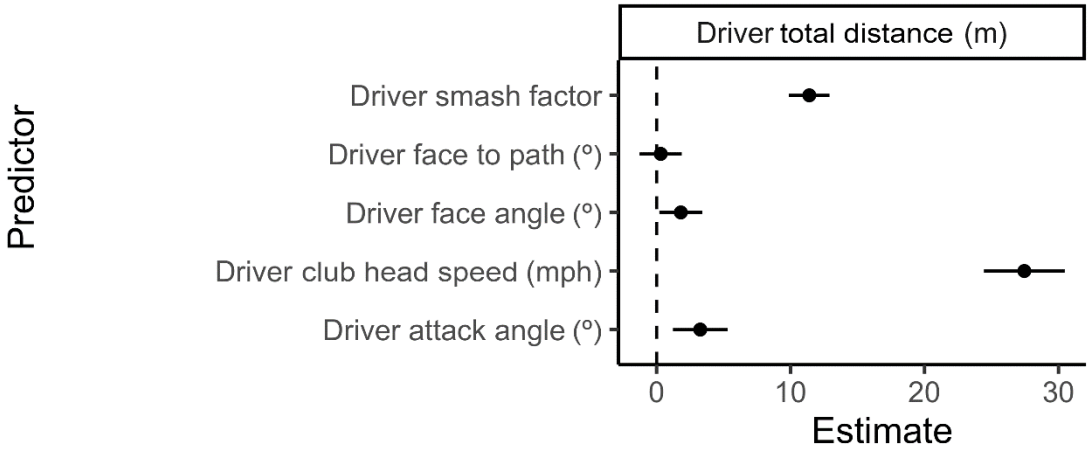


Figure 7.5 Stage 3-4 Club measure predictors for Driver Distance. Linear mixed model forest plot.

These predictors explain 85.6% of the variance in Driver Total Distance ± 4.20 m (RMSE) in the sample (Table 7.6).

Table 7.6 Stage 3-4 Club measure predictors for Driver Distance linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
5.42	1040.80	135	0.856	4.20

7.4.6 Stage 3-4 P-GPC Relationships: 120 m Shot Ball Kinematics – 120 m Accuracy

Longitudinal driver club and ball measures were combined in a LMM to explain the variance in HCP. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.6.

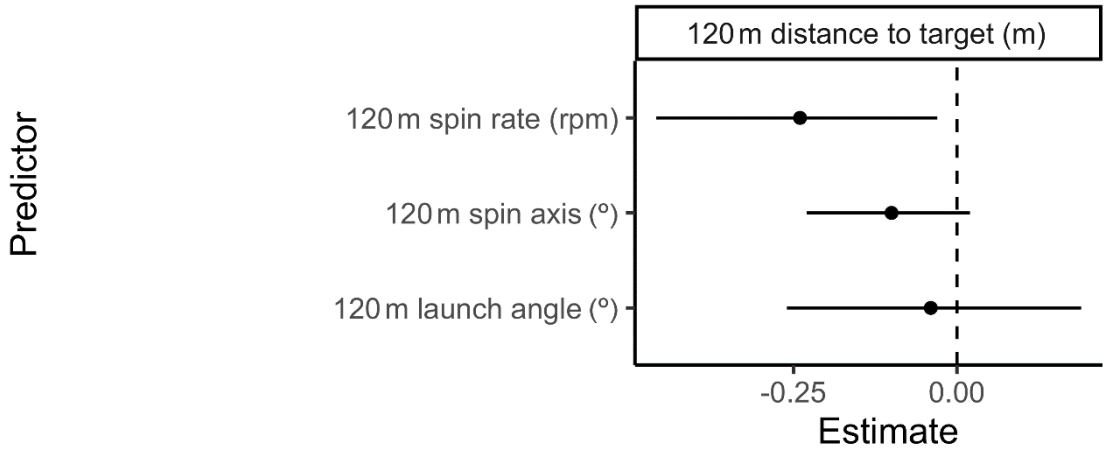


Figure 7.6 Stage 3-4 120 m Shot Ball measure predictors for Target Accuracy. Linear mixed model forest plot.

These predictors explain 17.3% of the variance in Distance to Target ± 0.60 m (RMSE) in the sample (Table 7.7).

Table 7.7 Stage 3-4 120 m Shot Ball measure predictors for Target Accuracy linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
0.65	308.11	132	0.173	0.60

7.4.7 Stage 3-4 P-GPC Relationships: 120 m Shot Club Kinematics – 120 m Accuracy

Longitudinal driver club and ball measures were combined in a LMM to explain the variance in HCP. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.7.

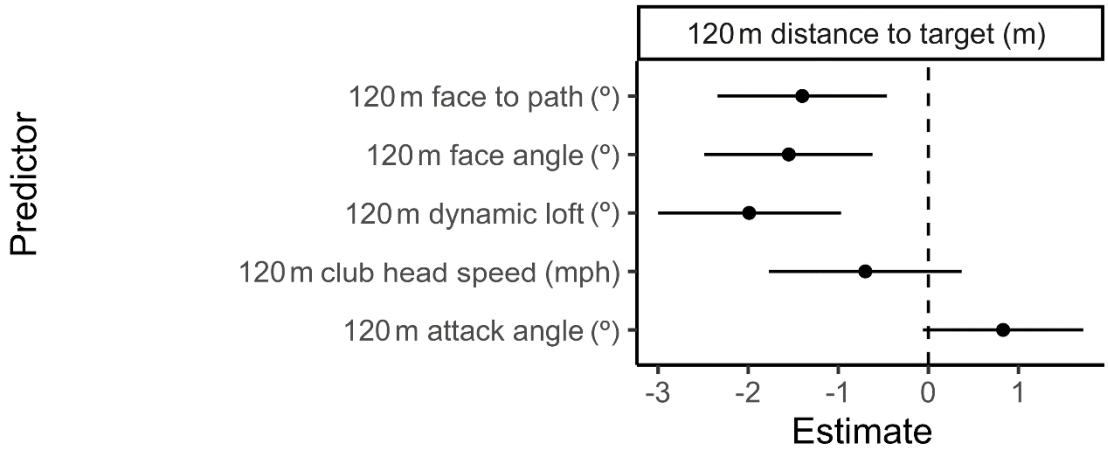


Figure 7.7 Stage 3-4 120 m Shot Club measure predictors for Target Accuracy. Linear mixed model forest plot.

These predictors explain 44.5% of the variance in 120 m Distance to Target ± 4.31 m (RMSE) in the sample (Table 7.8).

Table 7.8 Stage 3-4 120 m Shot Club measure predictors for Target Accuracy linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
4.54	784.34	123	0.445	4.31

7.4.8 Stage 2-4 P-GPC Relationships: Body Kinematics & GRF – Driver Total Distance

Longitudinal Maximum Driver Shot test body kinematic and GRF measures were combined in a LMM to explain the variance in Driver Total Distance. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.8.

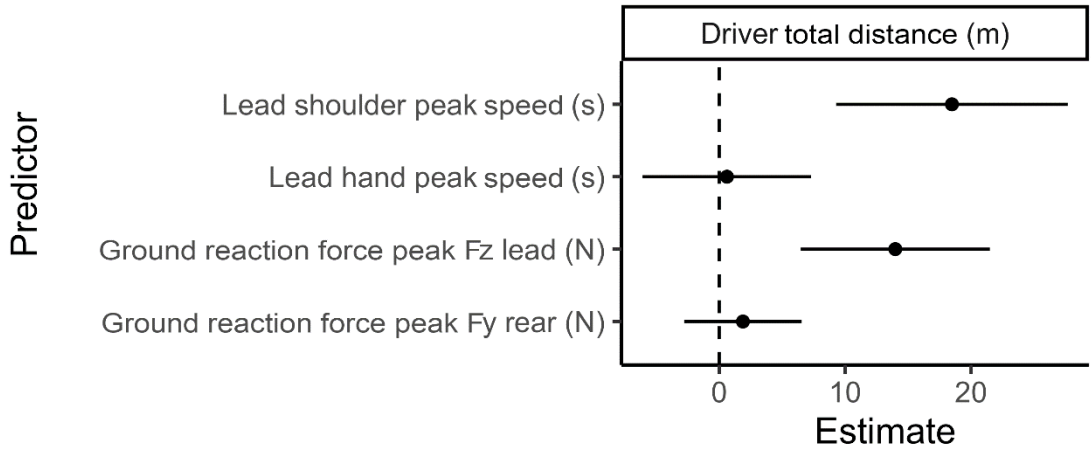


Figure 7.8 Stage 2-4 Body & GRF measure predictors for Driver Distance. Linear mixed model forest plot.

These predictors explain 24.5% of the variance in Driver Total Distance ± 7.86 m (RMSE) in the sample (Table 7.9).

Table 7.9 Stage 2-4 Body & GRF measure predictors for Driver Distance linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
12.28	716.61	71	0.245	7.86

7.4.9 Stage 2-3 P-GPC Relationships: Body Kinematics & GRF – Driver CHS

Longitudinal Maximum Driver Shot test body kinematic and GRF measures were combined in a LMM to explain the variance in Driver CHS. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.9.

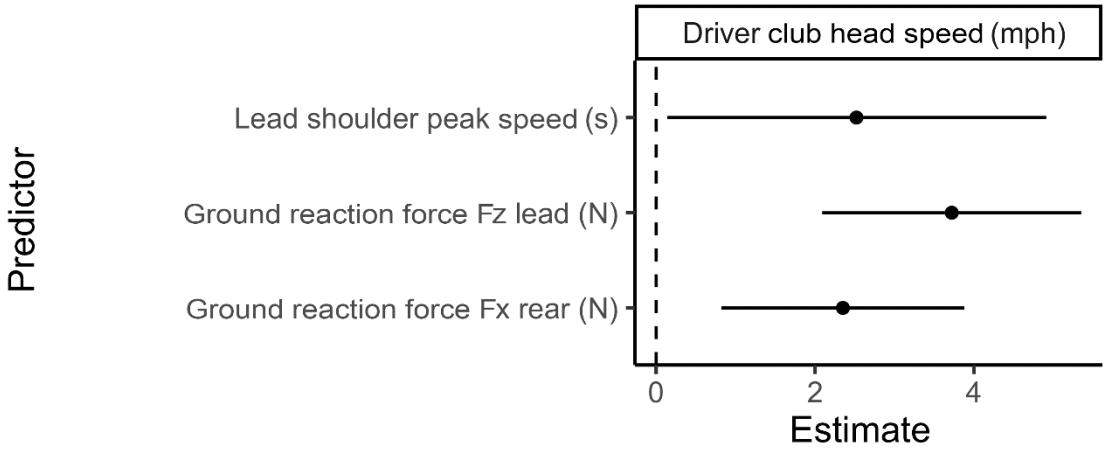


Figure 7.9 Stage 2-3 Body & GRF measure predictors for Driver Club Head Speed. Linear mixed model forest plot.

These predictors explain 22.8% of the variance in Driver CHS ± 1.11 mph (RMSE) in the sample (Table 7.10).

Table 7.10 Stage 2-3 Body & GRF measure predictors for Driver CHS linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
2.08	379.24	53	0.288	1.11

7.4.10 Stage 1-3 P-GPC Relationships: Physical – Driver CHS

Longitudinal physical measures were combined in a LMM to explain the variance in Driver CHS. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.10.

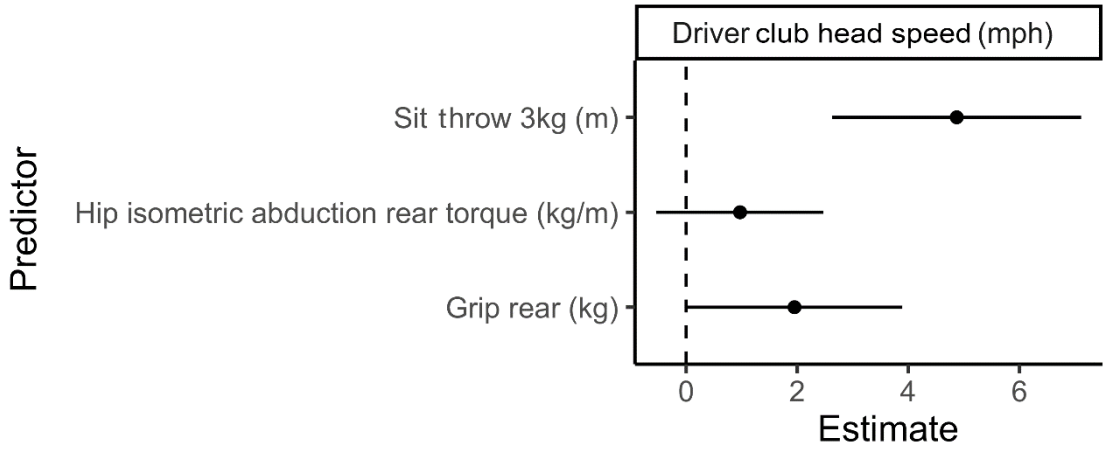


Figure 7.10 Stage 1-3 Physical measure predictors for Driver Club Head Speed. Linear mixed model forest plot.

These predictors explain 57.8% of the variance in Driver CHS ± 1.69 mph (RMSE) in the sample (Table 7.11).

Table 7.11 Stage 1-3 Physical measure predictors for Driver CHS linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
2.46	439.27	68	0.578	1.69

7.4.11 Stage 1-3 P-GPC Relationships: Physical – 120 m Shot Spin Rate

Longitudinal physical measures were combined in a LMM to explain the variance in 120 m Target Shot test Spin Rate. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.11.

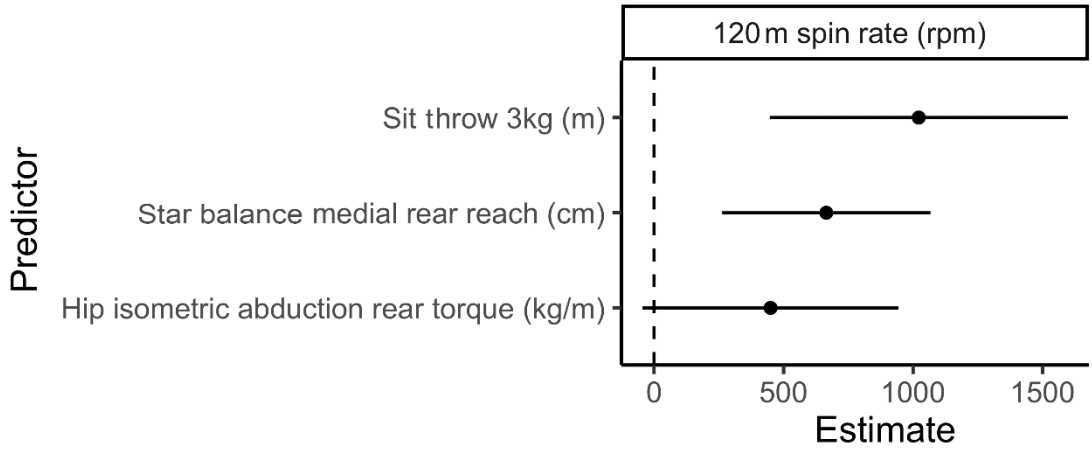


Figure 7.11 Stage 1-3 Physical measure predictors for 120 m Shot Spin Rate. Linear mixed model forest plot.

These predictors explain 48.5% of the variance in 120 m Target Shot test Spin Rate ± 926 rpm (RMSE) in the sample (Table 7.12).

Table 7.12 Stage 1-3 Physical measure predictors for 120 m Shot Spin Rate linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
1164.31	1340.58	73	0.485	926.20

7.4.12 Stage 1-2 P-GPC Relationships: Physical – Driver Lead Shoulder Speed

Longitudinal physical measures were combined in a LMM to explain the variance in Maximum Driver Shot test Lead Shoulder Speed. The estimated standardised beta coefficients for this model are provided with 95% confidence intervals are on the horizontal axis in the forest plot in Figure 7.12.

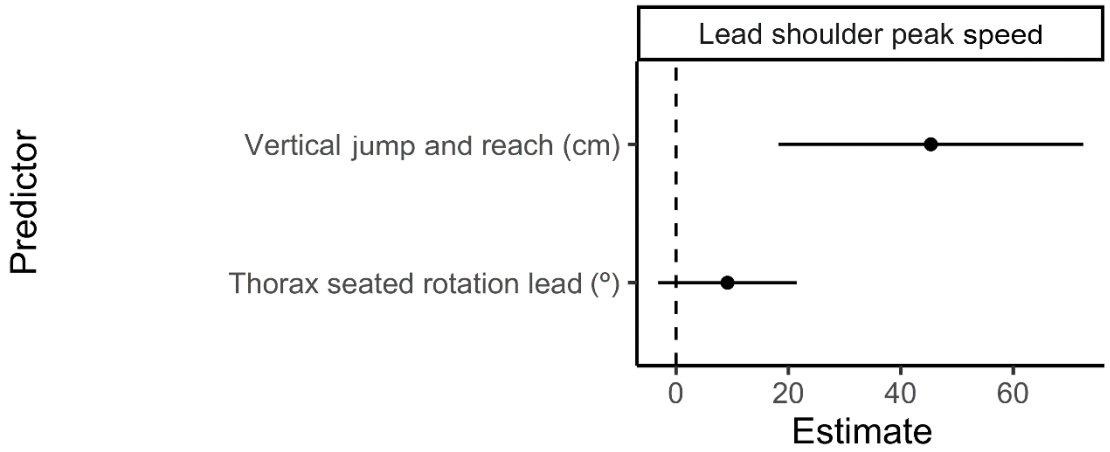


Figure 7.12 Stage 1-2 Physical measure predictors for Driver Lead Shoulder Speed. Linear mixed model forest plot.

These predictors explain 11.1% of the variance in Driver Lead Shoulder Speed ± 35.17°/s (RMSE) in the sample (Table 7.13).

Table 7.13 Stage 1-2 Physical measure predictors for Driver Lead Shoulder Speed linear mixed model summary

Sigma	AIC	Df residual	R^2 conditional	RMSE
44.93	1511.93	126	0.111	35.17

7.4.13 Summary comparison - Study IV regression and Study V linear mixed models

Similar, but not identical strongest predictors were found in the comparative (same predictor sets) 12 LMM's from this study and the 12 regression models from Study IV. Four of the 12 models had different measures as the strongest predictor (Table 7.14).

Table 7.14 Comparative summary of strongest standardised predictors between Study IV regression and Study V linear mixed models

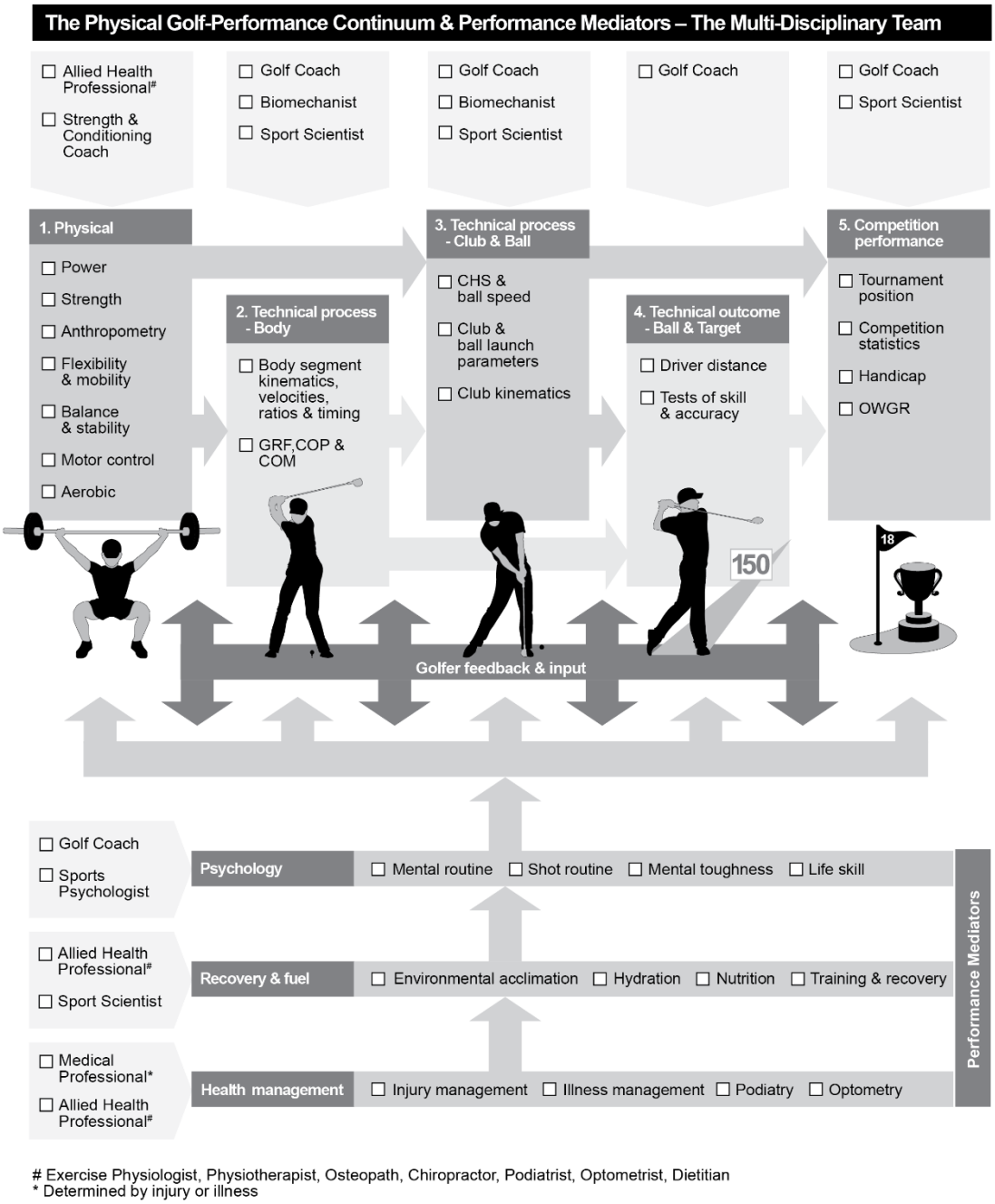
P-GPC Stage Relationships	Dependent Variable	Strongest Regression Predictors	Strongest LMM Predictors
4-5	HCP	Driver Total Distance	Driver Total Distance
3-5 Driver Test	HCP	CHS	CHS
3-5 120 m Target Test	HCP	Spin Rate	CHS
3-4 Driver Test (Ball)	Total Distance	Ball Speed	Ball Speed
3-4 Driver Test (Club)	Total Distance	CHS	CHS
3-4 120 m Target Test (Ball)	Accuracy	Spin Rate	Spin Rate
3-4 120 m Target Test (Club)	Accuracy	Club Path	Dynamic Loft
2-4 Driver Test	Total Distance	Lead Shoulder Speed	Lead Shoulder Speed
2-3 Driver Test	CHS	Lead Shoulder Speed	GRF Peak Fz Lead
1-3 Driver Test	CHS	Sit Throw 3 kg	Sit Throw 3 kg
1-3 120 m Test	Spin Rate	Sit Throw 3 kg	Sit Throw 3 kg
1-2 Driver Test	Lead Shoulder Speed	Lead Lateral Jump Relative to Leg Length	Vertical CMJ Reach

7.5 Discussion

On average, there were 19 ± 18 weeks between the first and last test of the 64 participants who returned to be re-tested at least once. Therefore, this is the longest and largest sampled repeated measures study in golf. Although LMM is a different analytical process to the regression technique used in Study IV, similar predictors were found to be important within the models. During model construction it was identified that there were generally more predictors within each set that had statistically significant correlations to the dependent variable for each model. This was likely due to a larger overall data set, which is a benefit of LMM (i.e., the ability to use all available data). This was particularly beneficial when considering GRF measures for models, which had only had relatively small samples available in Study IV. Overall, a larger array of measures were able to be included in models, leading to improved content validity for LMM compared to the regression models.

7.5.1 Stage 4-5 P-GPC Relationships: Driver distance & 120 m Accuracy – HCP

The two selected Stage 4 tests of skill, Driver Total Distance and 120 m Shot Distance to Target explained 11.7% of variance in HCP ± 0.88 (Figure 7.1 and Table 7.2). This was a much lower coefficient of determination, but more accurate model, than the 64.1% (RMSE = 5.36) with the same selected predictors in the regression model in Study IV. The ability to drive the ball a long way off the tee (82, 348, 513) and to hit an approach shot as close as possible to the target (347, 355) are important to golf performance over time. Other contributors to HCP, such as short game and other performance mediators (see



Exercise Physiologist, Physiotherapist, Osteopath, Chiropractor, Podiatrist, Optometrist, Dietitian
* Determined by injury or illness

, page 126) were not included in this model and may account for the remaining variance.

7.5.2 Stage 3-5 P-GPC Relationships: Driver Ball & Club Kinematics – HCP

Five driver ball and club measures were selected as predictors in the model that explained 16.3% of variance in HCP ± 0.93 (Figure 7.2 and Table 7.3). This was a much lower coefficient of determination, but more accurate model, than the 74.4% (RMSE = 5.41) in the regression model in Study IV built from the same predictor set (i.e., model building began with the same full predictor set available), although only two of the five predictors were the same. These club measures were CHS (with the strongest influence) and Smash Factor, which have previously shown to align with ability levels (82, 288) and

HCP (226). The three additional predictors selected into this LMM model were Carry Flat Time, Face to Path and Attack Angle. Carry flat time relates closely to Carry Distance and is therefore logical given the importance of distance to the golfer. A more positive Face to Path increases the chance of hitting a fade from the tee (if the club path is negative – typically indicative of hitting the ball as the club head moves upwards in highly-skilled golfers) and a more positive Attack Angle is understood to increase the launch height and lower the spin rate (82). Previous studies have identified the similar measures of Face Angle, Club Path and Dynamic Loft as the three most important swing factors that discriminate players above and below a HCP of 5 (293). Thus, HCP is partly determined by the power of the swing, an efficient ball strike with optimal launch parameters for distance and accuracy. However, the relatively low explanation of variance suggests that there are other factors that heavily influence HCP that are not contained in this model.

7.5.3 Stage 3-5 P-GPC Relationships: 120m Shot Ball & Club Kinematics – HCP

Four club and ball measures from the 120 m Shot test combined to explained only 1.6% of the variance in HCP ± 0.87 (Figure 7.3 and Table 7.4). This is much lower than the variance (47.8%) but also less error (RMSE = 5.97 m) than from the same predictor set in the regression model in Study IV. CHS, Spin Rate and Smash Factor were the strongest standardized beta coefficients for this model. Low point and Launch Direction were the other predictors in the model. The reason for such low explanatory of this model are possibly due to the many different types of approach shot available to a 120 m target. For example, both a low or a high shot could be successful in this test but would produce very different club and ball kinematics – causing a scenario where detecting the most important club and ball measures is difficult. Therefore, a study categorising shot type (i.e., high or low, or with a specific club) and level of prediction would be useful in the future.

7.5.4 Stage 3-4 P-GPC Relationships: Ball Kinematics – Driver Total Distance

Three ball measures were selected into the most effective LMM that explained 88.4% of variance in Driver Total Distance within ± 4.79 m (Figure 7.4 and Table 7.5). This was similar to the variance (98.4%) and error (RMSE = 3.55 m) from the same predictor set in the regression model in Study IV. Not surprisingly, Ball Speed was again the strongest predictor in the model. Ball Speed appears to be the most common ball measure to produce Driver Distance, and is therefore a useful benchmark for training transfer, as has been suggested previously (47). Launch Direction had the second strongest positive coefficient in the model. This indicates that starting the ball to the right of the target line

(a positive angle on Trackman™) has a positive influence on distance. Many of the shots that started to the right of the target line were likely to be a *push* or *push hook* as described by Tuxen (2009) (commonly known as a 'draw') – given that the ball had to finish on a 40 m wide fairway, which tend to roll out further than a *pull slice* or 'fade' (517). Driver Launch Direction Angle has also been shown to increase (more positive – starting more to the right) with proficiency level (82). The remaining two predictors was Carry Flat Time (the duration of time the ball is in the air) which has logical link to the dependent variable of Total Distance and provided a small positive standard beta coefficient. These predictors suggest that Driver Total distance is primarily subject to Ball Speed but is also benefitted by positive Launch Direction and greater Carry Time.

7.5.5 Stage 3-4 P-GPC Relationships: Club Kinematics – Driver Total Distance

Five club kinematic measures were selected into the LMM model that explained 85.6% of variance in Driver Total Distance within ± 4.20 m (Figure 7.5 and Table 7.6). This was similar to the variance (95.0%) and error (RMSE = 5.74 m) from the same predictor set in the regression model in Study IV. Once again Driver CHS and Smash Factor had the strongest positive beta coefficients of the candidate predictors as they did in the Chapter 6 regression models (see page 245). A more positive Attack Angle, Face Angle and Face to Path also optimizes distance and accuracy through an increased likelihood of a centred strike (288, 517), optimal launch and appropriate orientation of the club face with the target line. In particular, a positive Face to Path angle is necessary to off-set the left of target (negative) moving club path that typically occurs with a positive Attack Angle (517). Attack Angle and Face Angle tend to shower higher positive values with increased proficiency (288). Good power generation and optimal club face delivery for an efficient strike and launch are required for good distance and accuracy with Driver.

7.5.6 Stage 3-4 P-GPC Relationships: 120 m Shot Ball Kinematics – 120 m Accuracy

Spin Rate, Spin Axis and Launch Angle combined in the LMM to explain 17.3% of the variance in 120 m Shot Distance to Target ± 0.60 m (Figure 7.6 and Table 7.7). This was similar to the variance (23.5%) and error (RMSE = 3.57 m) from the same predictor set in the regression model in Study IV. Although lower in explanatory power than the driver distance ball LMM, these predictors still denote the importance of the climbing ball flight and stopping ability of a golf ball with higher spin rate for an approach shot. A positive spin axis was an unexpected finding as many tour players anecdotally prefer a negative spin axis for an approach shot, synonymous with a fade. However, this may again relate to the heterogenous sample where some of the older or adolescent hitters may have found a 120 m approach shot to be a longer shot than the test intended. Hence their

effort may have been focused on ‘making the distance’ rather than stopping the ball close’. Overall, these findings are similar to that of previous studies on approach shot accuracy (14, 247, 355).

7.5.7 Stage 3-4 P-GPC Relationships: 120 m Shot Club Kinematics – 120 m Accuracy

Five 120 m Shot club kinematic measures were selected into the LMM to explain 44.5% of the variance in 120 m Shot Distance to Target ± 4.31 m (Figure 7.7 and Table 7.8). This was much larger than the variance (13.4%), with similar error (RMSE = 3.25 m) as the same predictor set in the regression model in Study IV. Negative beta coefficients for Dynamic Loft and CHS suggest that shorter, higher lofted clubs with greater swing speed contributed to greater accuracy (i.e., less distance to target once the ball was at rest). A positive beta coefficient for Attack Angle suggests that a steeper (negative) attack angle towards impact is also important for accuracy – due to its role in generating spin (499). This can be achieved with a more vertical Swing Plane, which again, naturally occurs with shorter clubs (345). Better players also tend to show less variability in this measure (288). Positive (or at least less negative) Face Angle and Face to Path (similar to the driver shot) were also important to accuracy.

Some of these findings differ somewhat to the correlates of 7-iron club kinematics (also measured with Trackman™) with HCP in a previous study by Johansson et al (295). In agreement was CHS, which showed a moderate positive correlation, and Dynamic Loft was not assessed. However, the previous study showed that Attack Angle, Face Angle and Face to Path showed a positive correlation with HCP, which would be expected to align with distance to target. Although there were some analytical differences such as selecting a median shot (as opposed to best shot in this study) this difference in findings is most likely due to all players in the previous study using a 7-iron. Conversely, some of these club kinematic findings from this study may relate more to the variation in club used for the 120 m Target Shot. Therefore, the findings from this current study may only be generalizable to the 120 m Target Shot and not to a test where the same club is used by all participants.

7.5.8 Stage 2-4 P-GPC Relationships: Body Kinematics & GRF – Driver Distance

Two body kinematic and two GRF measures were selected into the LMM that explained 24.5% of the variance in Driver Total Distance ± 7.86 m (Figure 7.8 and Table 7.9). This is less than half the (59.8%) variance but with less error (RMSE = 20.49 m) than explained by the same predictor set in the regression model in Study IV. Lead Shoulder Speed (peak angular velocity) and Lead Hand Speed, were the strongest body kinematic predictors. The importance of using these measures pertains largely to the summation

of force that occurs with the PDS of the golf swing (304). The low association between these two measures (evidenced by both being selected into the model) is an interesting finding in itself. Given that hand speed was the least important predictor in the model, it is possible that different swing styles produce different hand speeds and/or variation the timing of the transfer from the shoulders to the hands, and when peak hand speed occurs is more important than the actual peak itself (309). Whereas the peak lead shoulder value appears to be more universally important across this heterogenous sample.

GRF Peak Fz Lead Leg and GRF Peak Fy Rear Leg were the two GRF measures in this LMM, with the former a stronger predictor. These two measures can work in concert during the weight transfer from the rear foot to the lead foot which then drives the forces used in the PDS. This is explained in part by Ball and Best (2007) where the velocity of the medio-lateral COPy was noted as an important power source early in the down swing (84). However, from this point onwards in the golf swing, this medio-lateral force would then be utilised in a different manner dependent on the swing style of the golfer. Even with swing styles considered, the lead foot GRF plays a crucial role in generating GRF moment (rotational force) about the front-back axis in the golf swing (336). The four predictors in this LMM suggest that higher peak body speeds and GRF can be generally beneficial to Driver Total Distance, however, individual swing styles and swing event timings of peaks are worthy of further investigation.

7.5.9 Stage 2-3 P-GPC Relationships: Body Kinematics & GRF – Driver CHS

Lead (Peak) Shoulder Speed, GRF Peak Fz Lead Leg and GRF Peak Fx Rear Leg explained 28.8% of the variance in Driver CHS with ± 1.11 mph accuracy (Figure 7.9 and Table 7.10). Again, this LMM explained less (69.2%) variance but with lower error (RMSE = 6.58 mph) than the same predictor set in the regression model in Study IV. The benefit of Lead Shoulder Speed towards power generation has already been discussed above. The GRF predictors in this LMM are involved in the 'shift-rotate' move of the down swing. In highly-skilled golfers the shift towards the lead leg has been shown to occur prior to the peak rotational moment (336), creating what could be described as an 'anchor-point' for rotation. In fact, all three peak lead-foot GRFs (Fx, Fy and Fz) are significantly correlated to maximum CHS (336). GRF Peak Fx force produced by the rear leg is an important driver of pelvic rotation during the down swing (487), creating pelvic rotation with a pivoting moment against the anchored lead foot (336). This provides a mechanistic explanation for a previous studies finding for the importance of pelvis angular velocity reported with cross-sectional data (122). Pelvis angular velocity was able to discriminate between high (n = 18) and low handicap (*n* = 38) golfers with the latter group on average 120°/s faster.

This model includes a logical combination of GRF and body kinematic predictors for Driver CHS that act as important intermediatory measures for the transfer of physical training to increased Driver CHS.

7.5.10 Stage 1-3 P-GPC Relationships: Physical – Driver CHS

Sit Throw 3 kg, Rear Hand Grip Strength and Rear Hip Isometric Abduction Torque explained 57.8% of the variance in Driver CHS ± 1.69 mph (Figure 7.10 and Table 7.11). This LMM explained a similar amount of variance (66.3%) but with lower error (RMSE = 6.66 mph) than explained by the same predictor set in the regression model in Study IV. The importance of core strength and power for Sit Throw 3 kg was described in Study IV (page 257). Grip strength has demonstrated importance for Driver CHS in previous studies (176, 258, 383). From a mechanical viewpoint, it is plausible that grip strength would be important for handling the mass and inertia of the driver to enable high angular speeds of the lead shoulder. Core power and a good capacity for Rear Hip Isometric Abduction Torque would greatly enable to golfer to generate the summation of forces through the PDS in the golf swing, particularly during the medio-lateral weight transfer of the down swing (84, 336). The importance of hip abduction strength is consistent with EMG studies that show the importance of glute maximus and medius in the downswing (192, 211). Finally, GRF Peak Fy Rear Leg These three physical measures provide a varied blend of physical traits that enable the golfer to generate Driver CHS that are worthy of testing and training.

7.5.11 Stage 1-3 P-GPC Relationships: Physical – 120 m Shot Spin Rate

Sit Throw 3 kg (MB), SB Medial Reach Rear and Rear Hip Isometric Abduction Torque explained 48.5% of variance in Spin Rate ± 926 rpm (Figure 7.11 and Table 7.12). This LMM explained a larger amount of variance (38.0%) and with lower error (RMSE = 1387 rpm) than explained by the same predictor set in the regression model in Study IV. Similar to the Study IV regression model, these findings suggest that both core power, lateral hip strength and dynamic balance ability contribute to approach shot accuracy, particularly the ability to create spin to stop the ball close to the target. The principle of specificity would suggest that the rapid shoulder extension in the Sit Throw 3 kg test has mechanistic transfer with the descending blow required to create back spin with a short iron shot (531). Good functional ROM (as measured by SB test) and strength of the rear hip would provide the physical capacities that enable the golfer to make effectively load the rear leg in the backswing and to start to the downswing by leading with the hips – both of which are hallmarks of a good golf swing (84, 336, 518). Balance, using a simple stork test, has been used as a predictor of stroke score in a previous study (193).

However, as recommended by previous authors (8), this is the first study to successfully use the highly investigated Modified Star Excursion Balance Test (SB Medial Reach Rear) (464) and a test of core power to predict an important technical aspect of an approach shot. These results show good validity of this simple field test for balance for a wide age and ability range of golfers. However, future studies should look to concurrently assess body kinematics of an approach shot test to determine the associated body-related golf swing measures.

7.5.12 Stage 1-2 P-GPC Relationships: Physical – Driver Lead Shoulder Speed

Vertical CMJ and Reach and Thorax Seated Rotation to the Lead Side explained 11.1% of variance in Lead Shoulder Speed ± 35 °/s (Figure 7.12 and Table 7.13). This LMM explained less variance (48.0%) but with lower error (RMSE = 108 °/s) than explained by the same predictor set in the regression model in Study IV. In previous studies, Vertical CMJ and Reach has shown moderate strong associations with CHS (39, 176), Ball Speed (66), Distance (66) and an ability to discriminate high and low CHS groupings, even within a cohort of professional golfers (46). In relation to CHS, leg power estimation equations derived from vertical jumps seem to appear favourable to the raw score of jump height, as they have stronger correlation to CHS and factor in bodyweight of the athlete (176, 231). Leg power metrics also avoid the confounding effects of maturation or hypertrophy over time and allow athletes of different bodyweight to be compared (74, 176). However, the results of this study suggest that the 'power to weight' athletic ability of jumping itself has a different effect on swing biomechanics, as opposed to CHS. Therefore, if the player is in need of generating greater Lead Shoulder Speed, improving their Vertical Jump and Reach height appears to have some relevance. This finding has face validity, as the ability to generate segment rotational speed may well be a movement skill better executed by the athletic (not necessarily heavier) golfer. It is advantageous that Vertical Jump and Reach raw and estimated leg power scores can be calculated from the same test if bodyweight is known (231), as they appear to underpin different aspects of GP.

Thorax Seated Rotation to the Lead side appears to be an important physical capacity as better golfers tend to rotate further in the direction in the follow through of the golf swing (40). During the golf swing, trunk and lower trunk left and right axial rotation assists with shoulder movement to maximise CHS through segment summation (40, 191, 192) and may allow for an effective X-factor stretch in the downswing (136). However, this flexibility measure (in both directions) has previously shown small negative associations with CHS, and X-factor during the golf swing (180). The author of another study purported that is was likely the golfers analysed were still able to generate CHS without

increasing the ROM of thoracic rotation in their swing (45). Therefore, this is the first study that has shown a relationship between this flexibility measure and a biomechanical measure – although not one that necessarily relies on ROM. Instead, healthy ROM may be synonymous with a lack of inhibitory signals in the body segment, enabling good speed generation, aligning with the neuro-muscular view of flexibility for golf (140).

7.5.13 Limitations

A limitation of this study was the drop out of participants across repeat test days, although LMM considering each individual as a random effect addressed this confounding factor from a statistical standpoint. Lower test cases with GRF (due partly to lack of equipment on several test days) will have reduced the power of these measures within the LMM, although three GRF measures were still selected into models. Future research could consider grouping players for analysis by pre-defined swing styles, noted by Ball and Best 2007 and Han et al 2019 (84, 86), which could increase the chances of further body kinematic measures being selected into models. To do this effectively, GRF and body kinematic data should be measured at specific golf swing events, via simultaneous video recording or 3D systems that are accurately oriented to swing events. Finally, competition measures with greater sensitivity, such as strokes gained, are likely to be more informative than HCP as a dependent variable, for reasons discussed earlier in this thesis (page 82) and may therefore produce models with different predictors that relate more specifically to aspects on on-course play (i.e., Strokes gained from the tee). Further limitations that relate to specific tests within the combine were discussed in earlier chapters (page 165 and 259).

7.5.14 Practical Applications

Similar to the application of the regression models in Study IV, the strongest predictors identified within these LMM's can be used monitorable benchmarks to produce athlete profiles. However, the LMM's provide greater analytical robustness for longitudinal aspects of the physical, technical and competition performance. These LMM's draw data from multiple time points and reduce the potential for bias by factoring in the individual and their repeat measures. Therefore, the identified predictors in this study are more likely to have validity for longitudinal applications than regression models built from cross-sectional data. The LMM models were built from almost twice the number of observations as used in Study IV, which typically allowed for more predictors to fit within models. A greater array of predictors provides greater content validity for a predictive model. For these reasons the LMM models presented in this study can improve processes for talent identification and development by collecting multiple markers at

different time points. This adds validity to the practical applications mentioned in Study IV (page 260) such as forming athlete profiles to determine improvement potential and then quantifying the transfer of training from physical and technical interventions across time. This evidence-based feedback loop has multiple applications to enhancing GP across the golf participation pathway.

7.6 Conclusion

This study used LMM for longitudinal repeated measure data collected with a comprehensive combine from a large heterogenous sample over an average period of 19 weeks. These design features have addressed many of the gaps that were apparent in the GP literature. There is immediate practical utility for the identified measures that span the P-GPC which directly inform the multi-disciplinary team in golf. Athlete profiling for golfers assisted by LMM's can form the basis of a feedback loop between members of the multi-disciplinary team and golfer. This feedback can be used to identify needs, potential for improvement, and then quantify the training transfer of physical and technical interventions over time.

Chapter 8: Summary and conclusions

8.1 Overview

Since the early 1990's, national golfing bodies worldwide have increased efforts to form systematic development programs to nurture talent and foster participation (23, 426, 532). In Australia, declining participation, barriers to evidence-based practice and industry fragmentation dictate that more work is needed from a physical and technical development perspective (2, 264). For example, there are many cases where amateur golfers reached national level competition despite being poorly trained physically (55, 216). Given the dynamic nature of interactions between the golfer's body, the environment and task constraints of their sport, rectifying the poor attention to physical training presents an opportunity to enhance golf skill development (212, 237, 533). This dynamic interplay between physical, technical and competition traits continues past maturation and into the ageing process of the golfer (117). Given the age profile of Australian golfers, informed interventions are also needed to assist older golfers' participation longevity, to maximise the community benefits from golf (2, 431). Therefore, a thorough understanding of golfers' physical and technical needs is required to foster talent development and participation longevity.

8.2 Summary and conclusions

The primary objective of this doctoral investigation was to determine the most important relationships between physical, technical and competition performance measures in competitive Australian male golfers. A secondary aim was to explore how these relationships vary with ability. This was addressed with multiple research designs and analytical approaches. A narrative review and a mapping review of the literature were conducted to determine the prevalence of peer-reviewed investigation with GP testing. This analysis was presented by GP parameter for various golfing cohorts (i.e., gender, age and ability) and ensured the content validity of the P-GPC. The P-GPC is a continuum developed to assist the formation of a comprehensive combine for golf and interpretation of the results of the subsequent studies. The combine was used to assess a large heterogenous sample of Australian male golfers, on two occasions, in parameters that span the P-GPC. Results from the combine were analysed to compare group differences. Next, multiple linear regression using cross-sectional and longitudinal data to identify important measures for GP. These findings inform a multi-disciplinary approach to development.

8.2.1 Study I

'A mapping review of the GP testing literature'

Study I provided a mapping review of the peer-reviewed GP testing literature, identifying strengths and gaps for the multi-disciplinary approach to golf development. Four ability cohorts were determined from HCP data and descriptions provided in the literature. Data extracted for analysis in the areas of research design, participant characteristics, as well as technical, physical and competition measures. The analysis provided guidance for a checklist of parameters for each stage of the P-GPC to be considered for assessing golfers, thereby ensuring content validity of future combines. The P-GPC extends on Smith's (2010) model because it a) provides a temporal organisation of mechanisms that contribute to GP, indicating inter-parameter relationships that require investigation, b) provides the tester with a checklist of parameters from each stage of the P-GPC, to assist comprehensive combine formation, c) provides a list of end-user practitioners involved in the multi-disciplinary approach at each stage of the P-GPC. In summary, male 18-49 golfers were more highly investigated than juniors, females and older golfers; technical parameters were more prevalent than physical parameters, but many studies assessed both. This study provides the reader with a 'quick-view' of the GP testing research by parameter and cohort and justification for the inclusions in the P-GPC.

8.2.2 Study II

'Formation of comprehensive golf combine to inform GP'

GP is influenced by the sequential mechanistic contributions of physical and technical parameters. The interplay of these mechanisms can be described by the P-GPC. Therefore, understanding GP can be facilitated through a comprehensive golf combine (i.e., collection of tests that cover parameters from each stage of the P-GPC) that incorporates tests of physical, technical and competition parameters. To ensure an effective combine is formed, the reliability, validity and sensitivity of each test can be sourced from the literature. Combine results can provide profiles of the athlete's strengths and weaknesses relative to benchmarks or existing data sets, informing physical and technical training programs. In this study, 25 tests with established measurement properties were selected to examine parameters from all stages of the P-GPC. This evidence-based golf combine was utilised in Study III, IV and V to investigate better methods for developing cohort-specific combines, golf-athlete profiling, talent identification and development, and the quantification of training transfer.

8.2.3 Study III

'Physical and technical traits of Australian male golfers'

The combine developed in Study III was utilised to investigate a large (*N* = 122) heterogenous sample of Australian male golfers. Visualisation of the estimated mean for the sample was provided. ES using Cohen's *d* quantify the mean differences for combine continuous measures across four ability cohorts (HCP = Elite: -6 – 0.4, Low-HCP: 0.5 – 7.4, Mid-HCP: 7.5 – 17.4, High-HCP:17.5 – 36). Measures of central tendency, including median and interquartile range for these measures are also reported relative to HCP as a continuous measure. Mostly large ES were seen across all ability levels for P-GPC tests of golf skill and distance measures, including total driver distance (*d* = 0.96 – 1.53), 120 m shot distance to target (*d* = -0.75 – -1.34). Large differences across all four ability levels were found in club and ball kinematic measures, including Driver CHS (*d* = 0.89 – 1.08) and 120 m Shot Spin Rate (*d* = 0.87 – 1.07). Physical measures showed typically smaller ES, although many medium-to-large ES were present between ability cohorts. Medicine Ball Lateral Throw was the only physical measure to show a large difference (*d* = 0.84) between Elite and Low-HCP golfers. The findings indicate the most important physical and technical traits across the P-GPC; refining the tests needed for profiling and intervention purposes for each golf cohort.

8.2.4 Study IV

'Explaining the mechanisms of golf performance'

The physical and technical capacities of golfers integrate to produce competition performance viewed along a continuum. Improving the understanding of the 5-Stage P-GPC will enhance the effectiveness of testing and training golfers. The cross-sectional (i.e., first test day) data set collected in Study IV was utilised for multiple linear regression analysis to explore the mechanisms of GP. Regression models were built in reverse order of the P-GPC to establish the strongest predictors between each stage of the continuum and the preceding stage (i.e., Stage 4–5, Stage 3–5, Stage 3–4, Stage 2–4 etc.). The strongest predictors for each given P-GPC Stage were used as the dependent variable for the preceding regression models. Two pathways for analyses through the P-GPC were created from the Stages 3 and 4 testing combine, one for the 120 m Target Shot and one for the Maximum Driver Shot. The stage of the P-GPC, dependent variable and strongest standardized predictors (respectively) were: Stage 5) Handicap – Driver Total Distance and Driver CHS, Stage 4) Driver Total Distance – Ball Speed, Club Head Speed and Lead Shoulder Speed, Stage 4) 120 m Distance to Target – Spin Rate, Stage 3) Driver Club Head Speed – Lead Shoulder Speed and Sit Throw 3 kg, Stage 3) 120 m

Spin Rate – Sit Throw 3 kg, Stage 2) Driver Lead Shoulder Speed – Lateral Jump Relative to Leg Length. These regression models and predictors can be used for initial athlete profiling to guide physical and technical interventions and talent identification.

8.2.5 Study V

'Explaining the mechanisms of golf performance longitudinally'

Study V used the combine formed in Study II to collect comprehensive longitudinal data on golfers from between one and four test days, with a mean of 19 weeks between the first and last tests. 12 linear mixed models were built with the same predictor sets and dependent variables used for Study IV regression models, with each individual golfer considered a random effect. The stage of the P-GPC, dependent variable and strongest standardized predictors (respectively) were: Stage 5) Handicap – Driver Total Distance and Driver CHS, Stage 4) Driver Total Distance – Ball Speed, Club Head Speed and Lead Shoulder Speed, Stage 4) 120 m Distance to Target – Spin Rate and Dynamic Loft, Stage 3) Driver Club Head Speed – Ground Reaction Force Peak Fz Lead Foot and Sit Throw 3 kg, Stage 3) 120 m Spin Rate – Sit Throw 3 kg, Stage 2) Driver Lead Shoulder Speed – Vertical Jump and Reach. These measures and LMM's have utility for longitudinal athlete profiling and quantifying the transfer of training. This could be achieved by inputting test scores into models for an individual player and determining whether they are above or below their predicted score by the model – thereby highlighting the performance 'breakdown' for the golfer. In this way, these findings from repeated measures can improve the processes of talent identification and development – which previously had to rely on findings cross-sectional data in the GP literature.

8.3 Practical implications of the research

A focus of this doctoral investigation was to inform multidisciplinary teams in golf. Various practitioners who provide aspects of golf development to the golfer benefit from understanding how their service or intervention integrates with the team approach. In relation to the ARMSS model, the studies are situated in stages 3 – 5. Therefore, they are translational with their outputs to the field but also, importantly set the scene for improving the effectiveness and efficacy of the future interventional studies. This was achieved in a number of ways:

- Study I, in addition to the Chapter 2 literature review, determined the checklist within the 5 stage P-GPC. The P-GPC is a temporal summary of the mechanisms of transfer from Stage 1 Physical traits to Stage 5 competition performance.

Parameter gaps in the GP research were also identified for specific ability cohorts and gender to be targeted in future research.

- Study II used the P-GPC to guide the scope of tests required to form a comprehensive combine for golfers. Rigor in test selection was exemplified by assessing the measurement properties of existing tests within the peer-reviewed literature. The P-GPC also guides the practical application of findings from the combine for members of the multi-disciplinary team.
- Study III identified the physical and technical traits with the largest group mean differences between ability levels. These traits are likely to be worthy of targeting in physical and technical training interventions. The measures of central tendency for measures can be used for benchmarks within athlete profiles to individualise interventions for golfers. The tests that discriminate between particular ability levels are also worthy of inclusion for combines to suit specific golf ability cohorts (e.g., aspiring Low-HCP golf squads).
- Study IV identified the strongest relationships between measures within eleven regression models that span the P-GPC. The regression equations have utility for determining the level to which an individual player's physical and technical priorities are transferring to golf performance, based on modelling from group data.
- Study V confirmed the strongest relationships between measures within twelve linear mixed models that span the P-GPC. These models constitute an additional level of scientific rigor by factoring in time and individual ability level as random effects with longitudinal data. This was an important extension to the existing regression modelling in the GP literature which has only been based on cross-sectional data, making assumptions that these measures remain important to golfers over time. The dependent variables and predictors from these models can be used to assess the transfer of training over time.

Combining the results from Study III, IV and V it is possible to create refined comprehensive combines by removing tests with small or trivial ES (relative to the adjacent ability cohort) or that were not selected as dependent variables or predictors in models (Table 8.1). A suggested application by this author is to consider an 'Express' (the most reduced) combine that only includes predictors and dependent variables included in models, with a 'Full' combine also including additional measures with ES > ±0.5 and CI95 widths that do not stretch beyond ES < ±0.2. The ES vary across ability cohort comparisons and therefore variations for combines are indicated for each ability cohort in (Table 8.1). For example, taking this approach, the 'Express' combine for Elite and Low-HCP golfers is reduced from 25 to only 11 tests, enhancing combine feasibility.

Table 8.1 Refined comprehensive golf combine options for each ability cohort.

Test Measures	Elite (HCP: < 0.5)					Low-HCP (HCP: 0.5 - 7.4)					Mid-HCP (HCP: 7.5 - 17.4)					High-HCP (HCP: > 17.4)				
	ES	DV	RM	LMM	Combine	ES	DV	RM	LMM	Combine	ES	DV	RM	LMM	Combine	ES	DV	RM	LMM	Combine
Physical Tests																				
L thorax seated rotation	X	X	X	✓	Express	✓	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
L shoulder external rotation	X	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express
L Hip internal rotation	X	X	✓	X	Express	X	X	✓	X	Express	✓	X	✓	X	Express	X	X	✓	X	Express
R SB medial reach	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
R grip strength	X	X	✓	X	Express	X	X	✓	X	Express	✓	X	✓	X	Express	X	X	✓	X	Express
R hip isometric abduction torque	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	✓	X	X	✓	Express
Sit throw 3 kg	✓	X	✓	✓	Express	✓	X	✓	✓	Express	✓	X	✓	✓	Express	X	X	✓	✓	Express
Vertical CMJ reach	✓	X	✓	✓	Express	✓	X	✓	✓	Express	X	X	✓	✓	Express	X	X	✓	✓	Express
L lateral jump /leg length	X	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express
Chest pass 3 kg	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	Full	X	X	X	X	X
Lateral throw 3 kg	✓	X	X	X	Full	✓	X	X	X	Full	X	X	X	X	X	X	X	X	X	X
Maximum Driver Test: Body Kinematic & GRF Measures																				
L shoulder peak speed	X	✓	✓	✓	Express	X	✓	✓	✓	Express	X	✓	✓	✓	Express	X	✓	✓	✓	Express
R GRFpeak Fx	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
R GRFpeak Fy	X	X	✓	✓	Express	X	X	✓	✓	Express	X	X	✓	✓	Express	X	X	✓	✓	Express
L GRFpeak Fz	X	X	✓	✓	Express	X	X	✓	✓	Express	X	X	✓	✓	Express	X	X	✓	✓	Express
L hand peak speed	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
R GRFpeak Fz	✓	X	X	X	Full	✓	X	X	X	Full	X	X	X	X	X	X	X	X	X	X
Maximum Driver Test: Club Measures																				
CHS	✓	✓	✓	✓	Express	✓	✓	✓	✓	Express	✓	✓	✓	✓	Express	✓	✓	✓	✓	Express
Launch angle	X	X	✓		Express	X	X	✓		Express	X	X	✓		Express	X	X	✓		Express
Smash factor	X	X	✓	✓	Express	X	X	✓	✓	Express	X	X	✓	✓	Express	✓	X	✓	✓	Express
Face to path	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
Face angle	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
Attack angle	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	✓	X	X	✓	Express
CHS/armspan	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	Full	✓	X	X	X	Full
CHS/height	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	Full
Maximum Driver Test: Ball Measures																				
Ball speed (+)	✓	X	✓	✓	Express	✓	X	✓	✓	Express	✓	X	✓	✓	Express	✓	X	✓	✓	Express
Spin rate (-)	X	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express
Land ball speed (-)	✓	X	✓	X	Express	✓	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express
Land angle (-)	X	X	✓	X	Express	X	X	✓	X	Express	✓	X	✓	X	Express	X	X	✓	X	Express
Launch direction	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
Carry time	X	X	X	✓	Express	X	X	X	✓	Express	✓	X	X	✓	Express	X	X	X	✓	Express
Max height	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	Full	X	X	X	X	X
Max height distance	✓	X	X	X	Full	✓	X	X	X	Full	✓	X	X	X	Full	✓	X	X	X	Full
Carry length	✓	X	X	X	Full	✓	X	X	X	Full	✓	X	X	X	Full	✓	X	X	X	Full
120 m Target Shot Test: Club Measures																				
Attack angle	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
Dynamic loft	X	X	✓	✓	Express	X	X	✓	✓	Express	✓	X	✓	✓	Express	✓	X	✓	✓	Express
Low point	X	X	✓	✓	Express	X	X	✓	✓	Express	X	X	✓	✓	Express	X	X	✓	✓	Express
Face to path	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
Face angle	X	X	✓	✓	Express	X	X	✓	✓	Express	X	X	✓	✓	Express	X	X	✓	✓	Express
CHS	✓	X	X	✓	Express	✓	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
Club path	X	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express
120 m Target Shot Test Ball Measures																				
Spin rate	✓	✓	✓	✓	Express	✓	✓	✓	✓	Express	✓	✓	✓	✓	Express	✓	✓	✓	✓	Express
Ball speed (-)	X	X	X	X	Express	X	X	X	X	Express	X	X	X	X	Express	X	X	X	X	Express
Land ball speed (-)	X	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express	X	X	✓	X	Express
Spin axis	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express
Launch angle	X	X	X	✓	Express	X	X	X	✓	Express	X	X	X	✓	Express	✓	X	X	✓	Express
Land angle	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	Full
Max height	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	Full
Carry time	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	Full
Max height distance	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	Full
Carry length	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	Full
Maximum Driver & 120 m Target Test Outcome Measures & Handicap																				
Driver total distance	✓	✓	✓	✓	Express	✓	✓	✓	✓	Express	✓	✓	✓	✓	Express	✓	✓	✓	✓	Express
120 m distance to target	X	✓	✓	✓	Express	X	✓	✓	✓	Express	X	✓	✓	✓	Express	✓	✓	✓	✓	Express
Handicap	✓	✓	X	X	Express	✓	✓	X	X	Express	✓	✓	X	X	Express	✓	✓	X	X	Express

ES, effect size > ±0.5 & CI95 > ±0.2 (non-trivial) for Elite & Low-HCP relative to each other, Mid & High-HCP relative to adjacent higher ability cohort from Study III. RM,

predictor in Study IV regression models. LMM, predictor in Study V Linear mixed models. DV, dependent variable for RM and LMM. 'Express' combine includes only predictors and DV for RM & LMM. 'Full' combine includes additional 'ES' tests.

Much of the GP literature intimates the importance of measures included in the combine used across these doctoral studies. For example, many studies have had the primary focus of analysing the effectiveness of S&C interventions to improve measures such as CHS. The underlying assumption of these, and other GP studies, is that improving CHS, or similar GP related measures, does in fact lead to improvement in competition performance. However, cross-sectional data cannot infer relationships across time, and interventional studies are primarily focused on assessing the merits of their interventions. Therefore, the discussion of the temporal associations between GP measures are often *assumed* rather than *quantified* in the golf literature. Quantifying the relationships between measures with LMM using repeated measures provides an important additional layer of evidence that a given measure requires improvement over time for the golfer. Ultimately, the multiple analyses of each measure within the comprehensive combine provides a guide for simplified, cohort-specific combines for future testers. Outputs of such combines can create athlete profiles for individualised physical and technical interventions to improve GP over time with perpetual feedback loops.

8.4 Limitations of the doctoral investigation

The proposed P-GPC provides a comprehensive checklist for each of the 5 mechanistic stages of GP. As the framework for this thesis, the P-GPC only focuses on physical, technical and competition performance measures. Additional performance mediators can also influence GP and are listed in the *P-GPC & Performance Mediators* framework provided in Chapter 1 (page 126). These were considered outside the scope of this doctoral investigation. This broader model includes checklists from the domains of health management, recovery and fuel and psychology. Indeed, within each stage of the P-GPC there are temporally sensitive inter-relationships between measures that have been proven worthy of their own investigation (e.g., the influence of club kinematics on ball kinematics (82)). Hence these different categories of measures could form their own distinct Stage. However, these distinctions between measures can be made at all Stages of the P-GPC. Perhaps most importantly, each Stage focuses on a different golf development discipline – within the scope of practice of a given set of practitioners (i.e., S&C coach, golf coach etc.). Therefore, rather than creating endless distinct stages of the continuum, the P-GPC can support an integrated multi-disciplinary approach in data collection, analysis and dissemination amongst the team. Larger, more diverse practitioner teams may require the additional performance mediators provided within the

GP Continuum, presented in Chapter 1. This broader version of the continuum incorporates the additional broad domains of psychology, nutrition and injury management. The P-GPC and GP Continuum provide a guide to testing and the team approach for golf development programs.

Several considerations for GP testing were discussed in the literature review that were mentioned as limitations within each relevant chapter. It is important to recognise confounding factors in any research as they can influence results without being quantified. Different swing effective styles have been identified in previous studies, defined by 3D biomechanical (86) and GRF differences (84, 276). These inherent differences coupled with functional movement variability (87) between swings, can introduce error into golf swing measurements. Although these factors were not quantified within Studies 5 to 7, they were considered within the interpretation of results. Future research could also quantify the relationships of body kinematics (using a 3D system with a larger number of sensors than the K-Vest™ used in this study) and GRF at specific swing events with other measures in the continuum – particularly as the GRF measures exhibited typically lower cases (due to equipment availability) in this investigation. Although the combine used in this doctoral investigation was the more comprehensive (in number of tests and parameters investigated) than any other combine that appears in the literature, many other parameters and tests still warrant further investigation in a similar manner to this study.

Regarding participants, retaining greater numbers for the repeat test days in Study V would have been advantageous, although LMM does handle this methodological weakness by factoring in each individual as a random effect. Finally, there has been limited research on female golfers, compared with their male counterparts, as highlighted in Study I. This study only focussed on male golfers due to access to participants. Due to the physical and technical differences between the genders in golf, the results of these studies cannot be generalised to female cohorts (115, 172). Factoring the abovementioned limitations for future research methodologies will serve to strengthen future findings and the evidence-base for improving GP.

8.5 Future directions for research and practice

Future research is needed that explores the relationships between the additional performance mediators, from the domains of health management, recovery and fuel and psychology, that influence GP and the parameters within the stages of the P-GPC. Findings from this research would serve to build the evidence-base for the practitioners specific to these disciplines (e.g., medical practitioners) in the same manner that the

benchmarks and models from this investigation inform S&C and golf coaches. These mediators may indeed explain some of the variance not explained by the models in this current study. Similarly, relationships between parameters of the same stage within the P-GPC were not investigated in this study and could provide further evidence to base physical, technical and competition interventions upon. For example, understanding the relationships between stage 2 GRF and body kinematics, or competition statistics and tournament position across a season would be useful additions to the GP literature. As with any models, further validation of the regression or LMM models constructed in Study IV and V with future golf cohorts to replicate findings is warranted. Larger samples, different cohorts and golfers from different regions would provide greater certainty as to the value of the predictors sets and predictive ability of models identified in this doctoral investigation.

Studies I-V have defined and addressed many of the research priorities within stages 1 to 5 of Bishop's (2008) ARMSS, related to the GP research (51). Therefore, future longitudinal and interventional studies will benefit from the findings in this thesis. Future research can better target specific cohorts and their unique physical and technical needs. For example, Study I identified many cohort-parameter gaps in research for female golfers. Golf research with large heterogenous samples, using repeated measures over longer durations, is more representative of real-world athlete development. These research designs are more likely to lead to ecologically valid findings in sport and were a strength of this investigation. Therefore, any research designs or methods used in this thesis would benefit the female cohort, and many novel findings would be expected.

Appendix A: GOLF COMBINE TEST PROTOCOLS

A.1 Golf combine protocols

This appendix includes a detailed explanation of each testing protocol used in the golf test combine. The tests are grouped and ordered by performance parameter-category as follows: anthropometry, flexibility, balance, strength, power, endurance, technical (hitting bay).

The combine included 25 tests, with a total ~ 156 measurements per golfer, collected during a two and a half hour testing session. All tests were conducted in a climate controlled indoor biomechanics laboratory. All measurements were recorded as absolute scores. Subsequently, additional relative metrics such as torque kg/m and relative to % bodyweight /kg/m/kg were calculated to be considered in analysis.

Each physical test was administered by an accredited exercise scientist. At each physical testing station participants were provided with a demonstration and a standardised warm-up was used prior to the jump station for consistency and safety purposes. For physical tests, each participant was allowed one practice attempt on each test, for familiarisation, and then performed three trials for physical tests and four trials for technical tests. The best performing trial was recorded for analysis (39, 147).

Participants undertook two tests of technical skill, a 120 m approach shot accuracy test and a driver shot for maximum distance with accuracy. The technical tests were administered by an experienced PGA professional with a constructed hitting bay in the same indoor biomechanics laboratory. A standardised warm-up was utilised prior to the hitting bay tests for consistency and safety. The participant was given four attempts at each test of skill.

A.2 Anthropometry

A.2.1 Height

With shoes removed, feet were flat on the base of a *Seca 213 portable stadiometer*, participant was instructed to stretch up tall.

Measures: height cm

Derived metrics: CHS relative to height mph/cm

A.2.2 Weight

Shoes were removed but participants remained fully clothed as clothing remained the same throughout the full testing battery in the climate-controlled laboratory. Weight was recorded in kilograms using *Seca 719 column scales*, accurate to ± 0.2 kilograms.

Measures: weight kg

Derived metrics: CHS relative to weight mph/kg, all Isometric torque measures relative to weight kg/m/kg, estimated peak leg power W (from vertical CMJ and reach), lateral jump relative to weight cm/kg

A.2.3 Arm span

A tape measure was affixed to the wall using a spirit level. The participants arm span was measured from the fingertips outstretched parallel to the measuring tape.

Measures: arm span cm

Derived metrics: CHS relative to arm span cm

A.2.4 Femur length

A tape measure was used to quantify the length from the apex of greater trochanter to the superior margin of lateral joint line of the knee. These measurements were entered into the Kanga-tech™ software to automatically calculate torque values for strength tests where the electronic dynamometer was placed at the joint line of the knee.

Measures: None reported

Derived metrics: Isometric torque measures (hip adduction and abduction) relative to leg length kg/m

A.2.5 Tibial length

A tape measure was used to quantify the length from the apex of the greater trochanter to the superior margin of lateral joint line of the knee. These measurements were entered into the Kanga-tech™ software to automatically calculate torque values for strength tests where the electronic dynamometer was placed at the ankle.

Measures: None reported

Derived metrics: Isometric torque measures (hip external rotation) relative to leg length kg/m

A.2.6 Full leg length

A tape measure was used to quantify the length from the apex of the greater trochanter to the apex of the lateral malleolus.

Measures: None reported

Derived metrics: Lateral jump distance m/m and MSEBT reach distances m/m and Isometric torque measures relative to leg length kg/m/m.

A.2.7 Arm length

A tape measure was used to quantify the length from the clavicular notch on acromion process to radial condyle. These measurements were entered into the Kanga-tech™ software.

Measures: None reported

Derived metrics: Trunk rotation torque kg/m

A.3 Flexibility

A.3.1 Sit and reach

Lower back flexibility was measured using the validated sit-and-reach method (534). The participants were instructed to be seated in front of the sit-and-reach box with their legs straight and with their heels touching the assigned border on the box. The participants then inhaled. Slowly exhaling, they had to reach forward with their arms straight one hand on top of the other, gradually pushing the small box as far as they could without bending their knees. Once they reached their maximal stretching point, they had to hold that position for approximately three seconds.

Measures: Sit and reach distance cm

Derived metrics: Nil

A.3.2 Seated thoraco-lumbar rotation test

The protocols were taken from previous publications (11, 535). The participants sat in a chair with the feet stabilised on the floor and knees stabilised against the wall or a wooden box. The participant then held a stick (1.5 m dowel rod) pressed flat against the shoulders of the participant – also gave the tester a visual line with which to align the goniometer. The participant is told to “sit tall and rotate smoothly as far as they can and

then hold that position for three seconds" allowing the tester to measure the position. The golfer rotated towards the rear side (back swing) first, followed by the lead side (follow-through). This goniometer alignment was as follows (Goniometers with a level attached to the proximal arm are helpful for novices): Centre fulcrum/proximal arm of the goniometer in line with the initial stick position, then move the distal arm to match the final position of the stick to gain the angular ROM of the movement.

Measures: Bilateral – thoracic rotation ROM°

Derived metrics: Nil

A.3.3 Seated hip internal rotation

The protocols were taken from Norkin & White (2016) (536). The participant was seated on a firm surface with the knees flexed to 90 degrees over the edge of the surface. The participant's hip is placed at zero degrees of adduction and abduction and 90 degrees of flexion. A rolled-up towel can be used under the femur if needed to achieve 90 degrees of hip flexion. Place one hand at the distal femur to provide stabilisation and use the other hand at the distal tibia to move the lower leg laterally. The hand performing the motion also holds the lower leg in a neutral position to prevent rotation of the tibia on the femur. The end of the ROM occurs when resistance is felt and attempts at further motion cause lateral tilting (elevation or hiking) or rotations of the pelvis or lateral flexion of the trunk. If the individual reports discomfort in the knee joint during testing, then do not put forces across the knee joint but rather passively medially rotate the hip by moving the distal end of the femur. This goniometer alignment was as follows (Goniometers with a level attached to the proximal arm are helpful for novices): Centre fulcrum of the goniometer over the anterior aspect of the patella; Align proximal arm so that it is perpendicular to the floor or parallel to the supporting surface; Align distal arm with the anterior midline of the lower leg, using the crest of the tibia and a point midway between the two malleoli for reference.

Measures: Bilateral – hip internal rotation ROM°

Derived metrics: Nil

A.3.4 Seated hip external rotation

The protocols were taken from Norkin & White (2016) (536). Participant is seated on a firm surface with the knees flexed to 90 degrees over the edge of the surface. Hip is placed if zero degrees of adduction and abduction and 90 degrees of flexion. A rolled-up towel can be used under the femur if needed to achieve 90 degrees of hip flexion.

Place one hand at the distal femur to provide stabilisation and use the other hand at the distal tibia to move the lower leg medially. The hand performing the motion also holds the lower leg in a neutral position to prevent rotation of the tibia on the femur. The end of the ROM occurs when resistance is felt and attempts at further motion cause lateral tilting (depression or dropping) or rotations of the pelvis or lateral flexion of the trunk. If the individual reports discomfort in the knee joint during testing, then do not put forces across the knee joint but rather passively medially rotate the hip by moving the distal end of the femur. This goniometer alignment was the same as for seated hip internal rotation.

Measures: Bilateral – hip external rotation ROM°

Derived metrics: Nil

A.3.5 Modified Thomas test

The protocols were taken from Norkin & White (2016) (536). Place the individual in the sitting position at the end of the examining table, with the lower thighs, knees, and legs off the table. Assist the individual into the supine position by supporting the back and flexing the hips and knees. This sequence is used to avoid placing strain on the individual's lower back. Once supine, flex the hips by bringing the knees toward the chest just enough to flatten the low back and pelvis against the table. In this position, the pelvis is in about 10° of posterior pelvic tilt. Either the examiner or the individual holds the hip not being tested in flexion (knee toward the chest) to maintain the low back and pelvis flat against the examining table. If the individual cannot reach the thigh, then a towel or sheet placed behind the knee can be used to hold the thigh in flexion. Passively extend the hip being tested by slowly lowering the thigh toward the examining table. Be sure the lower extremity remains in the sagittal plane by keeping the hip from rotating, abducting, or adducting. The examiner confirms that the thigh and lower leg are relaxed and not being actively held in flexion. Often individuals require extra cues to relax the muscles in the limb being tested. This goniometer alignment was as follows: Centre fulcrum of the goniometer over the lateral aspect of the hip joint, using the greater trochanter of the femur for reference; Align proximal arm with the lateral midline of the pelvis; Align distal arm with the lateral midline of the femur, using the lateral epicondyle for reference. Measure the angle between the greater trochanter of the femur and the mid-point of the lateral epicondyle of the femur.

Measures: Bilateral – hip extension ROM°

Derived metrics: Nil

A.3.6 Shoulder complex supine external (lateral) rotation

Protocols from Norkin & White (2016) (537). Position the individual supine, with the arm being tested in 90° of shoulder abduction. Place the forearm perpendicular to the supporting surface and in 0° of supination and pronation so that the palm of the hand faces the feet. Rest the full length of the humerus on the examining table. The elbow is not supported by the examining table. Place a pad under the humerus so that the humerus is level with the acromion process. Rotate the shoulder laterally by moving the forearm posteriorly, bringing the dorsal surface of the palm of the hand toward the floor. Maintain the shoulder in 90° of abduction and the elbow in 90° of flexion during the motion. The end of ROM occurs when resistance to further motion is felt and attempts to overcome the resistance cause extension or rotation of the spine. This goniometer alignment is used for measuring glenohumeral and shoulder complex lateral rotation: Centre fulcrum of the goniometer over the olecranon process; Align proximal arm so that it is either parallel to or perpendicular to the floor; Align distal arm with the ulna, using the olecranon process and ulnar styloid for reference.

Measures: Bilateral – shoulder external rotation ROM°

Derived metrics: Nil

A.4 Balance

A.4.1 The Modified Star Excursion Balance Test (mSEBT)

The protocols were taken from Lockie et al 2015 (204) and Gribble and Hertel 2003 (203). This collection of tests can assess dynamic stability using functional reaching of the lower limbs and has been shown to be valid and reliable (Gribble, 2003; Hertel et al., 2000). This test will involve a participant assuming a unilateral stance and performing and performing the posteromedial, medial, and anteromedial excursions on a commercially available purpose-built mat. Prior to beginning the test leg length is to be measured. Leg length was measured on each limb with participants lying supine. A tape measure was used to quantify the distance from the anterior superior iliac spine to the centre of the ipsilateral medial malleolus. Participants are to be barefoot and stand on the centre marker of the mSEBT (truncated to 'SB' in the results sections), with the ankle malleoli aligned with the desired angle lines, which is visually assessed by the researcher. Participants then use their free leg to reach in the afore-mentioned order. With each attempt, the participant attempts to reach as far as possible along each line and make a light touch on the ground with the most distal part of the reaching leg. The participant then returned the reaching leg to a bilateral stance, without allowing contact

to affect overall balance. The researcher notes the reach distance after the first successful attempt on each position for each leg. Participants place their hands on their hips during the mSEBT and are required to keep them there throughout all reach attempts. A trial is disregarded if the researcher feels the participant used the reaching leg for an extended period of support, removed the stance leg from the centre of the grid, removed their hands from their hips, or was unable to maintain balance. A minimum of three practice trials are to be used prior to data collection to familiarize participants to the movements required, and to serve as a warm-up. This will can be done whilst participants are waiting on a second available mat. The following order of the stance leg used during testing was maintained across participants: postero-medial (reaching leg moves behind the body at a 45° angle); medial (reaching leg moves behind the body at a 90° angle); antero-medial (reaching leg moves in front of the body at a 45° angle). Reach distances were considered relative to leg length and expressed as a percentage according to the formula relative reach distance = reach distance/leg length x 100 (203, 204).

Measures: Bilateral – anterior-medial reach distance cm, medial reach distance cm, posterior-medial reach distance cm

Derived metrics: Bilateral – sum scores of 3 measures m, reach distance relative to leg length m/m, sum scores of 3 measures relative to leg length m/m

A.5 Endurance

A.5.1 YMCA 3-minute step test

The Young Men's Christian Association (YMCA) step test was selected as a measure of cardio-vascular fitness for our broad sample which included juniors, elites and seniors, due to its relatively low step height (30.5 cm), compared to step heights used in other step tests (41.3–50.8 cm). Previous studies have developed equations that estimate maximum oxygen intake by using the YMCA step test (484, 538). An adaptation of previous protocols was used to ensure accuracy of results (538, 539). Equipment required: 30.5 cm (12 inch) steps; Metronome set to cadence of 96 BPM (24 step-ups per minute); Finger pulse reading devices.

Prior to starting the test, demonstrate to the applicant how to perform the test by stepping up and down on the step keeping in time with the beat of the metronome. The applicant can lead with either foot and is allowed to change the leading leg during testing but MUST stay in time with the metronome. The stepping must be UP / UP / DOWN / DOWN. Participants should not be holding on to a railing or wall during the test.

Conduct testing: Have the applicant start testing at the same time as starting the stopwatch or electronic clock. Watch for uneven weight bearing between left / right legs, use of hands on thighs for support, forward flexed posture, signs of fatigue etc. If the applicant deviates from the beat, instruct them a few times but if they keep slowing down due to fatigue, cease testing. During testing check the HR at least three times (you may ask the applicant to tell you, you may just look at the watch, but inform them that you need the HR and not to stop or slow down). At the end of the three minutes have the applicant sit down, rest for 45 s. During this 45 s place a finger pulse measurement device on the participants and determine the pulse exactly at the 45 s mark (as this has been most accurately linked to Vo_2 Max (538)) and record this score. If the applicant is unable to complete testing (self-determined or clinician instructed) record: did not complete.

Measures: Recovery heart rate 45 s after completion of test

Derived metrics: Nil

A.6 Strength

A.6.1 Grip strength

Protocols taken from Hughes, Lyons & Mayo (2004) (540). Left and right-hand grip strength will be assessed using a *TTM Original Hand-Held Dynamometer, Japan*. Subjects were familiarised with the dynamometer and adjusted so that the middle phalanx of the third digit rested comfortably and squarely on the distal aspect of the gripping apparatus while the heel of the palm rested squarely on the proximal aspect of the dynamometer. The participant's elbow was by their side and flexed at 90 degrees and wrist flexed between 0 and 30 degrees. The participant was asked to give a maximal effort for three seconds on each trial, measured by electronic clock. Both hands were tested three times, allowing at least a 60 s rest between trials.

Measures: Bilateral – Grip strength (peak force) kg

Derived metrics: Nil

A.6.2 Kanga-tech^{TM} isometric strength testing

Four isometric strength tests were selected based on previous research by Sell et al (2007) (11). These tests were conducted using a commercially available unit that has been utilised in several professional sports. The unit consists of an adjustable frame, mat and 4 position-adjustable electronic dynamometers connected to a touch-screen tablet

with tailored software. This unit was utilised to undertake the isometric strength tests based on the manufacturers test protocols. Each test required the participant to position themselves in a standardized manner to isolate the specific target muscle group and then take two attempts at isometrically squeezing the electronic dynamometers as hard as they can for 5 seconds. Having the participant watch the output graph on the tablet was important as it provided augmented feedback for maximal effort on each test.

Prior to undertaking the tests, the participants leg and arm lengths were measured with a measuring tape to accurately calculate torque Nm exerted in each test. These were entered into the Kanga-tech tm software for each participant prior to the test. Femur length was measured from the apex of greater trochanter to superior margin of lateral joint line of the knee. Fibula length was measured from the apex of fibula head to apex of lateral malleolus. Humerus length was measured from the lateral aspect of the acromion to the lateral joint line of the elbow. Radius length was measured from the apex of the lateral epicondyle of the elbow to the apex of the radial styloid.

A.6.3 Kanga-tech^{TM} trunk rotation isometric strength

The asymmetry of isokinetic trunk rotational strength, via peak torque at different speeds, via the Biodex system, has been identified as worthy of investigation professional golfers (252), with standing trunk rotation to the lead side being significantly ($p < 0.05$) stronger. This study measured the isometric bidirectional strength, via peak torque and derived metrics, in a kneeling position using electronic dynamometry. The participant assumed a kneeling golf stance with open palms pressed firmly together in front of the mid-sagittal plane of their body. The participant then pressed against the electronic dynamometer with the back of their hand as firmly as possible for 5 seconds. The participant did this in both directions which represented their backswing and forward swing. Previous rotational strength testing of golfers has suggested that rotational strength and endurance data can be presented in absolute terms (not normalized) when making between-subject comparisons (257).

Measures: Bilateral – trunk rotation strength kg

Derived metrics: Bilateral – trunk rotation torque kg/m, trunk rotation torque relative to weight kg/m/kg

A.6.4 Kanga-tech^{TM} hip adduction isometric strength

Participant lays in supine with a foam roller under their knees to support a small amount of knee flexion and placed the medial superior aspect of both knee joints on the electronic dynamometers. The participant then pressed against the individually positioned

electronic dynamometers with their knees as firmly as possible for 5seconds, maximally contracting the adductor muscle groups.

Measures: Bilateral – hip adduction isometric strength kg

Derived metrics: Bilateral – hip adduction isometric torque kg/m, hip adduction isometric torque relative to weight kg/m/kg

A.6.5 Kanga-tech^{TM} hip abduction isometric strength

The participant laid supine with a foam roller under their knees to support a small amount of knee flexion and placed the lateral superior aspect of both knee joints on the electronic dynamometers. The participant then pressed against the electronic dynamometers with their knees as firmly as possible for 5 seconds while maximally contracting their abductor muscle groups.

Measures: Bilateral – hip abduction isometric strength kg

Derived metrics: Bilateral – hip abduction isometric torque kg/m, hip abduction isometric torque relative to weight kg/m/kg

A.6.6 Kanga-tech^{TM} hip external rotation isometric strength

The participant laid on their side with 90 degrees of hip and knee flexion and placed the medial distal aspect of their tibia (just above the medial malleolus, on the electronic dynamometer. The participant then pressed against the individually positioned electronic dynamometers with their lower leg, in an external rotational manner, as firmly as possible for 5 seconds, maximally contracting their external hip rotators of the hip that lay on the ground. This measurement was then repeated on the other side.

Measures: Bilateral – hip external isometric strength kg

Derived metrics: Bilateral – hip external rotation isometric torque kg/m, hip external rotation isometric torque relative to weight kg/m/kg

A.7 Leg power

Three valid and reliable jump tests were selected to assess various aspects of leg power in the golfers. The jump tests were performed in consistent order and were preceded by the following standardised warm-up protocol subjects: 10 air squats, 10 calf raises, 5 sub-maximal countermovement jumps with hands on hips, 5 sub-maximal countermovement jump and reach, 5 sub-maximal lateral jumps in both directions.

Participants were instructed not to undertake any of the jump testing if they experienced pain during the warm-up. The participants were then instructed to undertake the jump testing within 2 to 5 minutes of completing the warm-up.

A.7.1 Vertical jump and reach test

The protocols from the Swift Yardstick Instructions were used for these combine tests (541). The standing height of the subject with one arm fully extended upward was recorded by adjusting the lowest measurement vanes of the Swift Yardstick. The participant then jumped up and touch the highest possible vane. The jump height is the difference between standing height and jumping height. The participant could freely swing their arms and create the countermovement they desired.

Measures: Jump and reach height cm

Derived metrics: Estimated peak leg power W, using Sayers (1999) power estimate equation (231).

A.7.2 Counter movement jump 'hands-on-hips'

The participants performed a countermovement, whilst standing on a single Kistler 3D force plate, following protocols from Hellstrom (2008) (176). They started from an upright position so that they could freely bend their knees to do a counter movement before the jump. Hands remain on hips throughout, and participant was instructed to land on their toes to perform consecutive second jump upon landing, to standardise the jump. The participants undertake three trials, with a minimum of 1-minute rest between trials. The highest peak power created in the three countermovement jumps will be extracted off the Kistler 3D force plate software on completion of testing.

Measures: Peak vertical ground reaction force N

Derived metrics: Peak force relative to bodyweight N/kg

A.7.3 Lateral jump test

This test follows protocols from Lockie et al (2015) (204). The participant starts by standing on the testing leg with the medial border of the foot of the leg being tested level with the start line. The participant was allowed to self-select the depth and timing of their of their preparatory countermovement prior to jumping – provided only one foot was on the ground prior to take-off. The participant then jumped laterally to the inside and landed on two feet. To be consistent with other jump tests, participants were instructed to use a countermovement, and no restrictions were placed on the arm swing used or the range

of the countermovement. The distance jumped was measured with a standard tape measure (*HART Sport, Aspley, Australia*) to the nearest 0.01 m, perpendicular from the start line to the lateral margin of the take-off leg. If a participant did not 'stick' the landing and over-balance, the trial was disregarded and reattempted as per Lockie et al (2015) – which reduced the *learning effect* on the results (204). The lateral jump distance for each leg can then be calculated relative to body mass as the jump distance divided by body mass.

Measures: Bilateral – lateral jump distance m

Derived metrics: Bilateral – lateral jump distance relative to weight m/kg, lateral jump distance relative to leg length m/m

A.8 Upper body and core power

A.8.1 MB lateral throw

The testing protocols were taken from Read et al (2103) (39). Using a Crane Fitness 3 kg medicine ball, the participant assumed a golf stance with the outside of their lead foot behind a line of tape on the floor that is in line with the beginning of the two measuring tapes. Holding the medicine ball, the subject could rotate away in a backswing type action followed by an immediate rotation toward the target as in a golf swing, aiming for maximal distance. Feet are required to remain in contact with the floor, although the rear heel could rise in the follow through action promoting triple extension of the ankle knee and hip as would be present in the golf swing. The subject was allowed a warm-up throw and to ensure accuracy of measurement. A predetermined landing width was marked out with two measuring tapes 1.5 m apart, where the ball must land to be classified as a legitimate throw. The tester watched the ball land and measured with a 1.5 m wooden rod to determine the distance the ball was thrown. The ball was only thrown in the direction the golfer would hit the golf ball (i.e., not bilateral).

Measures: MB throw distance m

Derived metrics: Nil

A.8.2 MB seated throw

The testing protocols were taken from Read et al (39). This test is sometimes referred to as a 'Chest Pass'. A 45-degree angle incline bench was used to facilitate the optimal trajectory and ensure standardization. Subjects used a 3 kg medicine ball, performing a warm-up throw followed by three recorded attempts, with the best distance reported. For

each trial, the ready position is assumed with the subject placing the ball against their chest, and it is held statically for four seconds. The participant was instructed to throw maximally using only a concentric motion. The participants required to maintain their back and head in contact with the bench ensuring their feet remain on the floor. The same ball landing and measurement criteria for the lateral toss were adhered to.

Measures: MB throw distance m

Derived metrics: Nil

A.8.3 MB sit up throw

The testing protocols were taken from a modified version of Palao & Valdes (2013) (542) used in the TPI power test battery (543). The participants performed a warm-up throw using a 3 kg medicine ball. For each trial, the ready position is assumed with the subject placing the ball above their head, and it is held statically for 4 seconds. The participants were instructed to throw maximally using only a concentric motion. The participants were required to sit up and release the ball where and how they preferred. The participants backside needed to be behind the start of measuring tape. The same ball landing and measurement criteria for the lateral toss were adhered to.

Measures: MB throw distance m

Derived metrics: Nil

A.9 Golf technical test procedures

Participants performed a standardized warm up during the 10 minutes prior to entering the test hitting bay, in a designated warm-up area with the same mod-grass mat to be used in the test hitting bay. The warmup protocol was as follows: 10 swings with the iron intended for use for the 120m shot – start small and increase the range and force of the swing until they feel they are making a full shot; 10 swings with the driver – start small and increase the range and force of the swing until they are making a full shot. The participants used their own clubs during the golf performance measures as per previous similar research (47).

Participants took their stance on synthetic grass and hit balls from either the grass or tee towards a projected image on a wall behind a floor to ceiling net. The 120 m approach shot accuracy test was undertaken first. Next, the participant was fitted with a K-Vest™ 3D biomechanics vest, which was calibrated for each participant. The K-Vest™ captured body kinematics whilst the participant performed four Driver swings for maximum

distance and accuracy to a projected image of a fairway target. A Trackman™ launch monitor was set up behind the golf ball to capture club and ball variables. Dual 3D Kistler force plates were under the feet of the participants to capture ground reaction forces. Dual 3D Kistler force plates were built into the biomechanics laboratory floor. A large section of synthetic grass, typical to that found at a driving range, was placed over the top of the force plates. A stencilled, spray-painted box guided acceptable feet positions, allowing all participants to take their usual golf stance for each type of shot. The participant was instructed to stand with a foot within each white square on the blue mat (and that these are placed directly over the Kistler dual 3D force plate underneath). The participant was able to set up their ball and tee in their preferred position without receiving coaching from the tester. The tester encouraged the player to go through their usual pre-shot routine (standing behind the ball to line up the shot, practice swing to get used to the K-Vest™ etc). A Trackman™ doppler radar device was set up, according to manufacturer's instructions, behind the participant and connected to a projector to create a real-time image of the fairway, target (golf flag for 120 m shot and fairway for Driver shot) and ball flight as they hit the ball to provide feedback to the player as if they were in a competition setting. All devices recorded real-time shot and biomechanical information as the participants undertook the following tests.

A.9.1 120 m target shot

The 120m Shot aims to measure how accurate the player's approach game is from 120m, as dispersion to target is highly valuable in golf. The 120m shot was performed prior to the maximum driver test. The participant was able to use their own preferred club for the distance and was instructed to hit the ball as close as possible to the 120m target as possible. The participant was given four attempts at the test. At the analysis phase, the shot that finished closest to the target was selected.

Measures: Trackman club outputs – CHS, path, plane, direction, dynamic loft, face angle, face to path, attack angle, low point, smash factor. Trackman ball outputs – total distance & side, carry distance & side, carry time, landing angle & speed, spin rate and axis.

Derived metrics: Distance to target m (calculated from triangulation of horizontal and vertical measurements)

A.9.2 Maximum distance driver shot

The driver test aims to measure how well the player hits their driver, distance being a key component of competitive golf (362). The instruction given to the player is to 'hit the ball as though they are in a competition where distance and accuracy are both important',

as per Quinn et al (2016) (140). The participant was given 4 attempts to do so which has shown to be reliable for group analysis (544), and used in previous golf research (36). Trackman™, GRF and K-Vest™ measures described below were recorded for each of the four trials so that the best shot could be identified during the analysis phase. At the analysis phase, the longest total drive distance (m) that finished within 20m left or right of the target line, replicating a typical fairway and first cut of rough, was selected. This was slightly more stringent than previous research which only required to land within a 37m-wide fairway (136) or 40m margin (47), from launch monitor. An experienced PGA Teaching Professional was consulted to ensure this constituted appropriate criteria for the participant's 'best shot', such consultation has been used in previous studies (135). A previous study had utilised a similar approach and yielded high reliability (ICC = 0.971) and the highest swing speed selected for analysis (134).

A.9.3 Club and Ball Kinematics - Trackman™

Measures: Trackman club outputs – CHS, path, plane, direction, dynamic loft, face angle, face to path, attack angle, low point, smash factor. Trackman ball outputs – total distance & side, carry distance & side, carry time, landing angle & speed, spin rate and axis.

Derived metrics: CHS relative weight mph/kg, CHS relative to height mph/cm, CHS relative to arm span mph/cm

A.9.4 Ground reaction forces – Kistler 3D Force Plates

Measures: Bilateral – L&T Fx (anterior-posterior) maximum and minimum force values, L&T Fy (medial-lateral) maximum and minimum force values, L&T Fz (vertical) maximum and minimum force values

Derived metrics: All forces relative to weight N/kg, time between Fx, Fy and Fz rear and lead leg peaks s

A.9.5 3D body kinematics - K-Vest ™

Measures: Pelvis peak angular velocity °/s, Thorax peak angular velocity °/s, Lead shoulder peak angular velocity °/s, Lead hand peak angular velocity °/s, Pelvis turn ROM° at top of backswing, Thorax turn ROM° at top of backswing, X-Factor ROM° at top of backswing, Pelvis turn ROM° at impact, Thorax turn ROM° at impact, X-Factor ROM° at impact.

Derived metrics: Pelvis-thorax peak velocity ratio, Thorax-lead shoulder peak velocity ratio, Lead shoulder-lead hand peak velocity ratio.

A.10 Competitive performance test procedures

A.10.1 Handicap

At the date of testing each participant provided their Golf Australia HCP (359), as a measure of their current golfing ability.

Measures: HCP Index.

Derived metrics: Standardised HCP (used for analysis, where lowest HCP in the sample is converted to zero and all other participants standardised to this measure

Appendix B: PHYSICAL & TECHNICAL TRAITS

B.1 Remaining bi-variate charts

The bivariate charts with lower bi-directional effect sizes, presented in Chapter 5, are presented in this Appendix B.

B.1.1 Stage 3 & 4 Maximum Driver Shot: Ball & distance measures

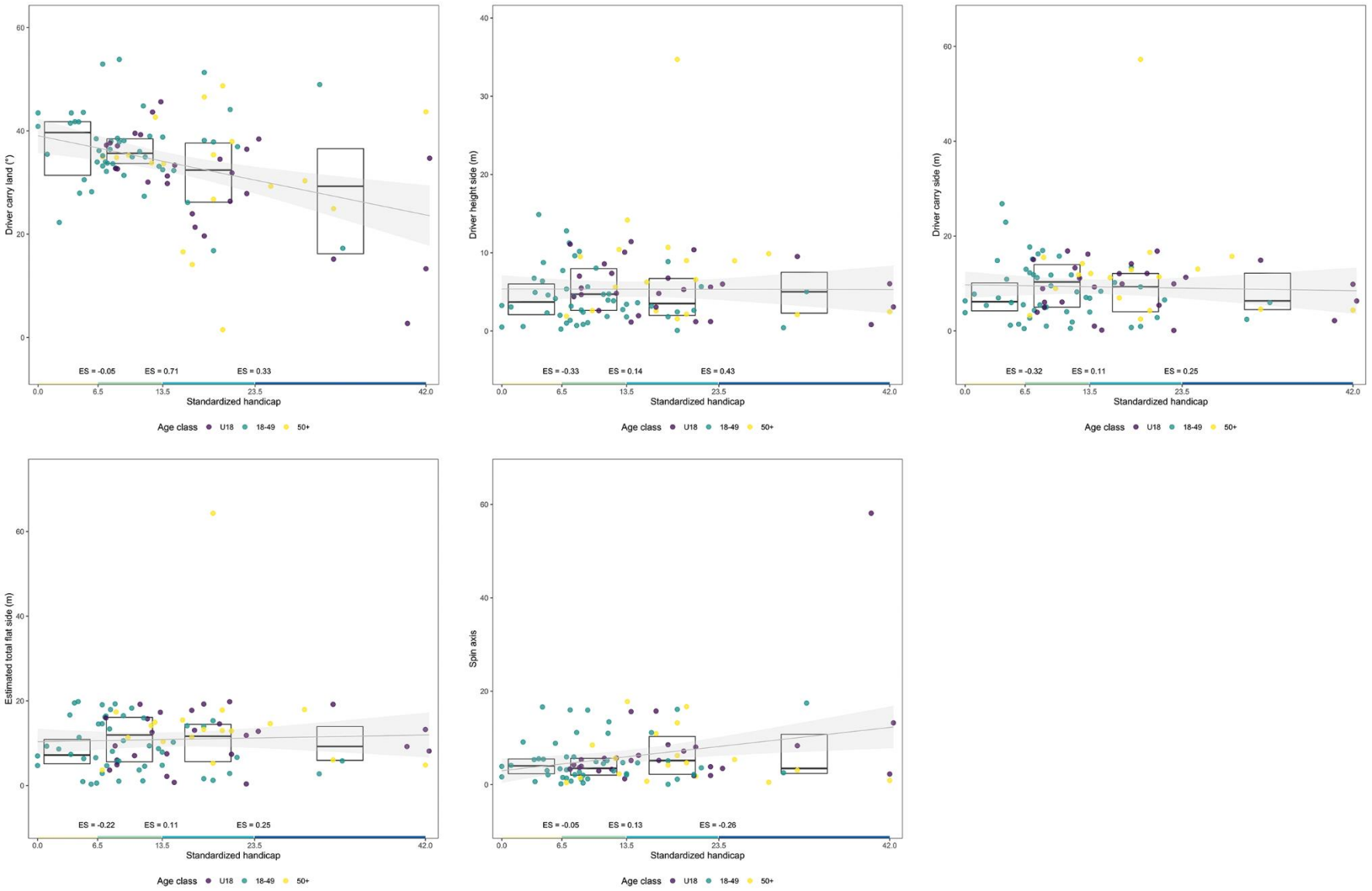


Figure B.1 Driver ball measures. (L-R, T-B) a) carry landing angle, b) maximum height side, c) carry side, d) total distance, e) spin axis. Measures plotted with standardised HCP. Box plots of interquartile range and median for ability cohorts.

B.1.2 Stage 3 Maximum Driver Shot: Club measures

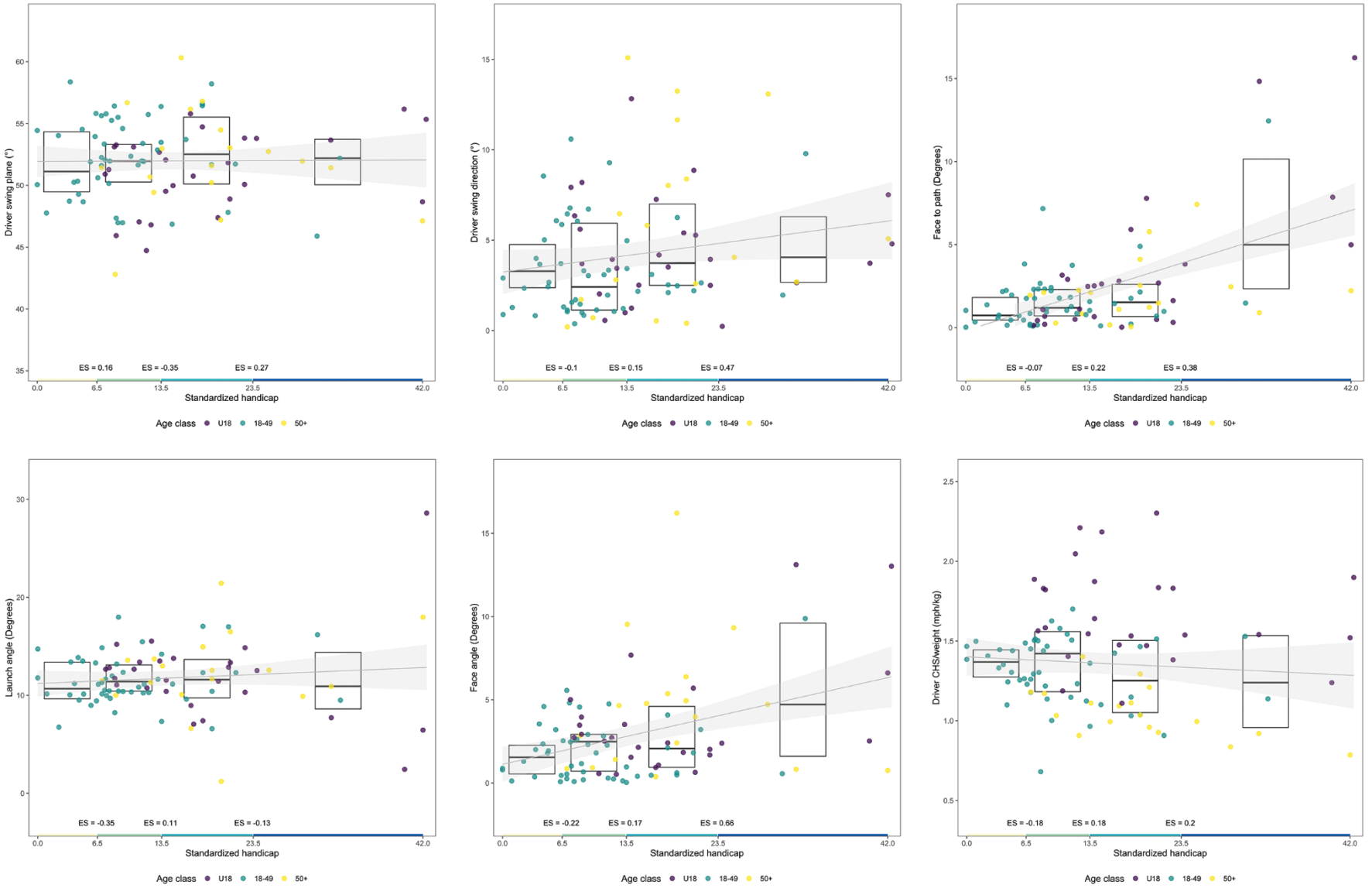


Figure B.2 Driver club measures (L-R, T-B) a) swing plane b) direction c) face to path d) launch angle e) face angle f) CHS/weight

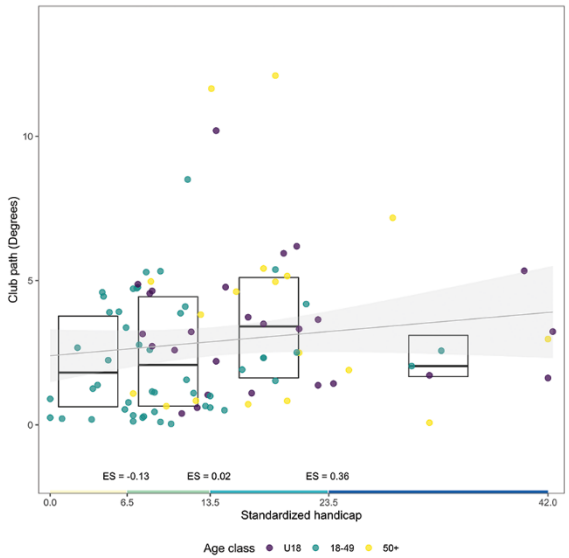


Figure B.3 Driver club path

B.1.3 Stage 3 & 4 120 m Target Shot: Ball & distance to target measures

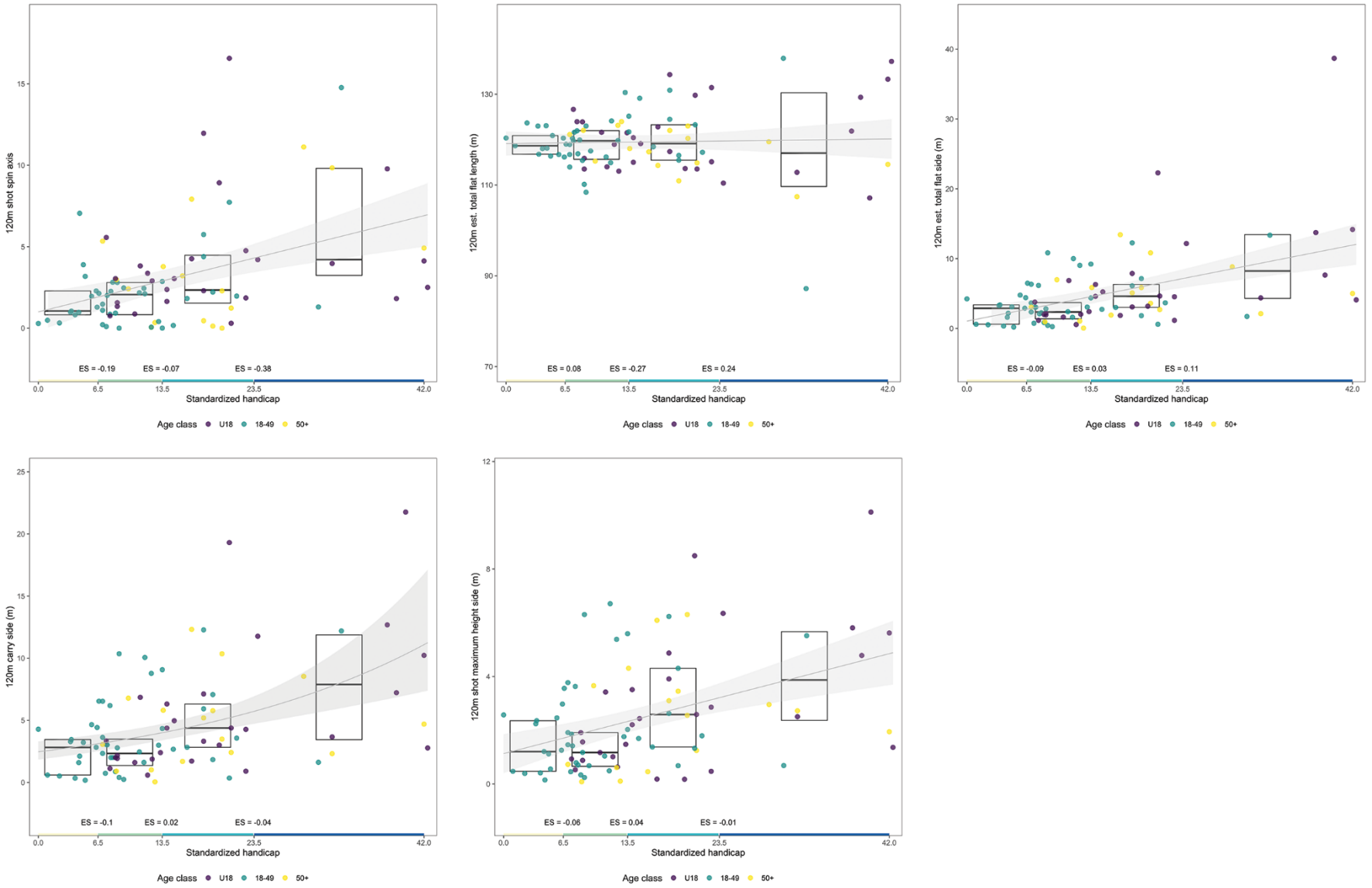


Figure B.4 120 m shot ball measures. (L-R, T-B) a) spin axis, b) total length, c) total side, d) carry side, e) maximum height side.

B.1.4 Stage 3 120 m Target Shot: Club & launch measures

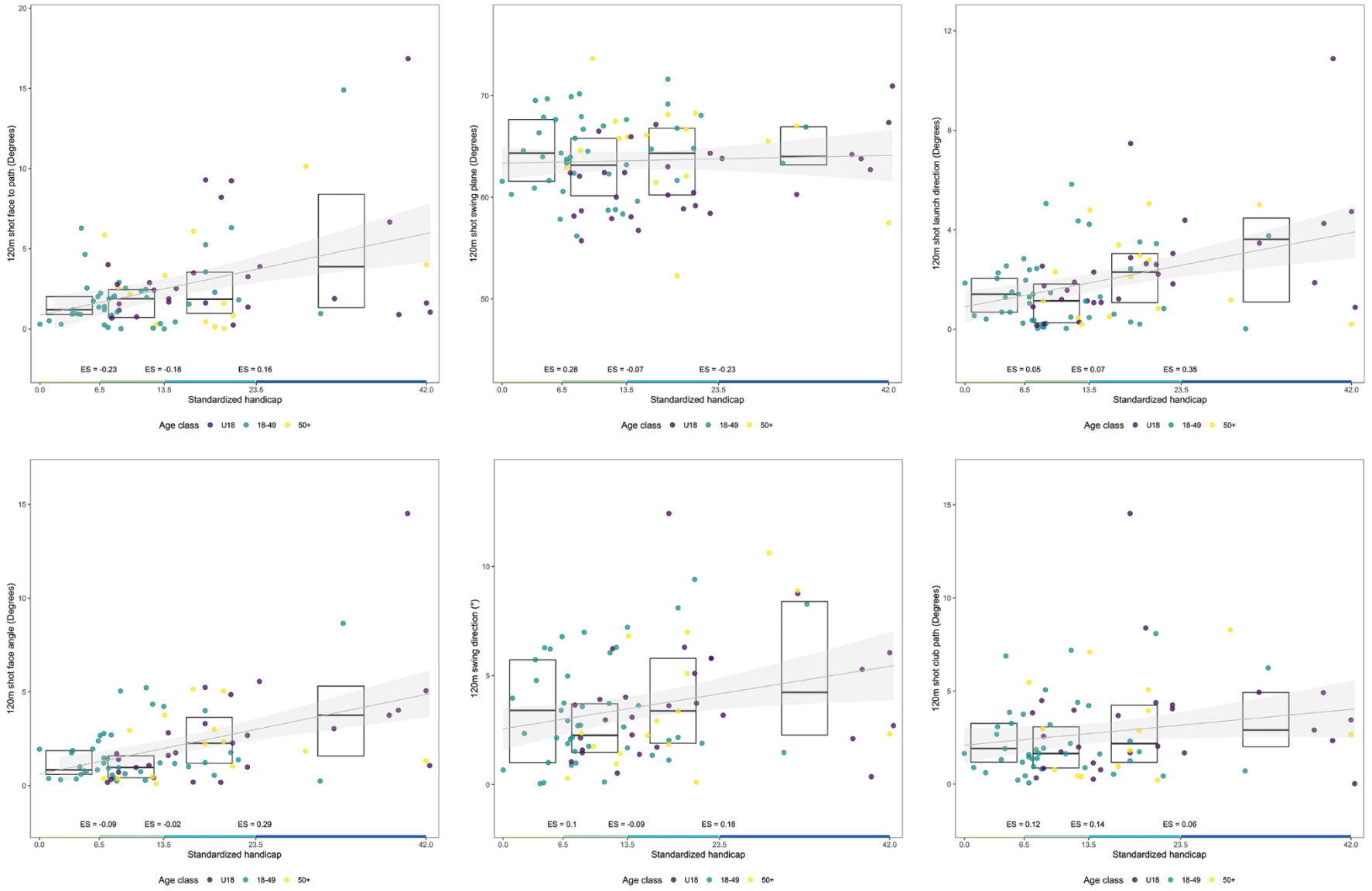


Figure B.5 120 m club measures. (L-R, T-B) a) face to path, b) swing direction, c) launch direction, d) face angle, e) swing direction f) club path

B.1.5 Stage 2 Maximum Driver Shot: Body kinematics

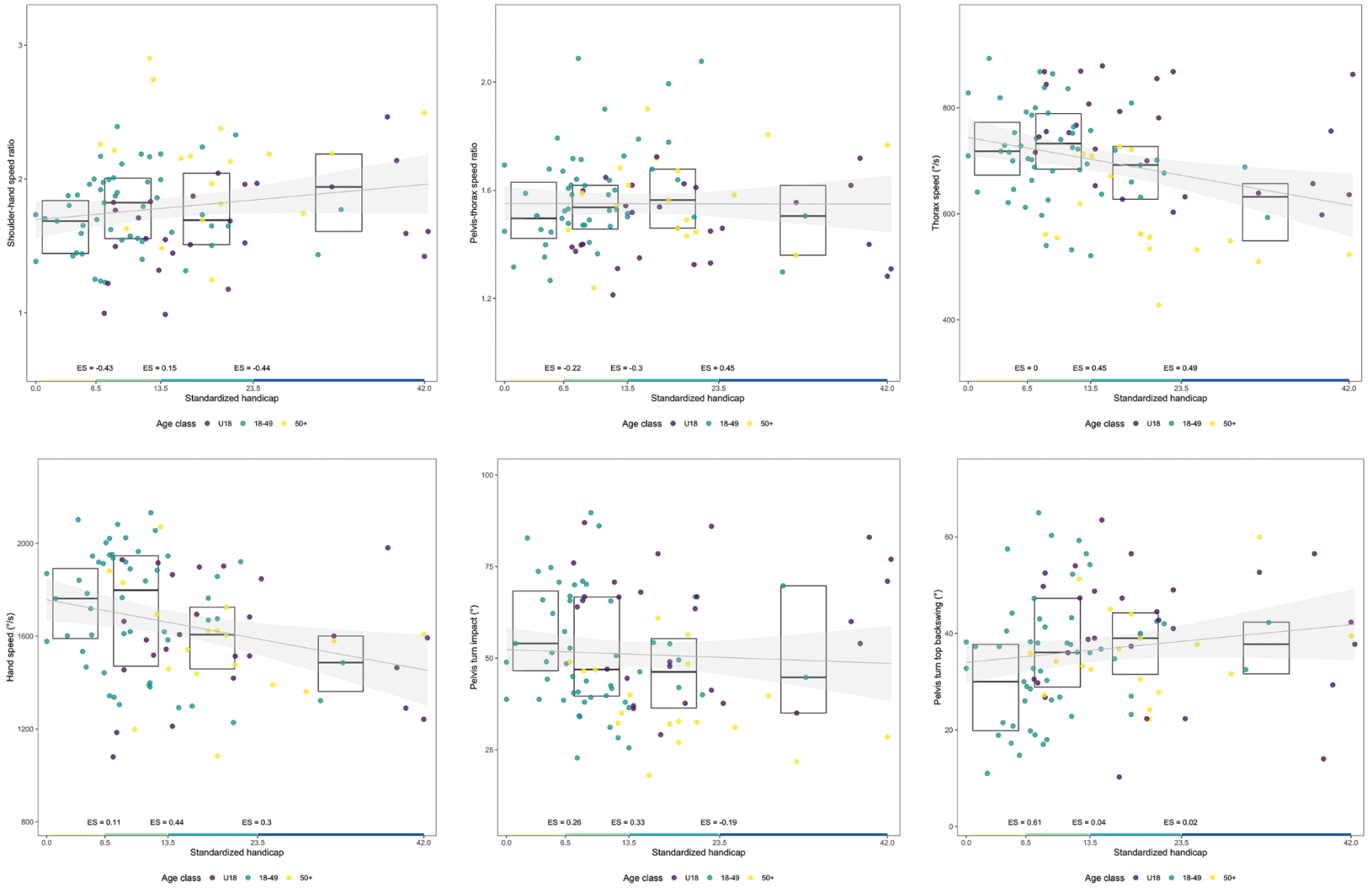


Figure B.6 Driver 3D body measures. (L-R, T-B) a) shoulder-hand speed ratio, b) pelvis-thorax speed ratio, c) thorax speed, d) hand speed, e) pelvis turn at impact, f) pelvis turn at top of backswing.

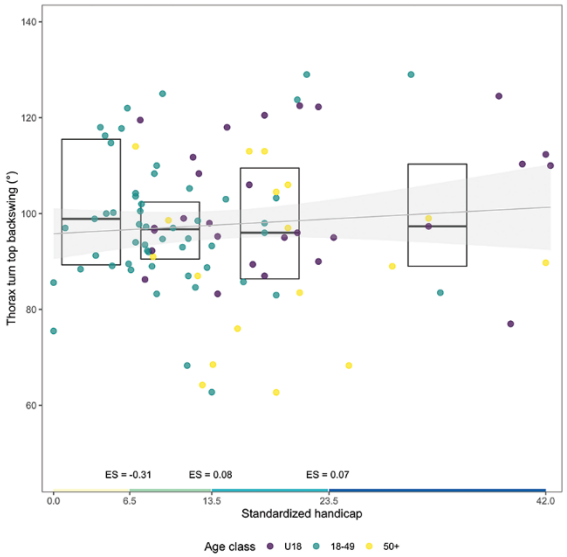


Figure B.7 Driver thorax turn at the top of back swing

B.1.6 Stage 2 Maximum Driver Shot: Ground reaction forces

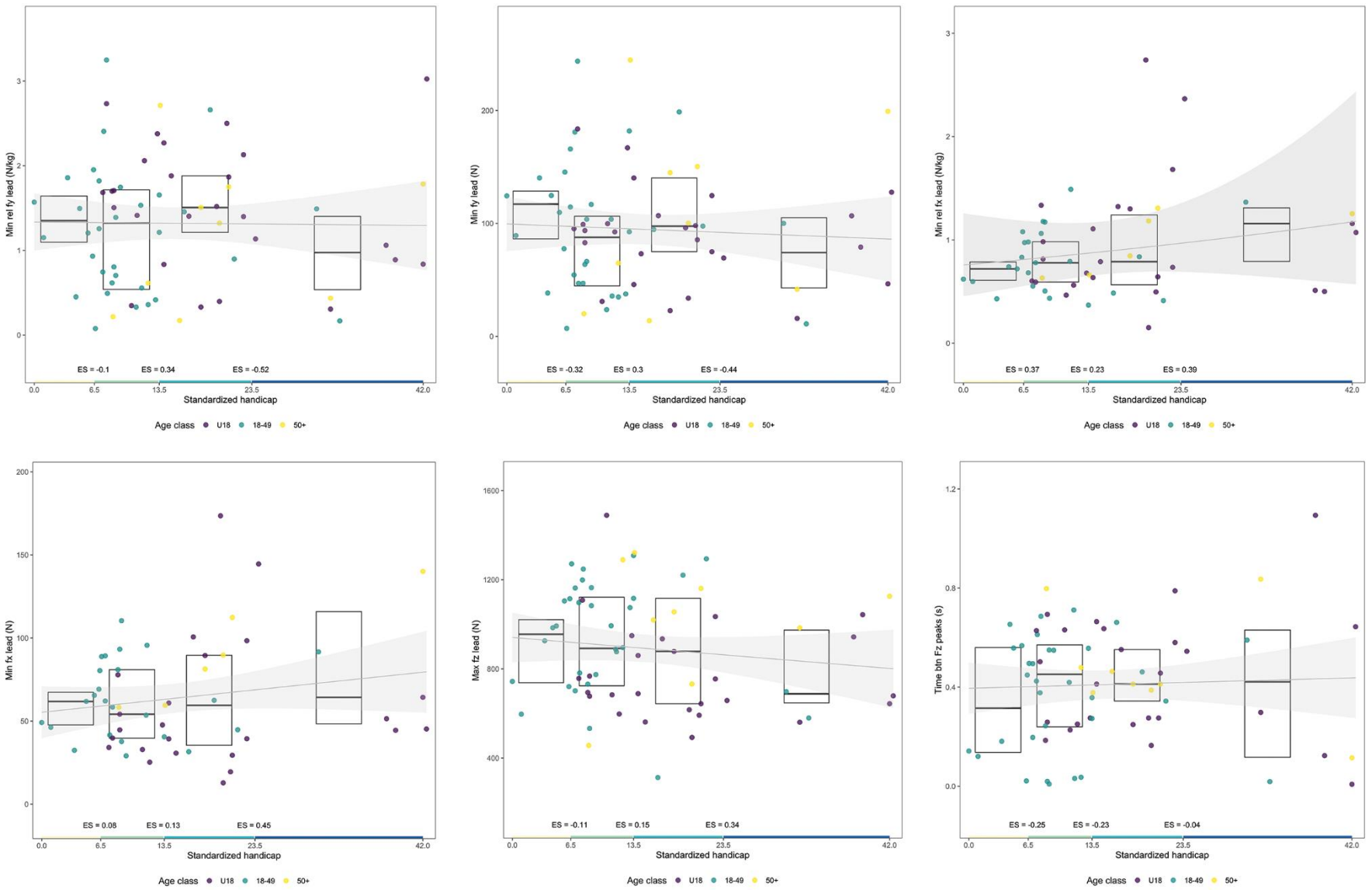


Figure B.8 Driver GRF measures. (L-R, T-B) a) minimum Fy lead leg relative to weight, b) minimum Fy lead leg, c) minimum Fx lead leg relative to weight, d) minimum Fx lead leg, e) maximum Fz lead leg, f) time between rear and lead Fz peaks

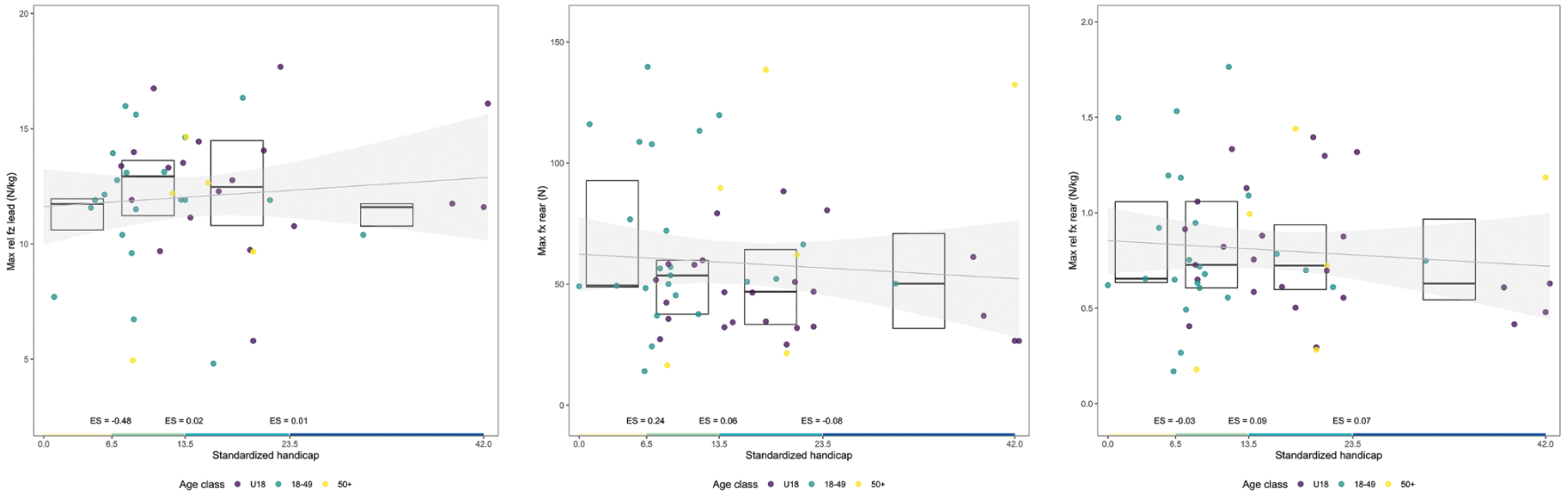


Figure B.9 Driver GRF measures. (L-R) a) maximum Fz lead leg relative to weight, b) maximum Fx rear leg, c) maximum Fx rear leg relative to weight

B.1.7 Stage 1 Physical – Power

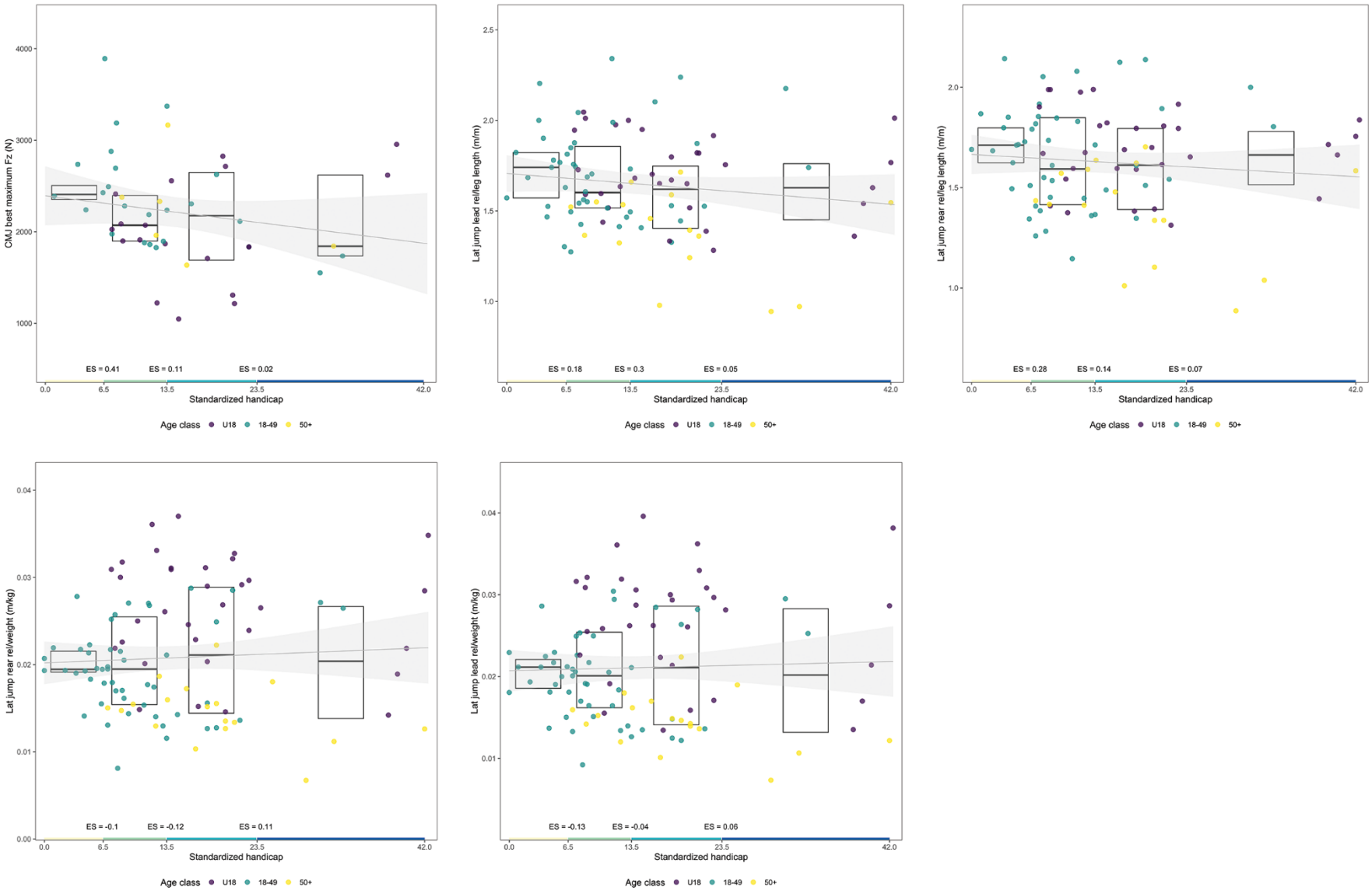


Figure B.10 Physical power measures. (L-R, T-B) a) CMJ best trial maximum Fz, b) lateral jump lead leg relative to leg length, c) lateral jump rear leg relative to leg length, d) lateral jump rear leg relative to weight, e) lateral jump lead leg relative to weight

B.1.8 Stage 1 Physical – Strength (Absolute)

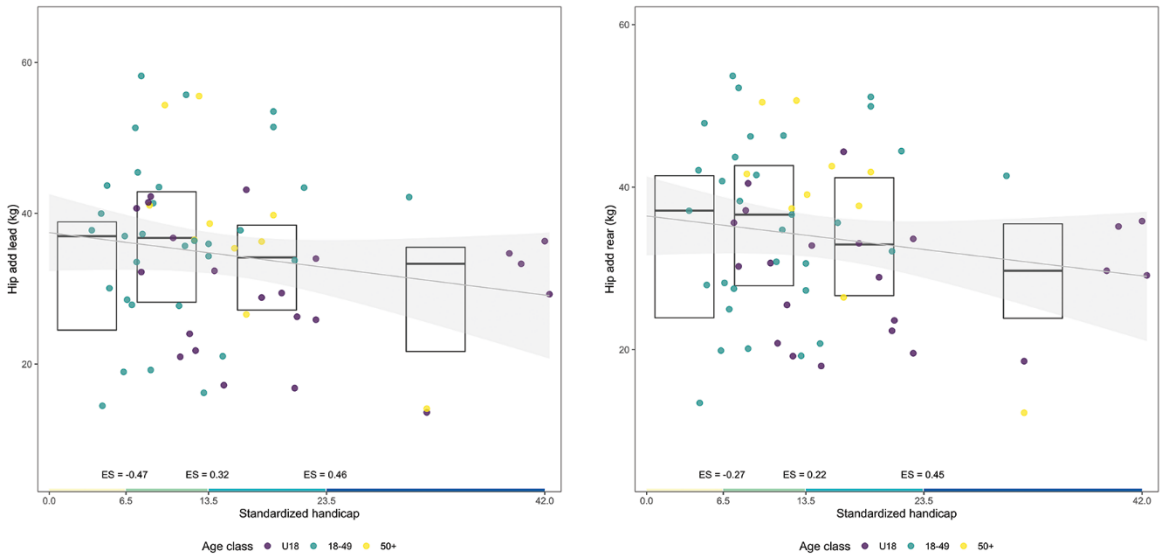


Figure B.11 Physical strength (absolute) measures. (L-R) a) Lead hip adduction peak force, b) Rear hip adduction peak force

B.1.9 *Stage 1 Physical – Strength (Torque and Relative Torque)*

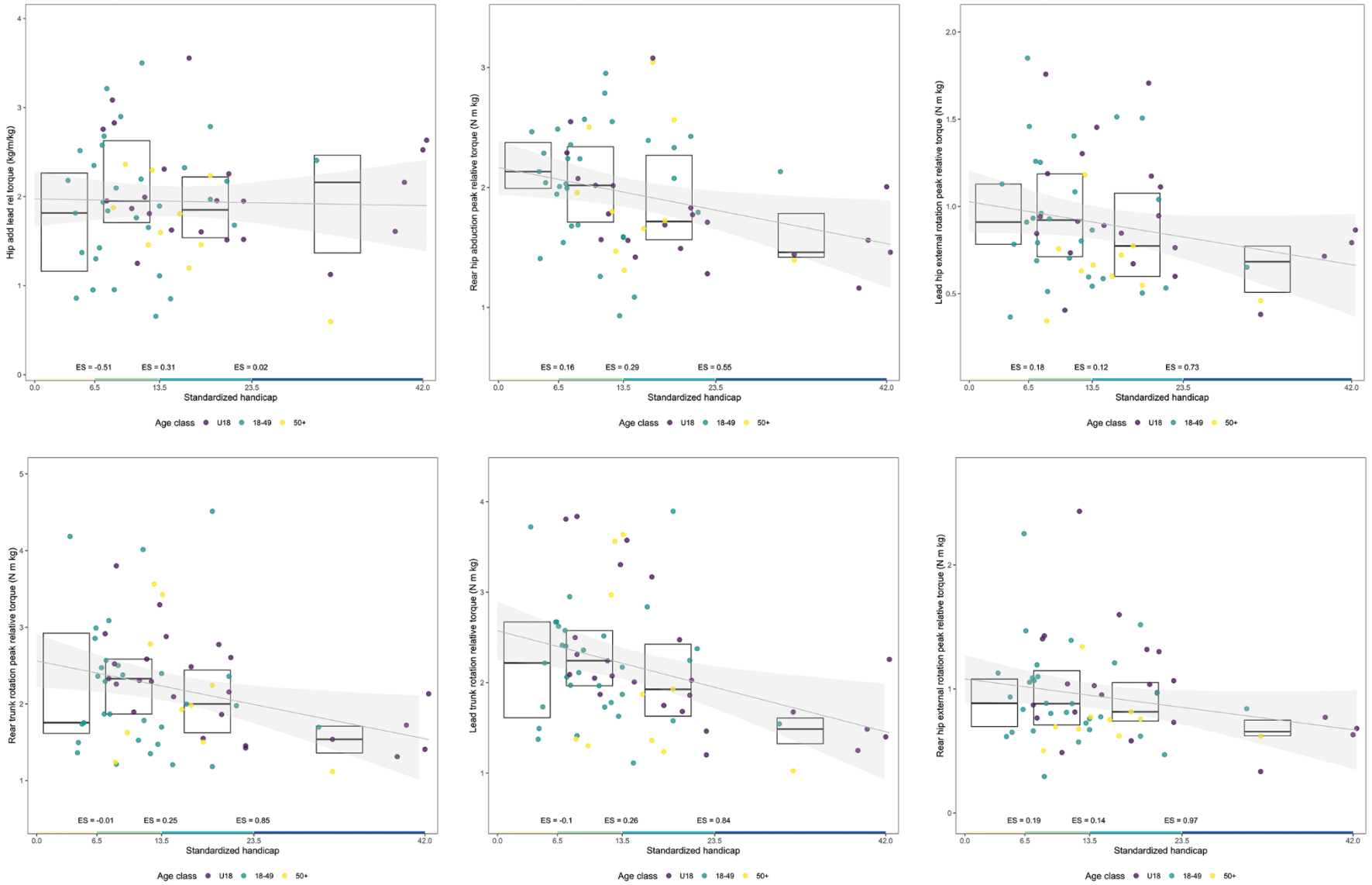


Figure B.12 Physical torque measures. (L-R, T-B) a) lead hip adduction torque relative to weight b) rear hip abduction torque relative to weight c) lead hip external rotation torque relative to weight d) rear trunk rotation torque relative to weight e) lead trunk rotation torque relative to weight f) rear hip external rotation torque relative to weight

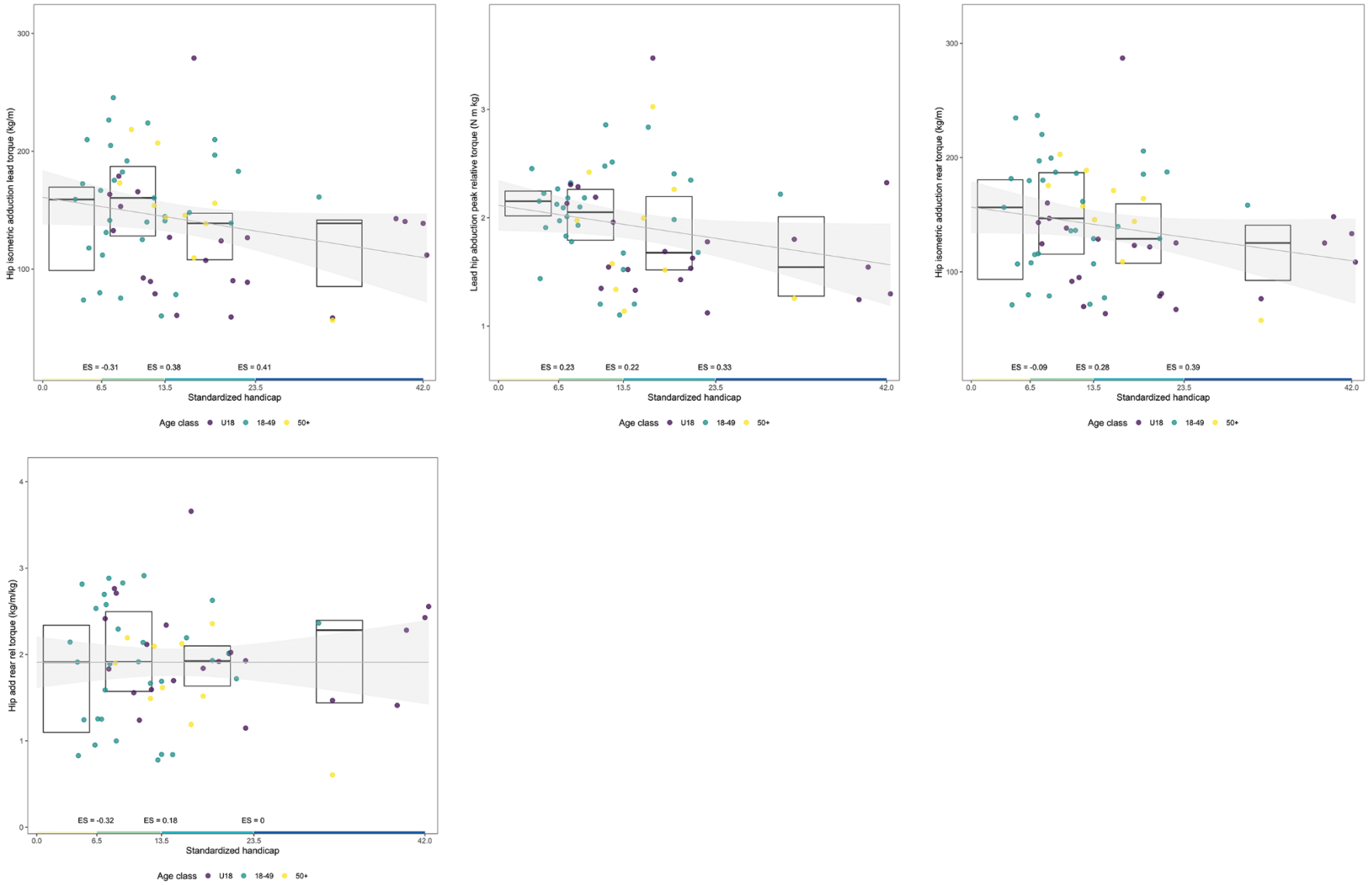


Figure B.13 Physical torque measures. (L-R, T-B) a) lead hip adduction torque, b) lead hip abduction torque relative to weight, c) rear hip adduction torque, d) rear hip adduction torque relative to weight

B.1.10 Stage 1 Physical – Balance

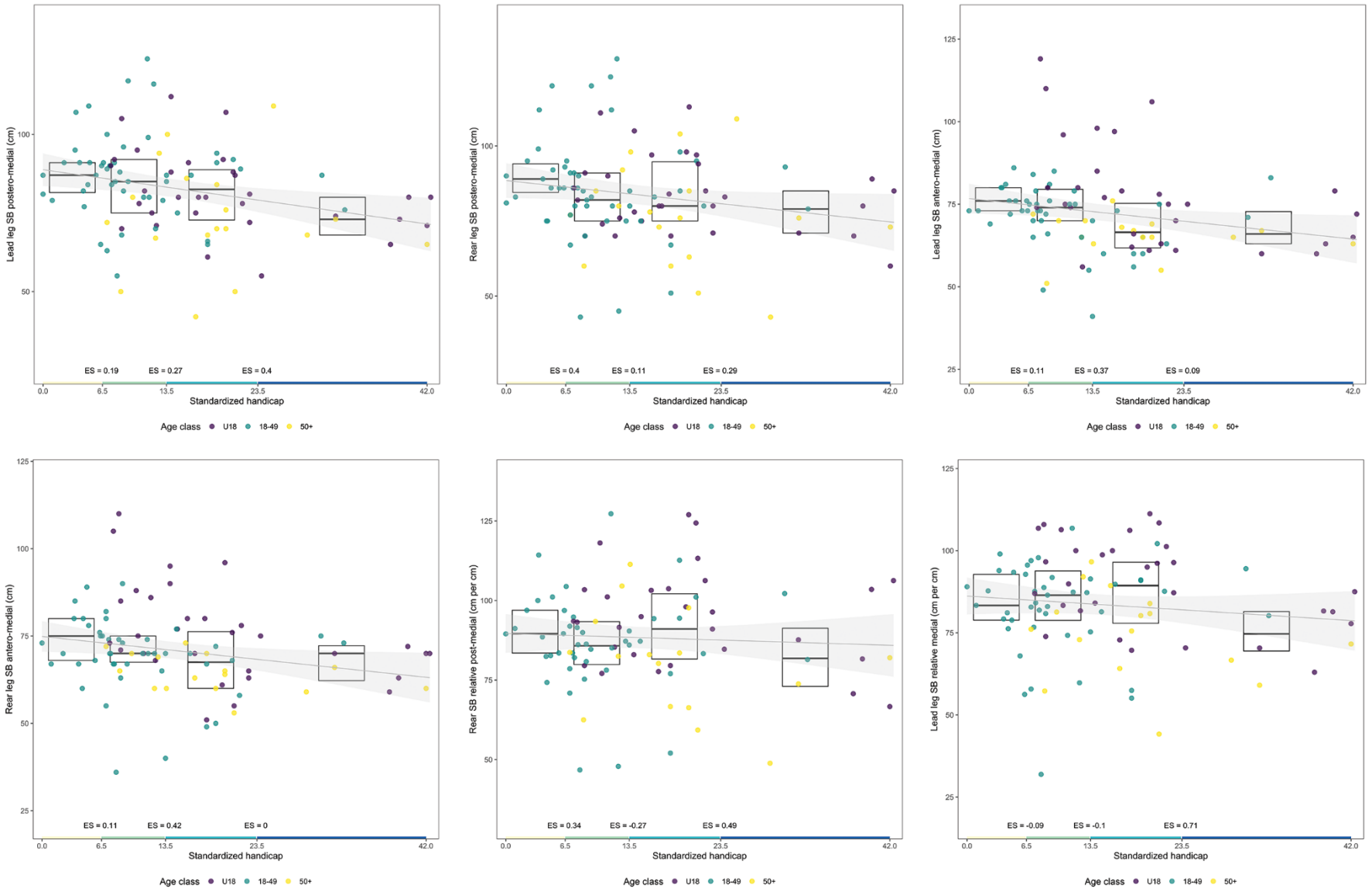


Figure B.14 Physical balance measures. (L-R, T-B) a) lead leg Star Balance (SB) postero-medial b) rear leg SB postero-medial c) lead leg SB antero-medial d) rear leg SB antero-medial e) rear leg SB postero-medial relative to leg length f) lead leg SB medial relative to leg length

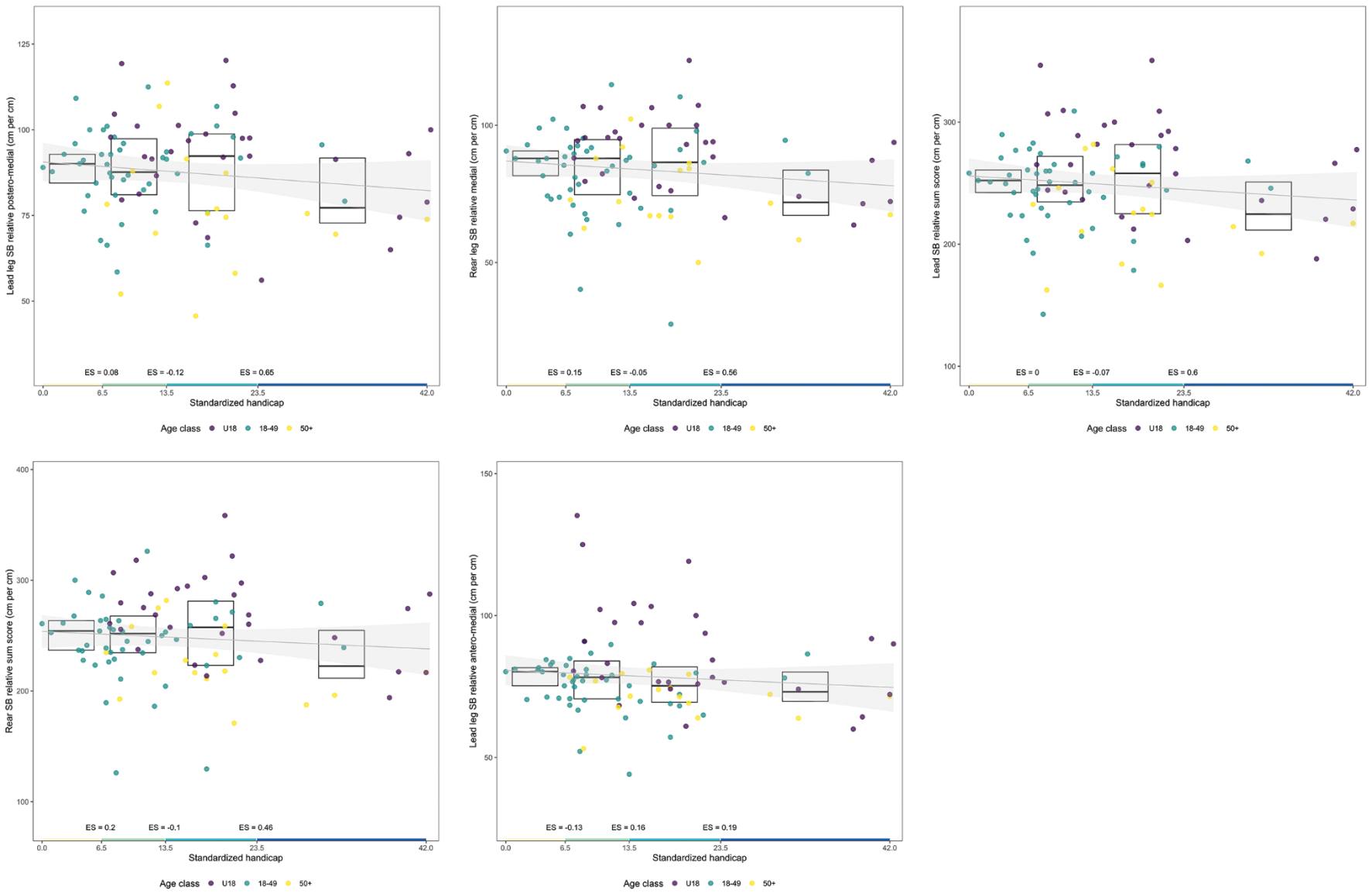


Figure B.15 Physical balance measures. (L-R, T-B) a) lead leg SB postero-medial relative to leg length b) rear leg SB medial relative to leg length c) lead leg SB sum score relative to leg length d) rear leg SB sum score relative to leg length e) lead leg SB antero-medial relative to leg length

B.1.11 Stage 1 Physical – Flexibility

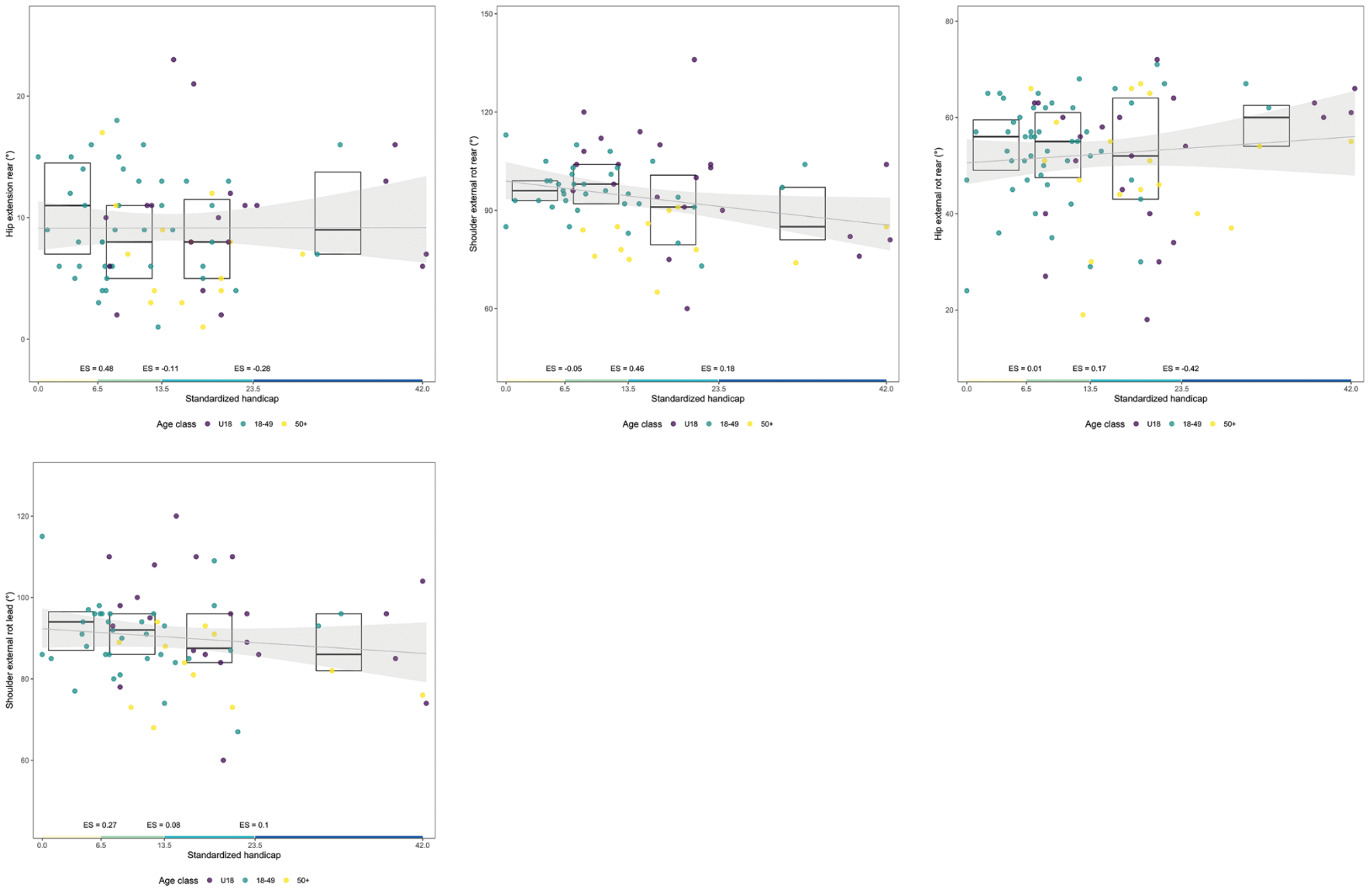


Figure B.16 Physical flexibility measures. (L-R, T-B) a) rear hip extension b) rear shoulder external rotation c) rear hip external rotation d) lead shoulder external rotation

Appendix C: REGRESSION MODEL RESIDUAL NORMALITY TESTING

C.1 Tables and charts for residual normality testing

Normality testing of multiple linear regression model residuals was undertaken to ensure that the distribution was normal. The subheading denotes the model and Chapter 6 sub-section that the tables and figures relate to. Tables and figures were produced after final residual outliers were removed.

C.1.1 Stage 4-5 P-GPC Relationships: Driver distance & 120m Accuracy – HCP

Table C.1 Stage 4-5 regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		-1.3769643	0.56400114
	95% Confidence Interval for Mean	Lower Bound	-2.5010170	
		Upper Bound	-0.2529116	
	5% Trimmed Mean		-1.3880540	
	Median		-1.3332214	
	Variance		23.539	
	Std. Deviation		4.85172129	
	Minimum		-13.62876	
	Maximum		10.39609	
	Range		24.02485	
	Interquartile Range		6.37259	
	Skewness		0.029	0.279
	Kurtosis		-0.099	0.552

Table C.2 Stage 4-5 residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.040	74	.200*	0.997	74	1.000
*. This is a lower bound of the true significance.						
a. Lilliefors Significance Correction						

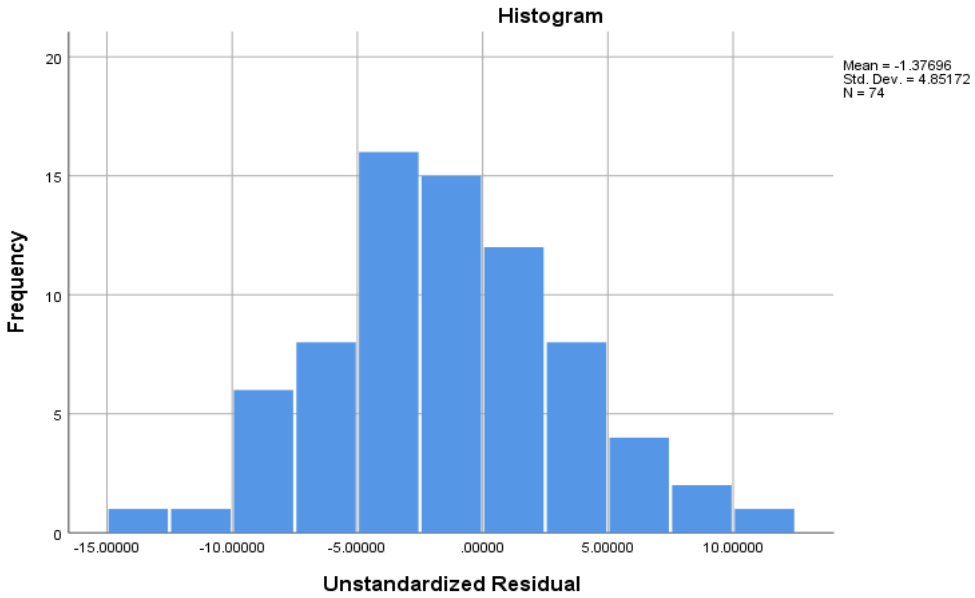


Figure C.1 Stage 4-5 residual histogram

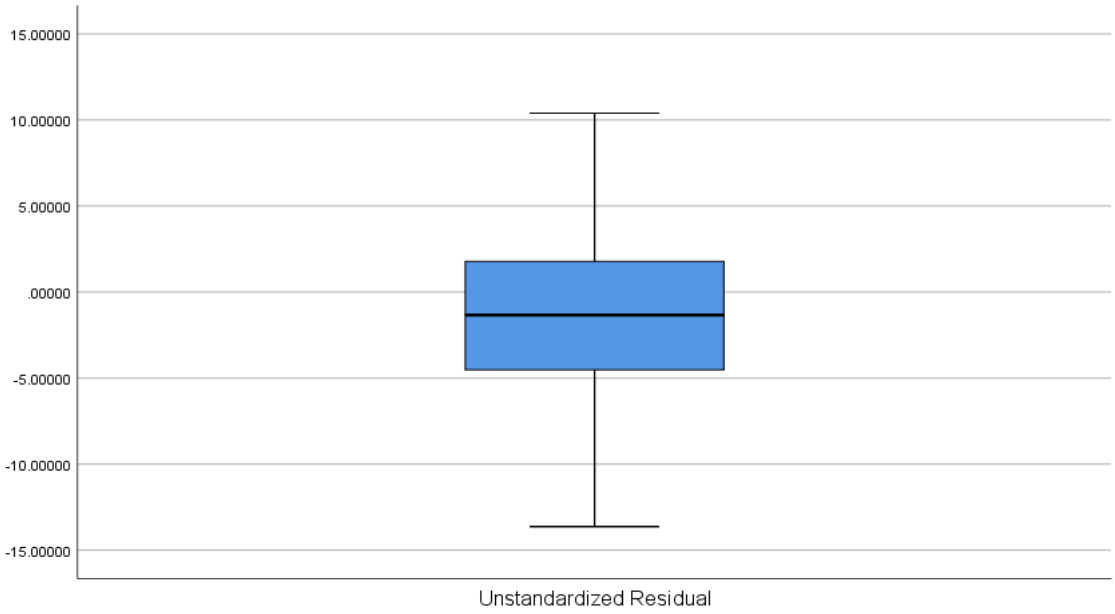


Figure C.2 Stage 4-5 residual distribution box plot

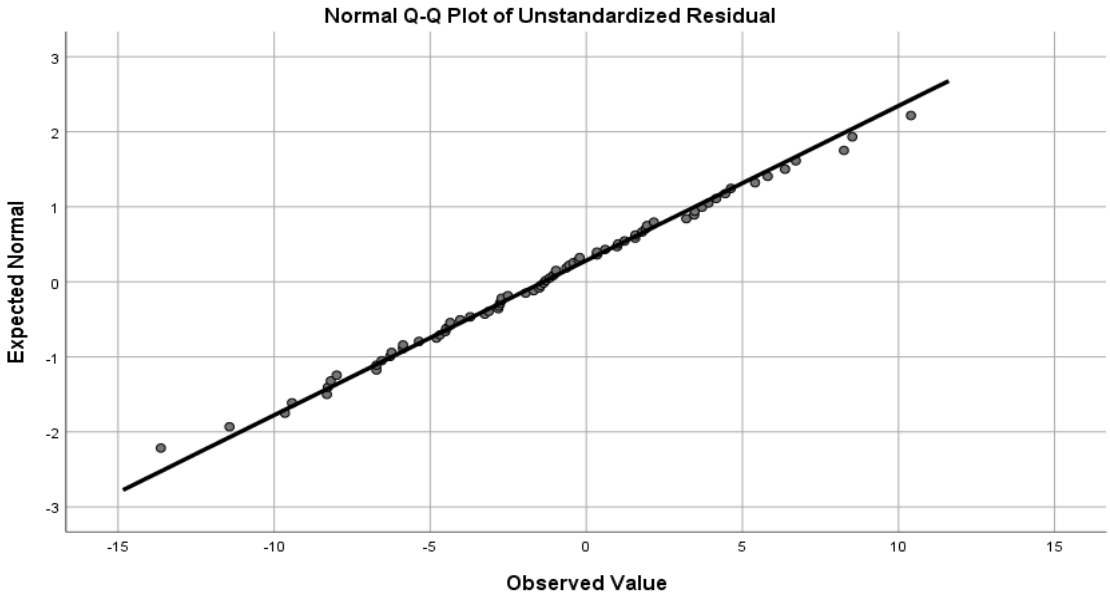


Figure C.3 Stage 4-5 residual Q-Q plot

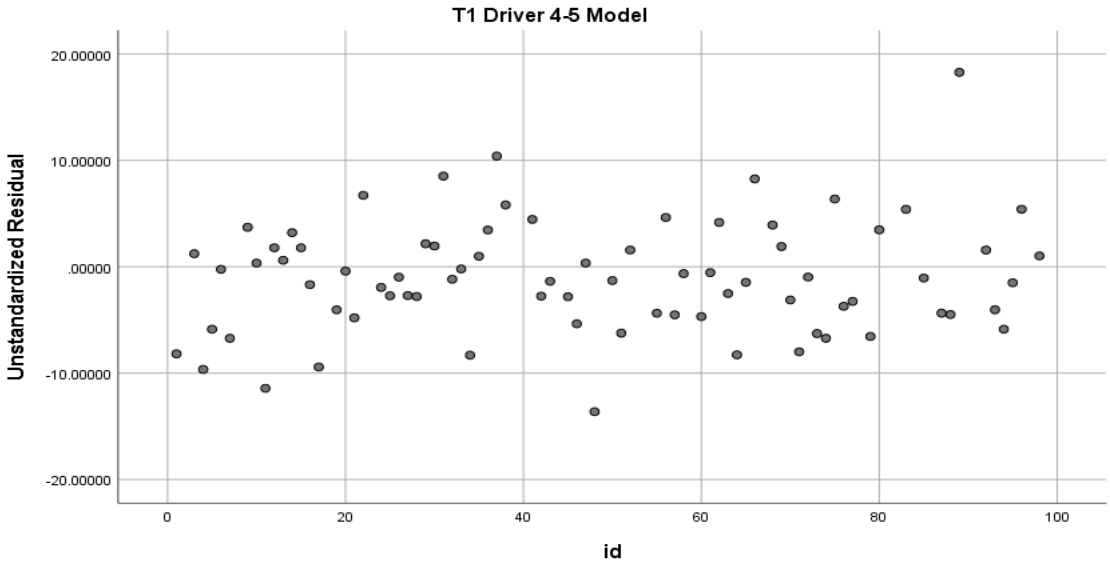


Figure C.4 Stage 4-5 residual scatter plot

C.1.2 Stage 3-5 P-GPC Relationships: Driver Ball & Club Kinematics – HCP

Table C.3 Stage 3-5 driver regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		-1.2287958	0.58855440
	95% Confidence Interval for Mean	Lower Bound	-2.4026305	
		Upper Bound	-0.0549611	
	5% Trimmed Mean		-1.3375865	
	Median		-1.2592037	
	Variance		24.594	
	Std. Deviation		4.95924749	
	Minimum		-10.97521	
	Maximum		10.34483	
	Range		21.32004	
	Interquartile Range		6.65945	
	Skewness		0.270	0.285
	Kurtosis		-0.286	0.563

Table C.4 Stage 3-5 driver residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.100	71	0.077	0.979	71	0.287
a. Lilliefors Significance Correction						

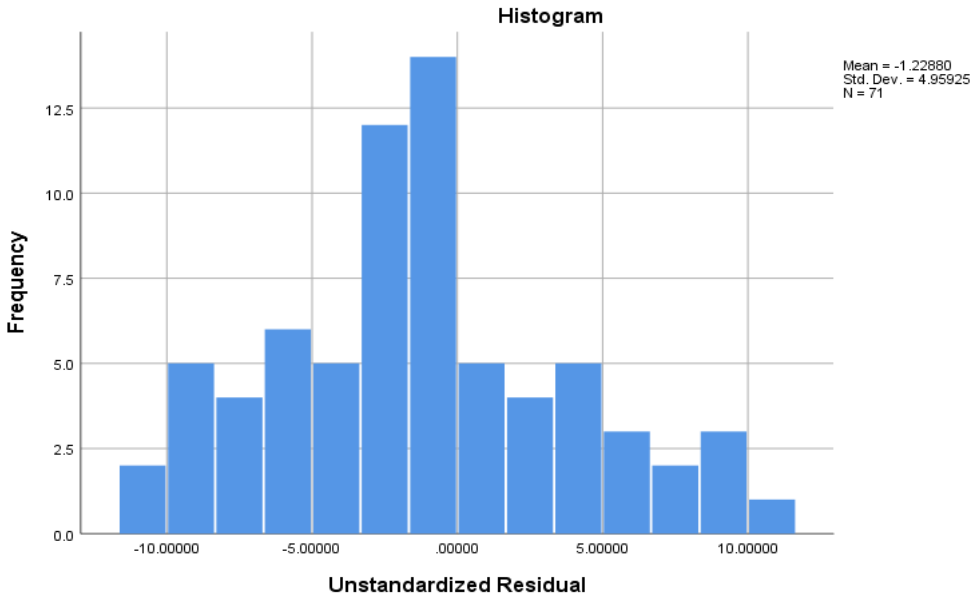


Figure C.5 Stage 3-5 driver residual histogram

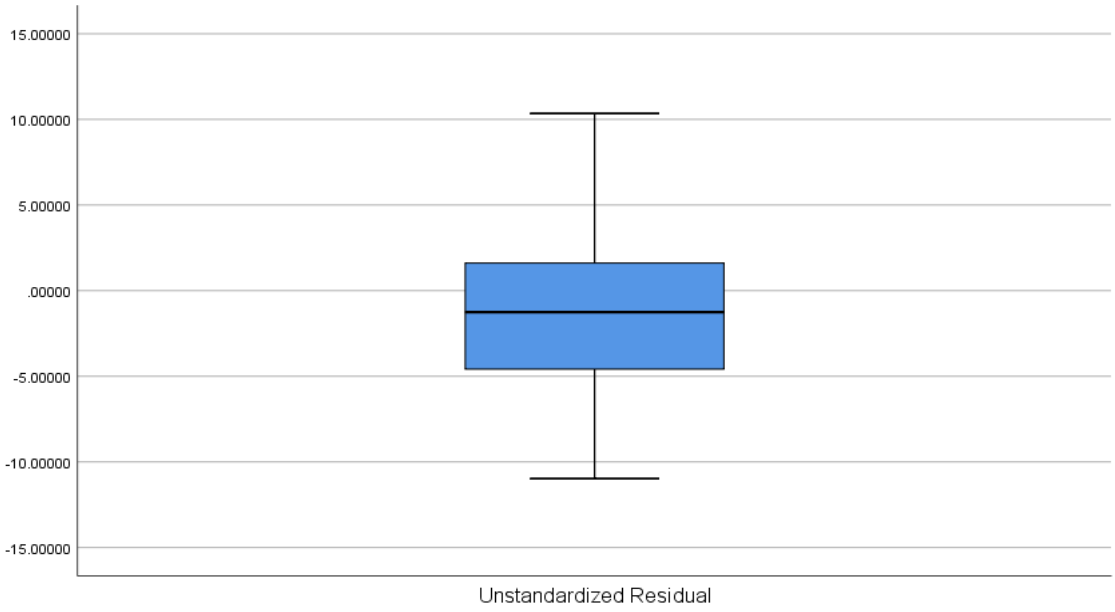


Figure C.6 Stage 3-5 driver residual distribution box plot

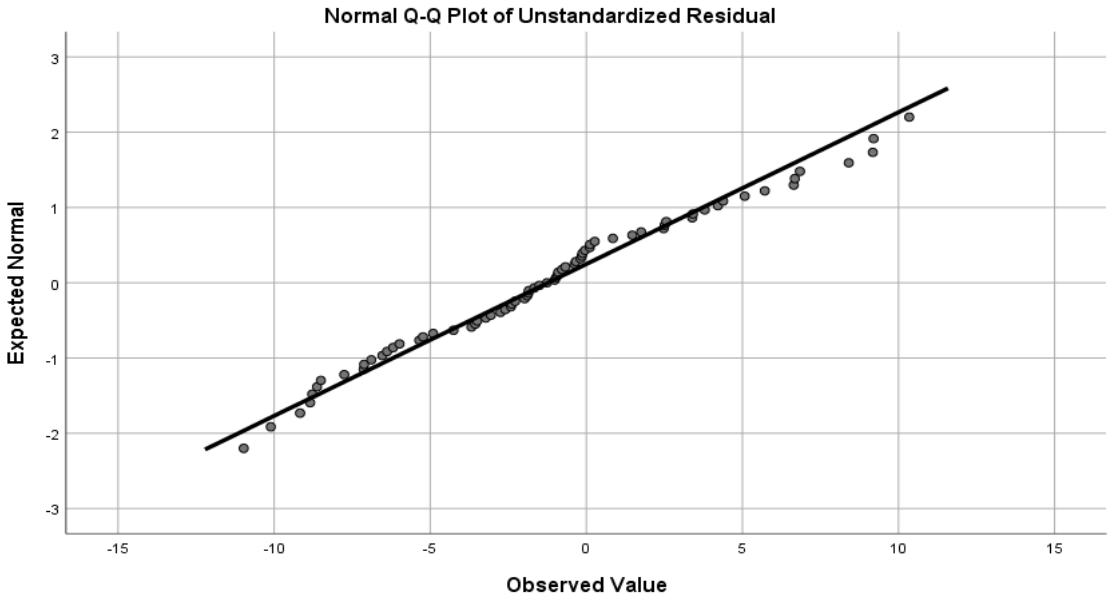


Figure C.7 Stage 3-5 driver residual Q-Q plot

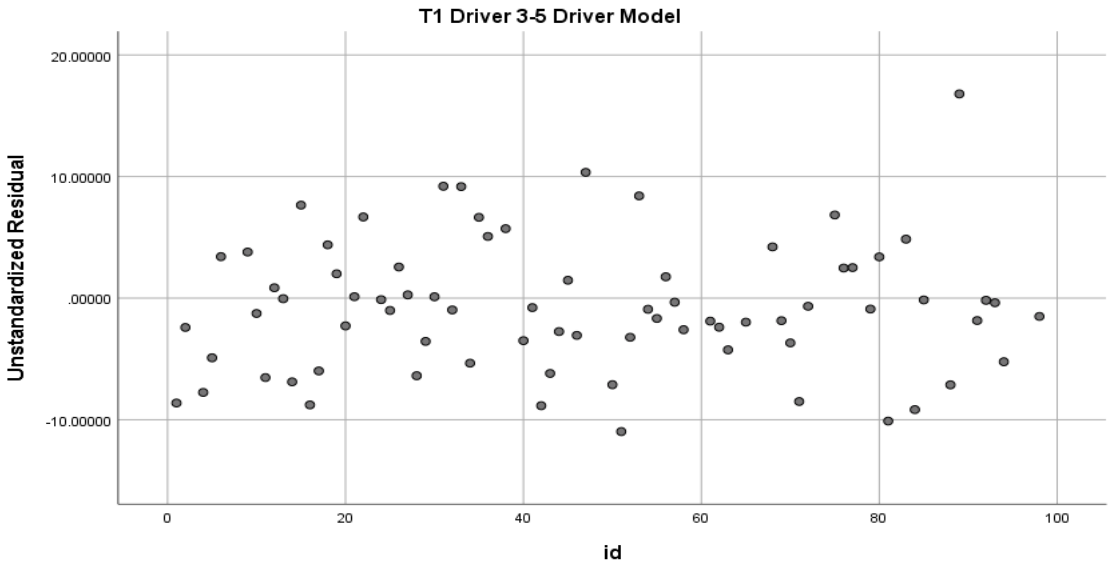


Figure C.8 Stage 3-5 driver residual scatter plot

C.1.3 Stage 3-5 P-GPC Relationships: 120m Shot Ball & Club Kinematics – HCP

Table C.5 Stage 3-5 120 m regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		-1.2477136	0.70271979
	95% Confidence Interval for Mean	Lower Bound	-2.6496013	
		Upper Bound	0.1541740	
	5% Trimmed Mean		-1.2889706	
	Median		-1.9688683	
	Variance		34.567	
	Std. Deviation		5.87937562	
	Minimum		-14.19724	
	Maximum		14.25785	
	Range		28.45509	
	Interquartile Range		8.65867	
	Skewness		0.219	0.287
	Kurtosis		-0.406	0.566

Table C.6 Stage 3-5 120 m residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.077	70	.200*	0.985	70	0.562
*. This is a lower bound of the true significance.						
a. Lilliefors Significance Correction						

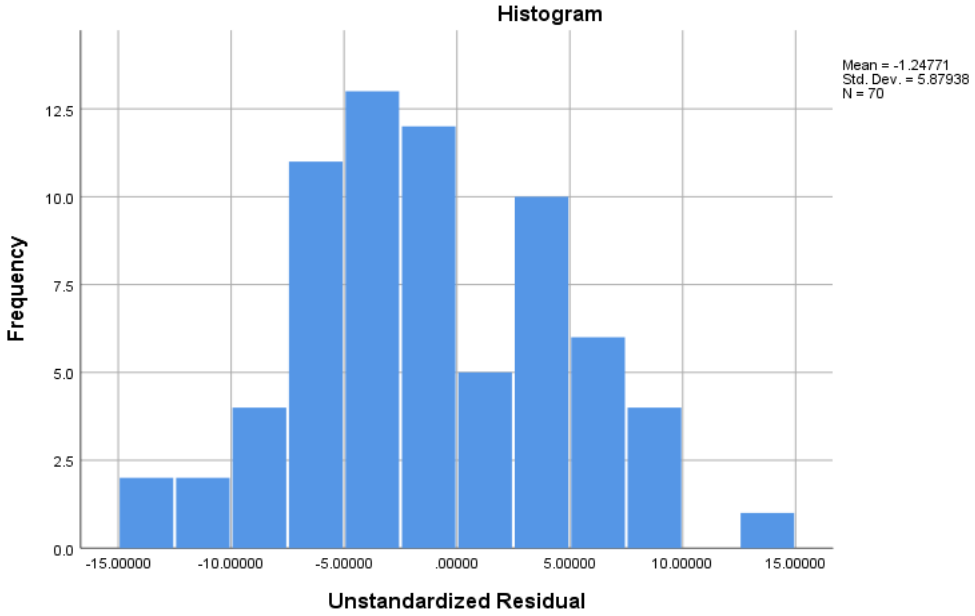


Figure C.9 Stage 3-5 120 m residual histogram

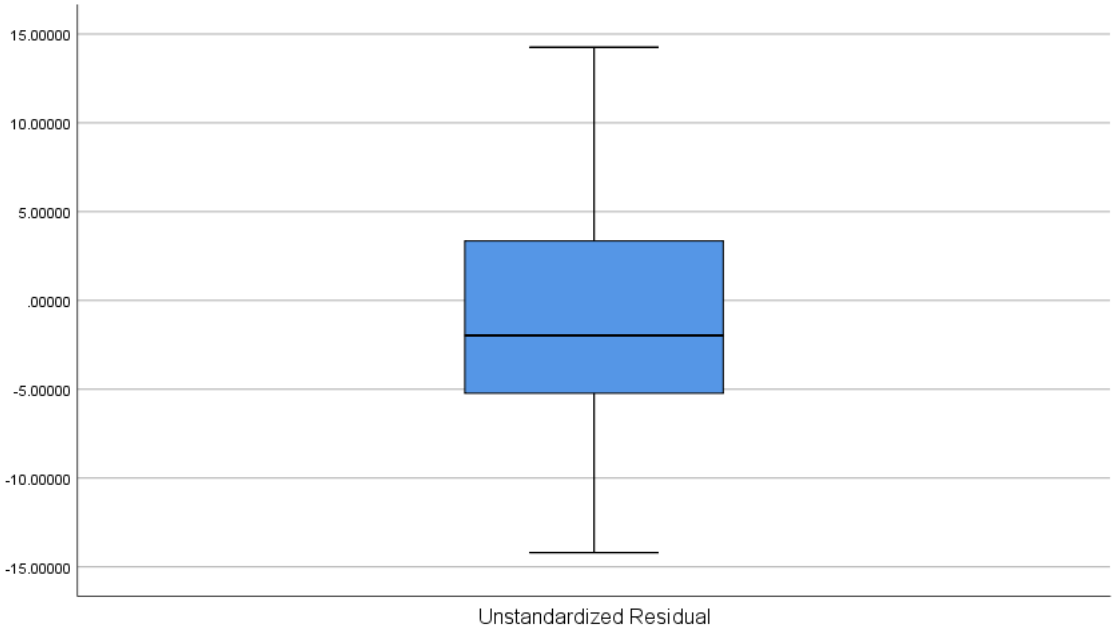


Figure C.10 Stage 3-5 120 m residual distribution box plot

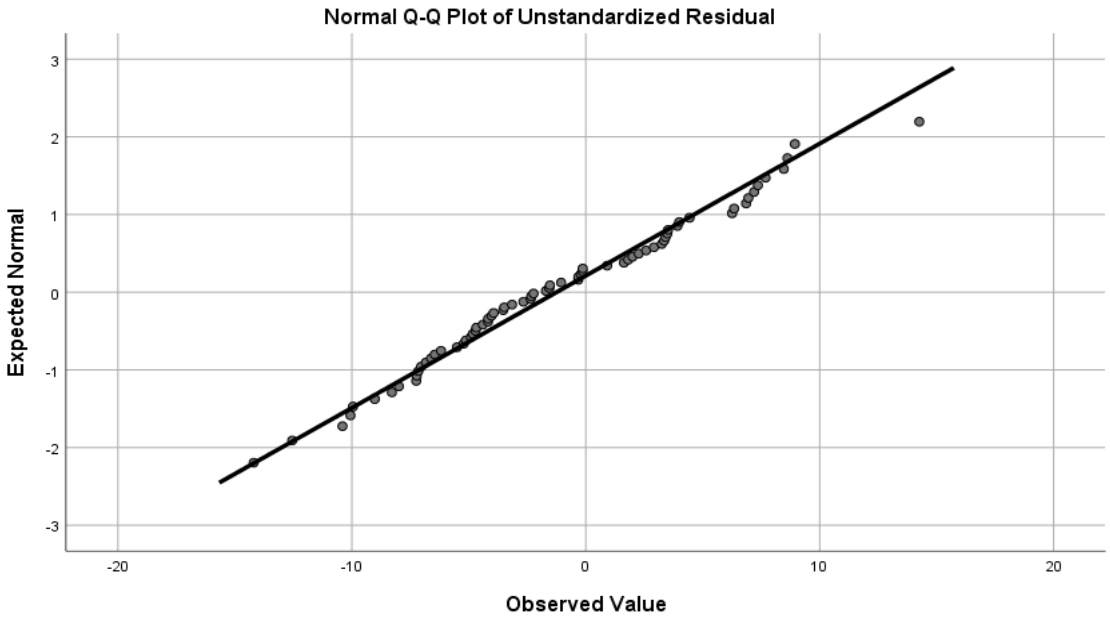


Figure C.11 Stage 3-5 120 m residual Q-Q plot

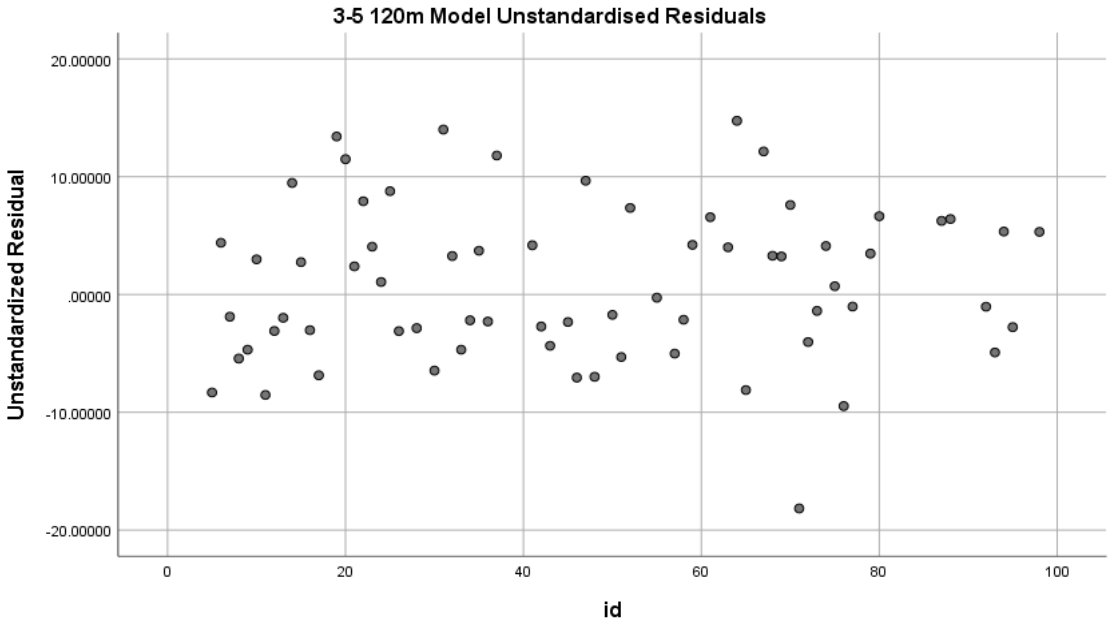


Figure C.12 Stage 3-5 120 m residual scatter plot

C.1.4 Stage 3-4 P-GPC Relationships: Ball Kinematics – Driver Total Distance

Table C.7 Stage 3-4 driver ball regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		-0.5799831	0.41867448
	95% Confidence Interval for Mean	Lower Bound	-1.4150030	
		Upper Bound	0.2550368	
	5% Trimmed Mean		-0.4435900	
	Median		-0.1685309	
	Variance		12.445	
	Std. Deviation		3.52781386	
	Minimum		-8.88906	
	Maximum		4.74156	
	Range		13.63063	
	Interquartile Range		5.86044	
	Skewness		-0.426	0.285
	Kurtosis		-0.496	0.563

Table C.8 Stage 3-4 driver ball residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.088	71	.200*	0.962	71	0.029
*. This is a lower bound of the true significance.						
a. Lilliefors Significance Correction						

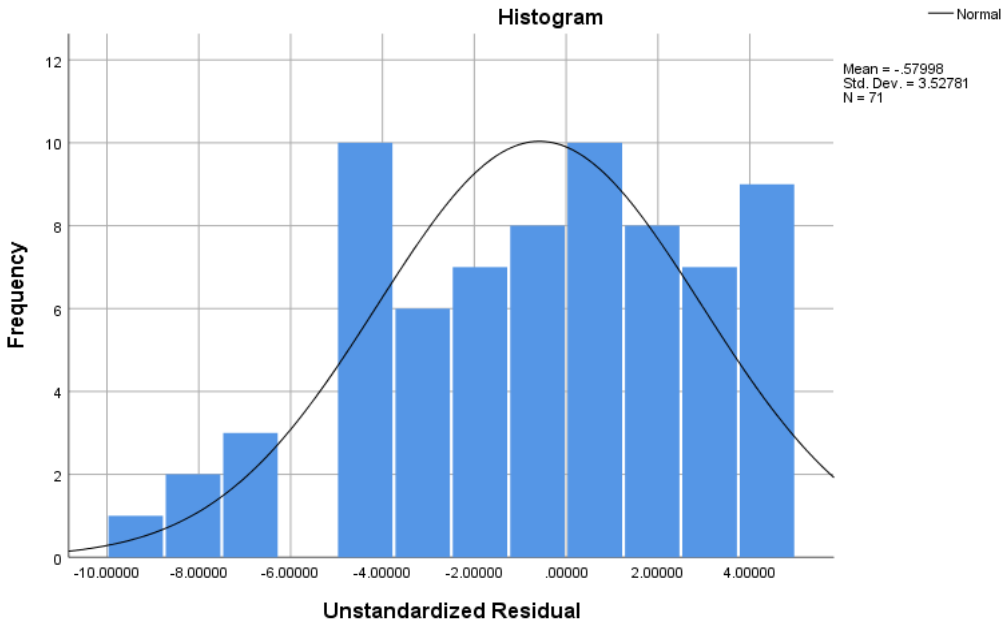


Figure C.13 Stage 3-4 driver ball residual histogram

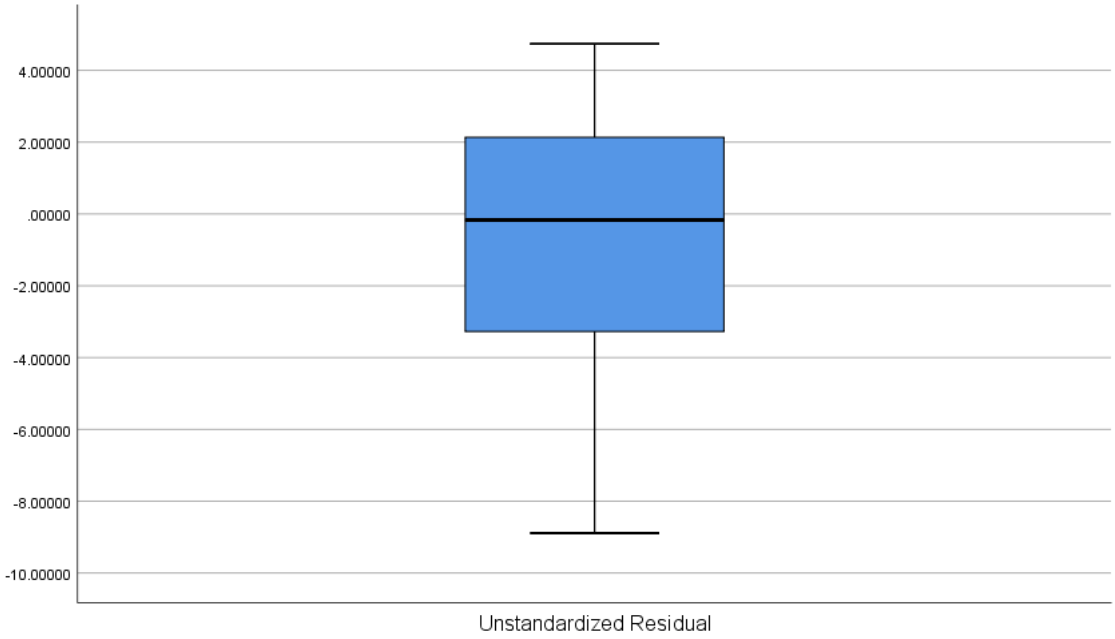


Figure C.14 Stage 3-4 driver ball residual distribution box plot

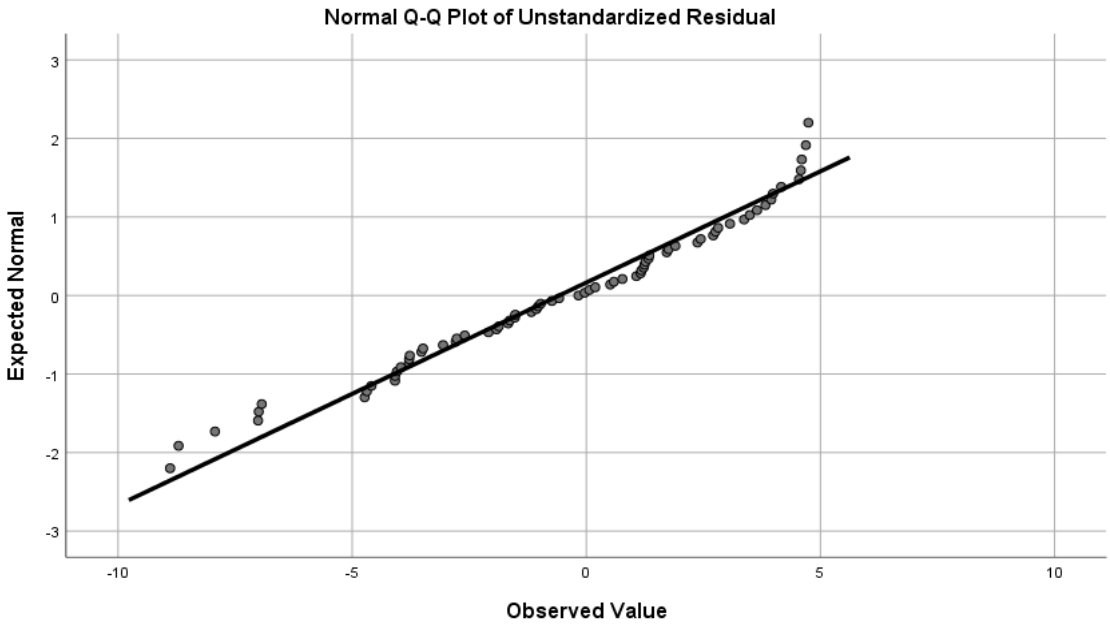


Figure C.15 Stage 3-4 driver ball residual Q-Q plot

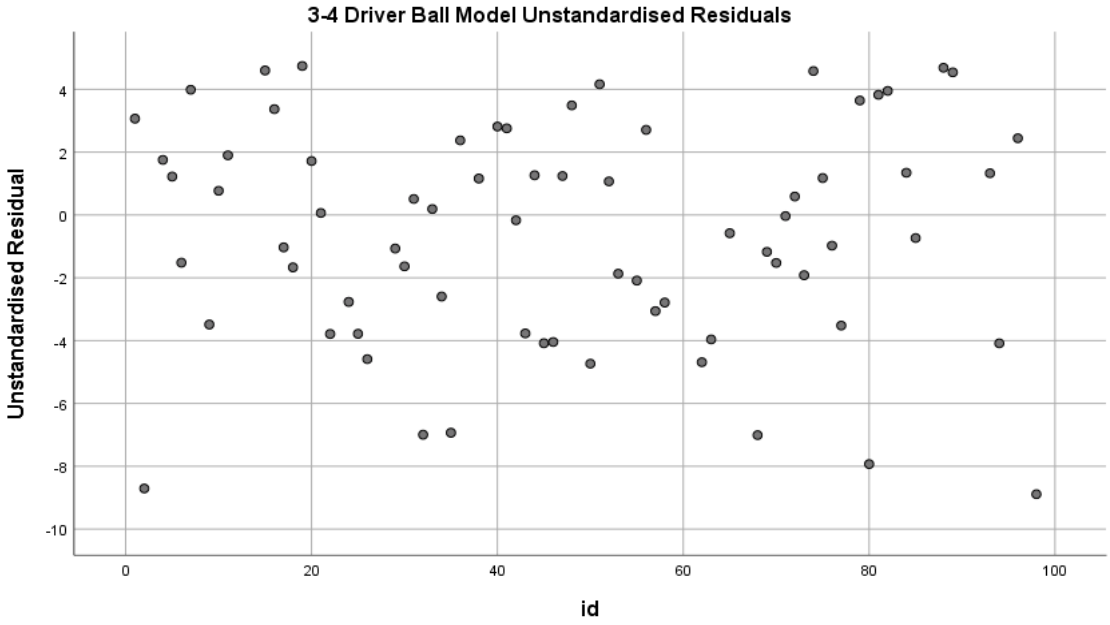


Figure C.16 Stage 3-4 driver ball residual scatter plot

C.1.5 Stage 3-4 P-GPC Relationships: Club Kinematics – Driver Total Distance

Table C.9 Stage 3-4 driver club regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		-0.5539852	0.63888988
	95% Confidence Interval for Mean	Lower Bound	-1.8254166	
		Upper Bound	0.7174461	
	5% Trimmed Mean		-0.5111427	
	Median		0.0452412	
	Variance		33.063	
	Std. Deviation		5.75000891	
	Minimum		-15.47246	
	Maximum		15.00580	
	Range		30.47827	
	Interquartile Range		6.09393	
	Skewness		-0.200	0.267
	Kurtosis		0.465	0.529

Table C.10 Stage 3-4 driver club residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.098	81	0.050	0.984	81	0.397
a. Lilliefors Significance Correction						

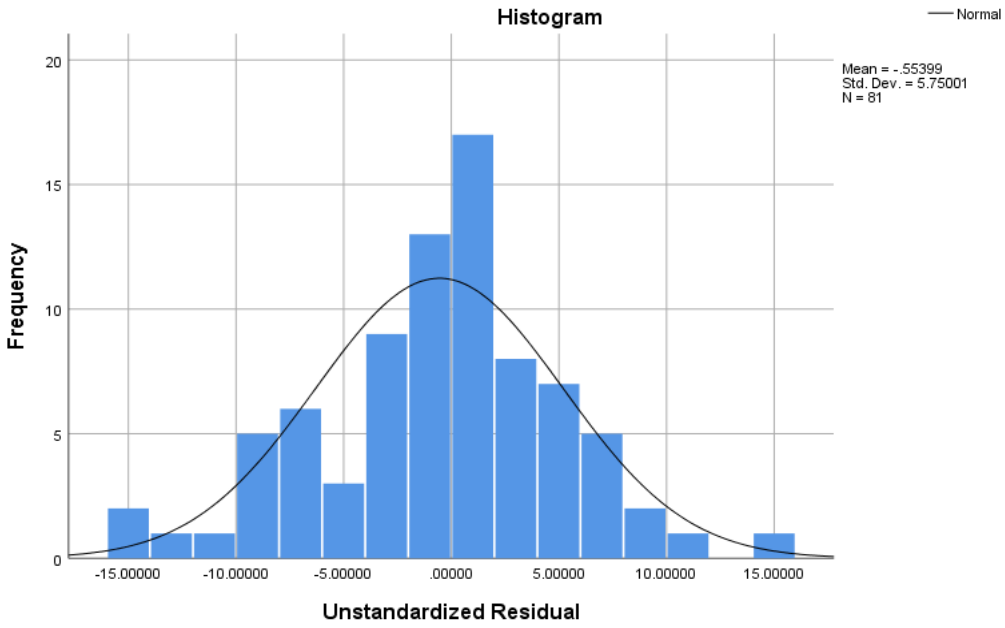


Figure C.17 Stage 3-4 driver club residual histogram

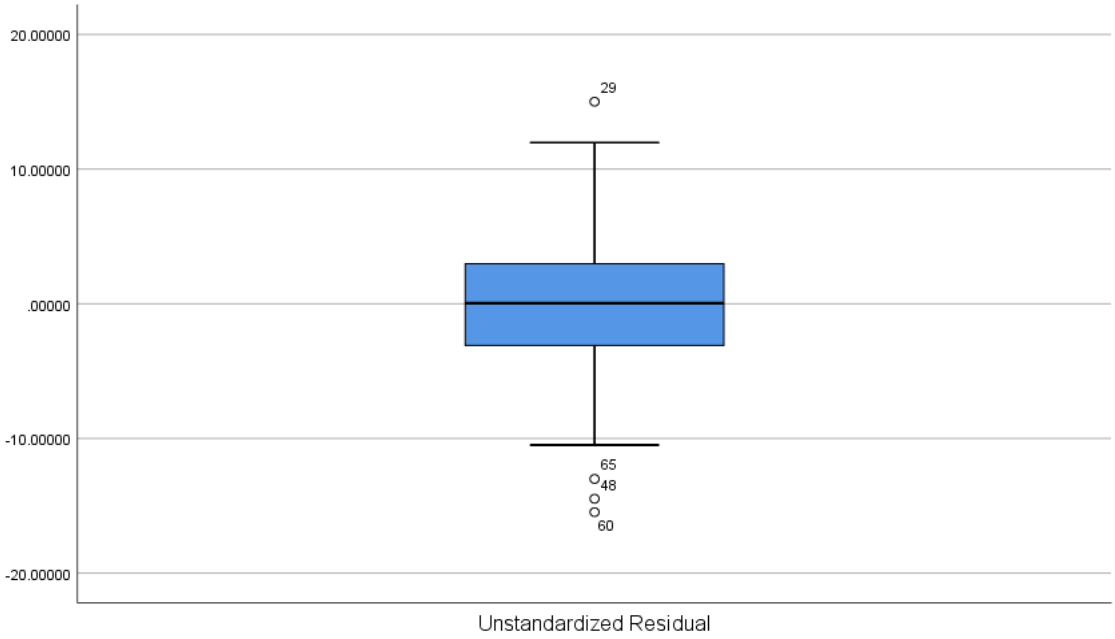


Figure C.18 Stage 3-4 driver club residual distribution box plot

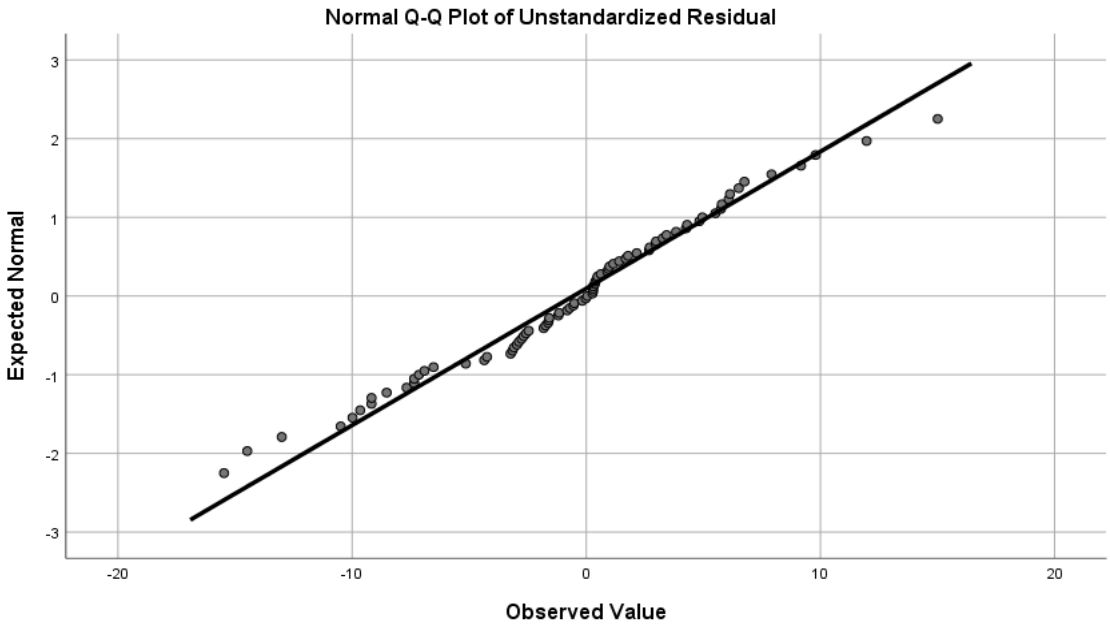


Figure C.19 Stage 3-4 driver club residual Q-Q plot

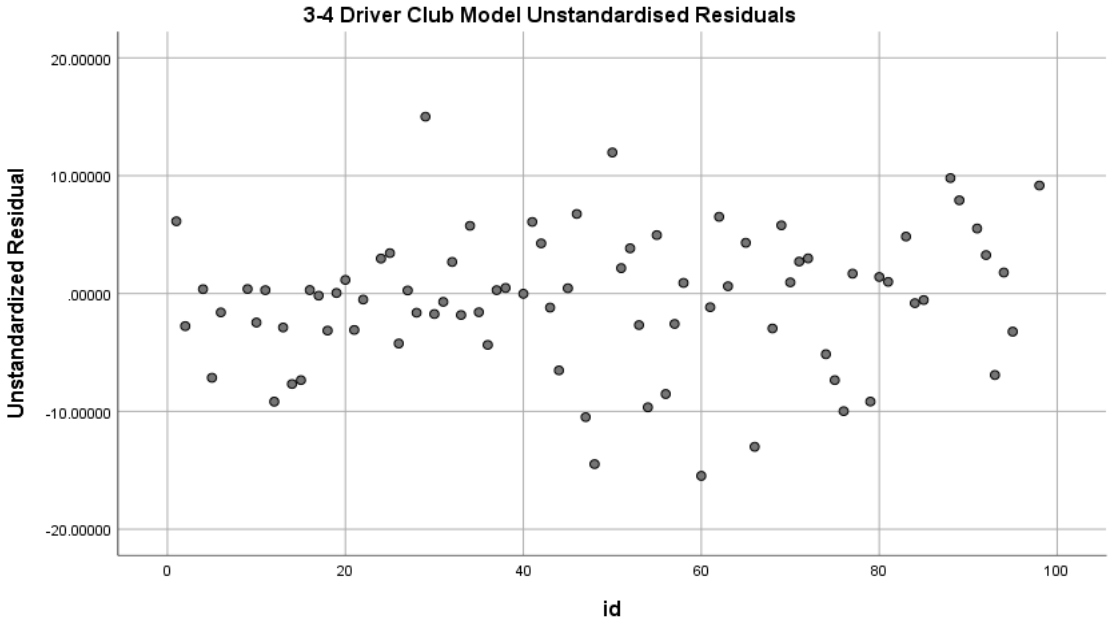


Figure C.20 Stage 3-4 driver club residual scatter plot

C.1.6 Stage 3-4 P-GPC Relationships: Ball Kinematics – 120m Distance to Target

Table C.11 Stage 3-4 120 m ball regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		-0.1067463	0.39843977
	95% Confidence Interval for Mean	Lower Bound	-0.8995165	
		Upper Bound	0.6860239	
	5% Trimmed Mean		-0.2296556	
	Median		-0.6513861	
	Variance		13.018	
	Std. Deviation		3.60802562	
	Minimum		-6.11736	
	Maximum		9.98519	
	Range		16.10255	
	Interquartile Range		5.71122	
	Skewness		0.407	0.266
	Kurtosis		-0.321	0.526

Table C.12 Stage 3-4 120 m ball residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.087	82	0.193	0.968	82	0.041
a. Lilliefors Significance Correction						

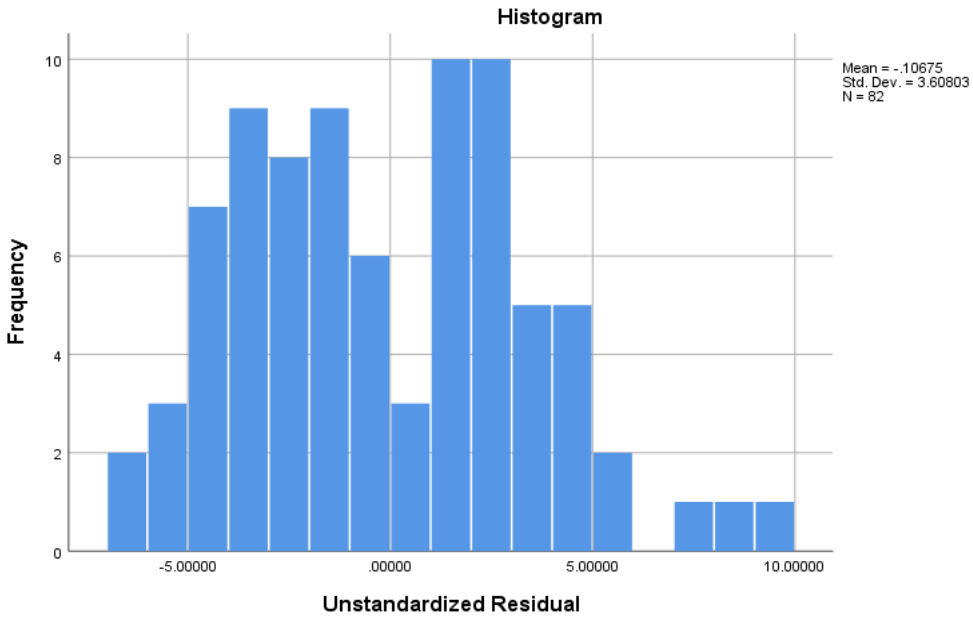


Figure C.21 Stage 3-4 120 m ball residual histogram

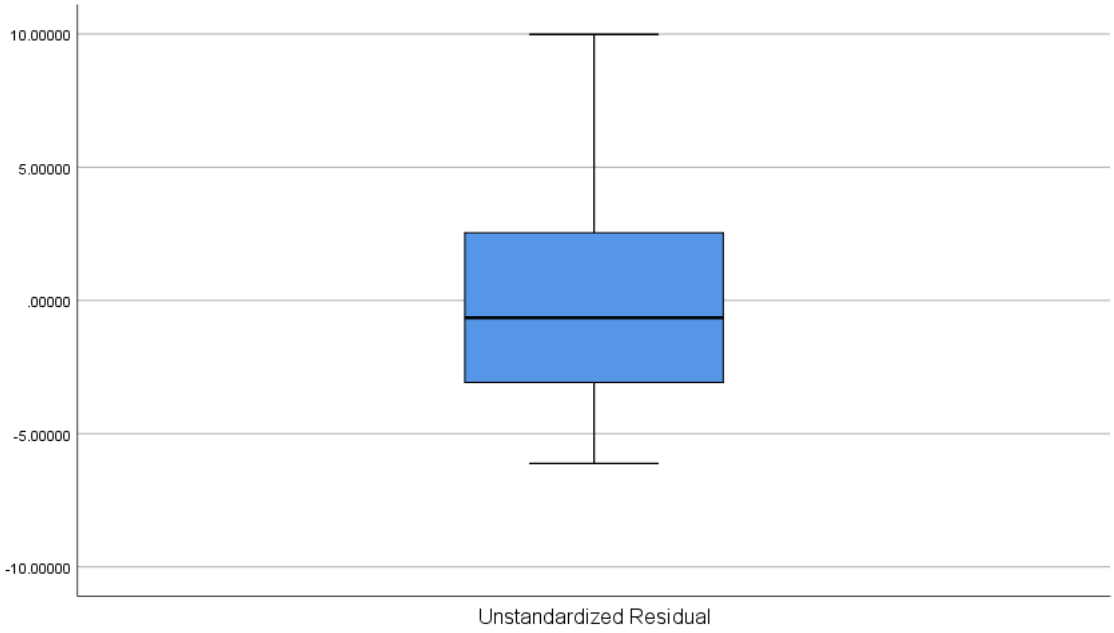


Figure C.22 Stage 3-4 120 m ball residual distribution box plot

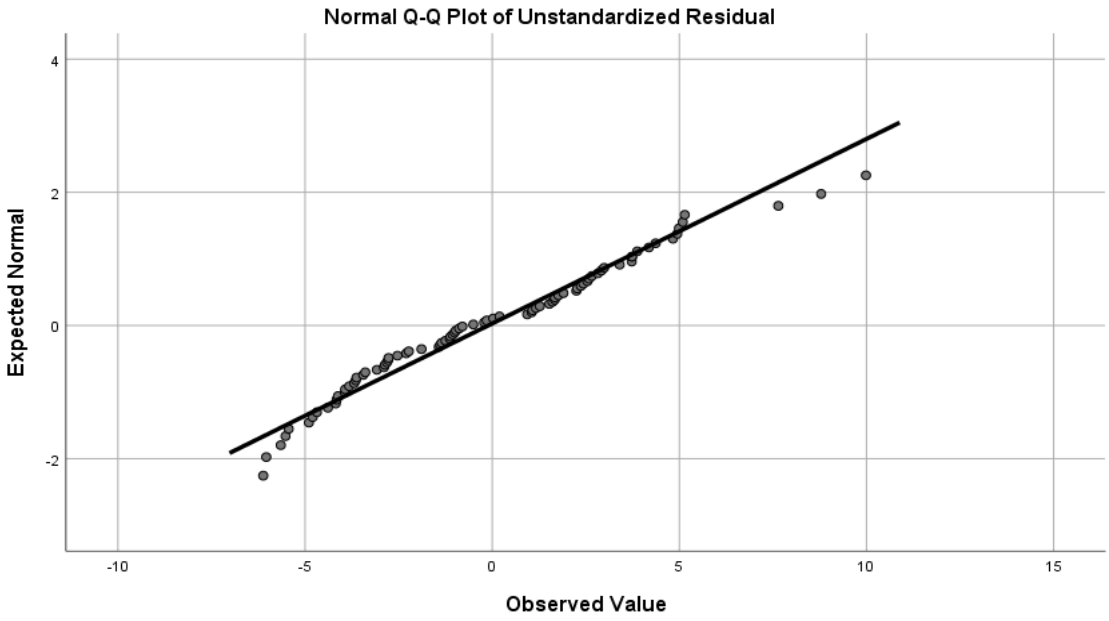


Figure C.23 Stage 3-4 120 m ball residual Q-Q plot

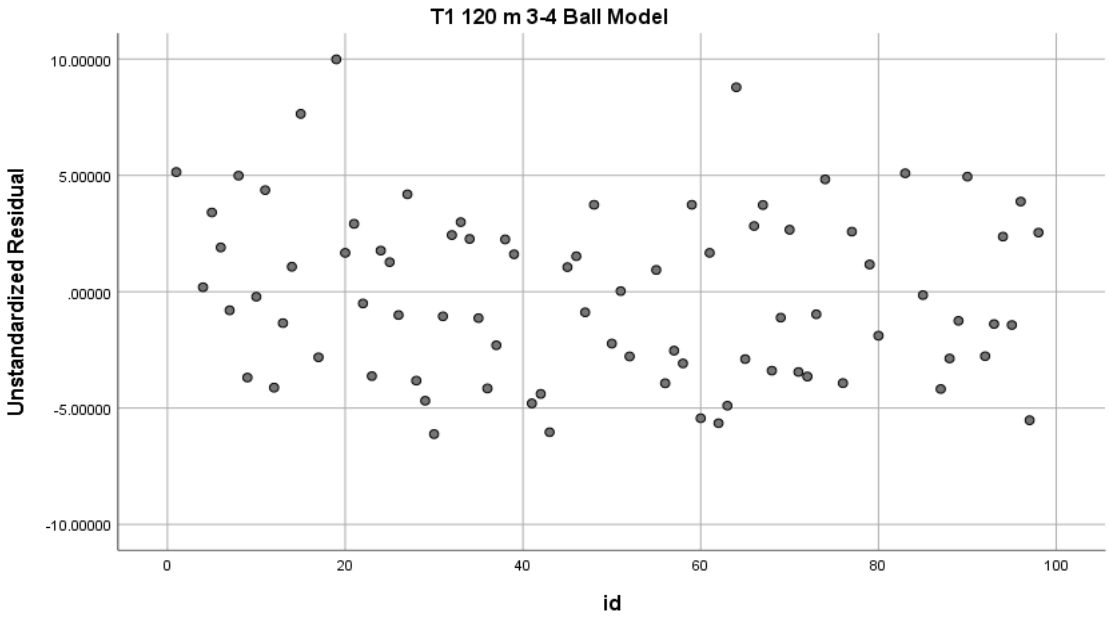


Figure C.24 Stage 3-4 120 m ball residual scatter plot

C.1.7 Stage 3-4 P-GPC Relationships: Club Kinematics – 120m Distance to Target

Table C.13 Stage 3-4 120 m club regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		-0.4314045	0.38569929
	95% Confidence Interval for Mean	Lower Bound	-1.2008535	
		Upper Bound	0.3380446	
	5% Trimmed Mean		-0.4743146	
	Median		-0.7703657	
	Variance		10.413	
	Std. Deviation		3.22699181	
	Minimum		-7.00788	
	Maximum		7.20522	
	Range		14.21310	
	Interquartile Range		4.83412	
	Skewness		0.216	0.287
	Kurtosis		-0.525	0.566

Table C.14 Stage 3-4 120 m club residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.070	70	.200*	0.983	70	0.481
*. This is a lower bound of the true significance.						
a. Lilliefors Significance Correction						

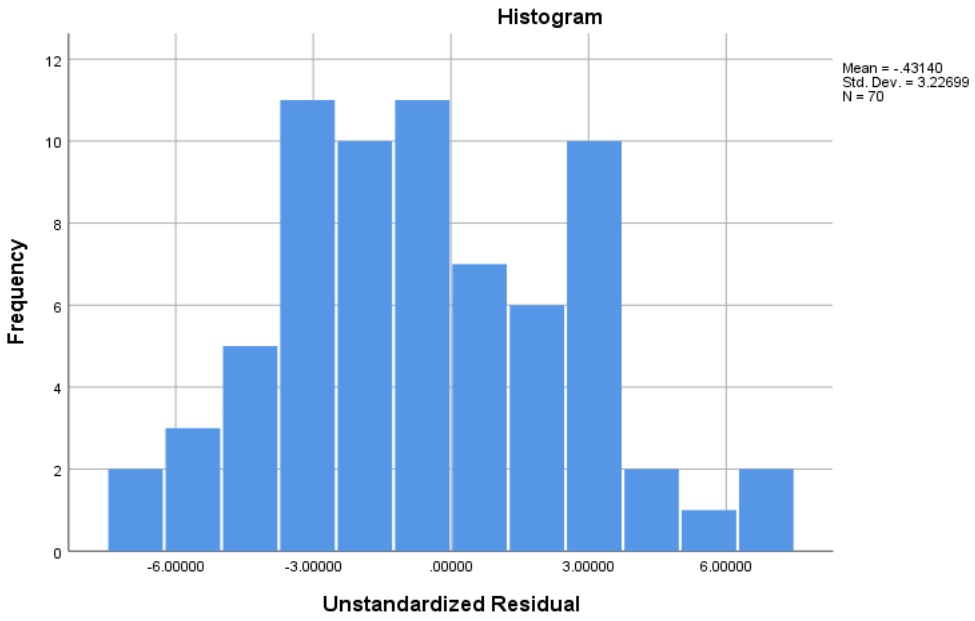


Figure C.25 Stage 3-4 120 m club residual histogram

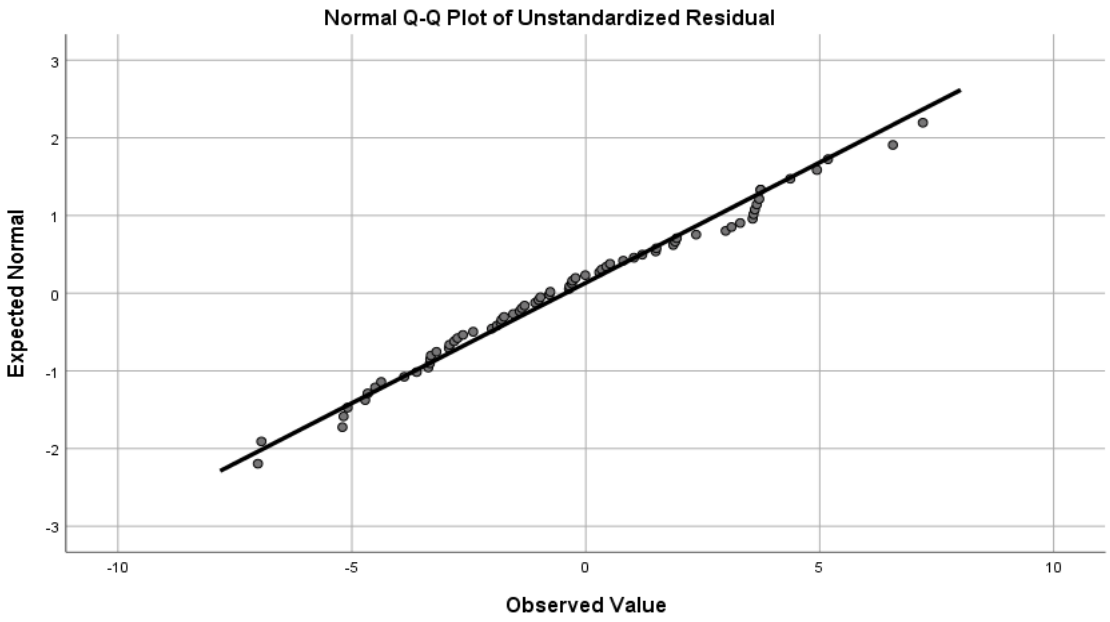


Figure C.26 Stage 3-4 120 m club residual Q-Q plot

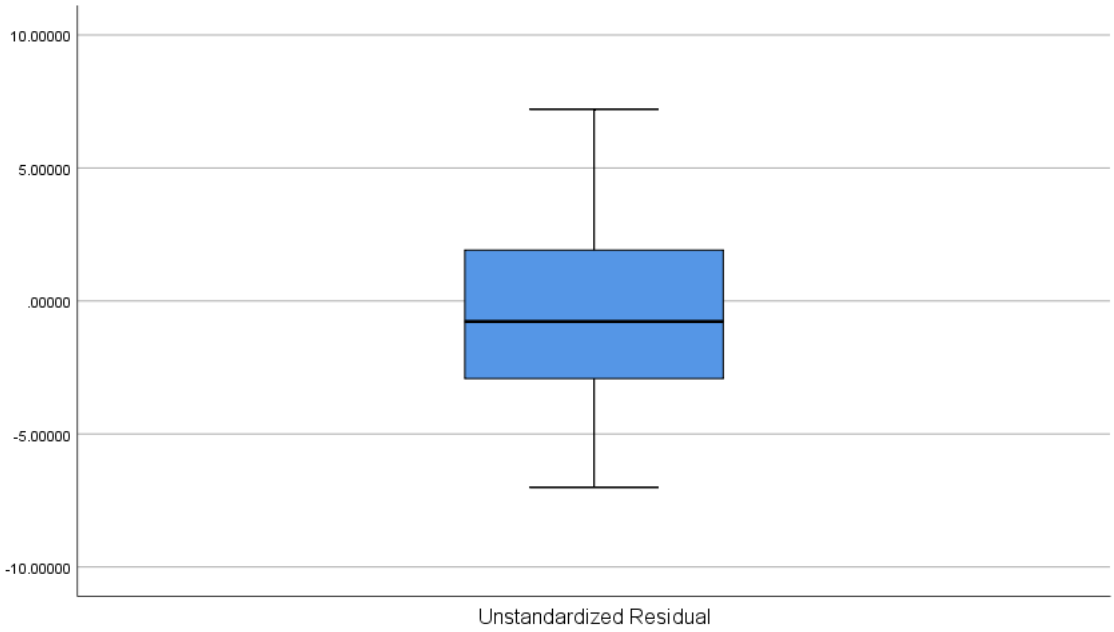


Figure C.27 Stage 3-4 120 m club residual distribution box plot

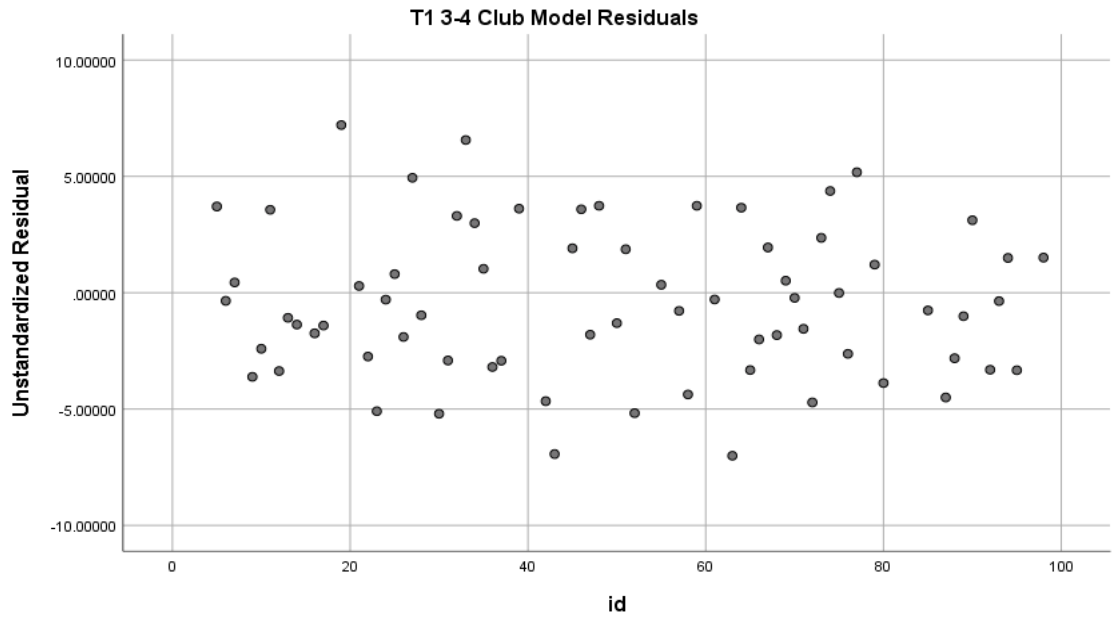


Figure C.28 Stage 3-4 120 m club residual scatter plot

C.1.8 Stage 2-4 P-GPC Relationships: Body Kinematics & GRF – Driver Distance

Table C.15 Stage 2-4 driver body & GRF regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		-6.9227440	3.01694154
	95% Confidence Interval for Mean	Lower Bound	-14.6669438	
		Upper Bound	2.2889079	
	5% Trimmed Mean		-7.3034374	
	Median		-8.2511341	
	Variance		473.301	
	Std. Deviation		21.75547482	
	Minimum		-50.92185	

	Maximum	47.36825	
	Range	98.29009	
	Interquartile Range	29.23866	
	Skewness	0.204	0.330
	Kurtosis	0.127	0.650

Table C.16 Stage 2-4 driver body & GRF residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.068	52	.200*	0.986	52	0.802
*. This is a lower bound of the true significance.						
a. Lilliefors Significance Correction						

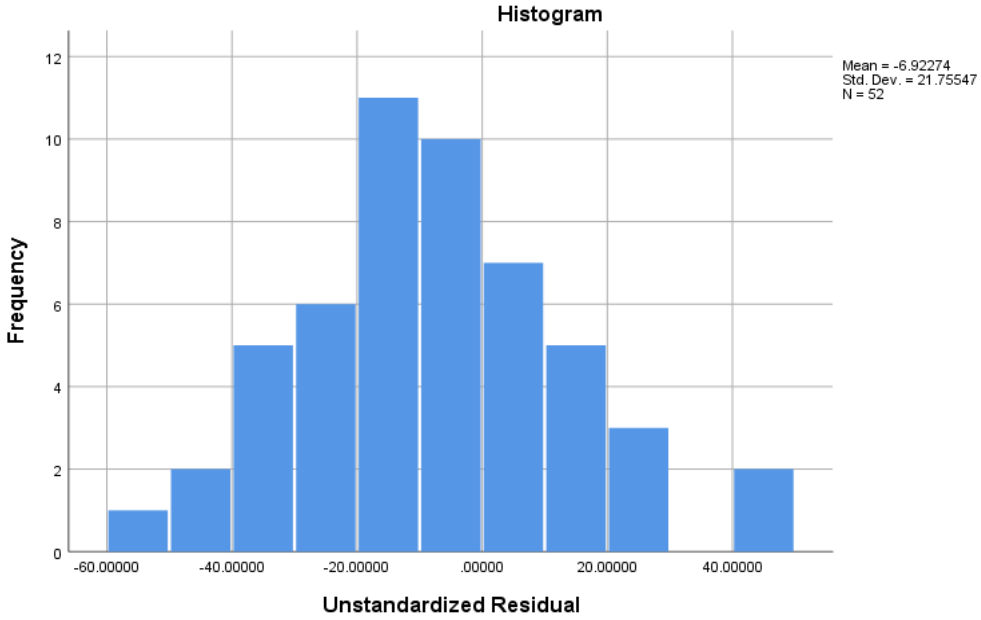


Figure C.29 Stage 2-4 driver body & GRF residual histogram

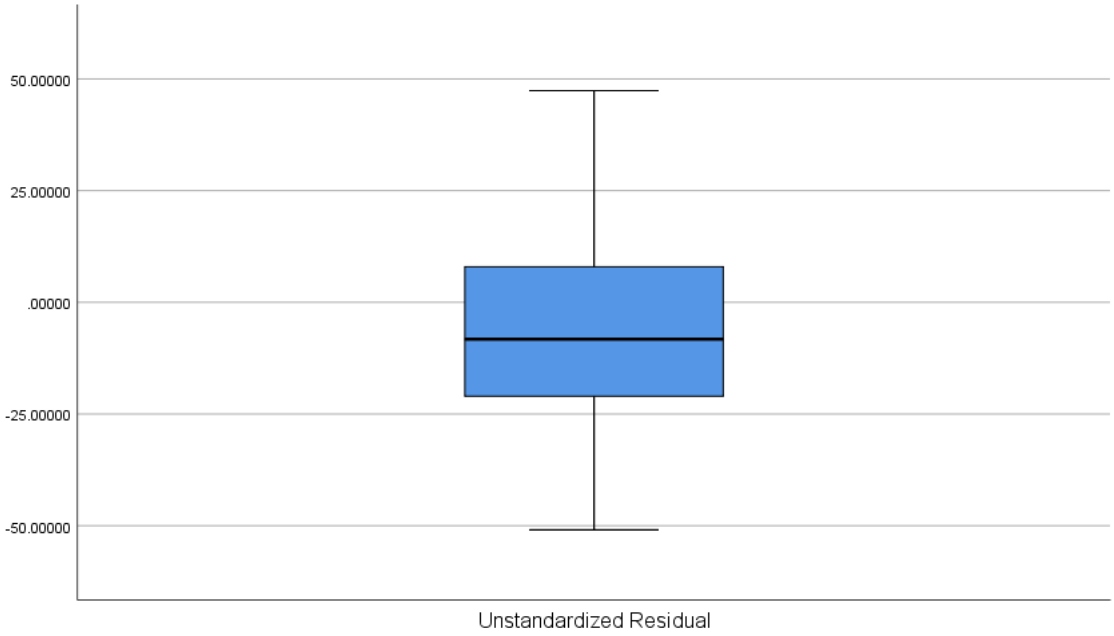


Figure C.30 Stage 2-4 driver body & GRF residual distribution box plot

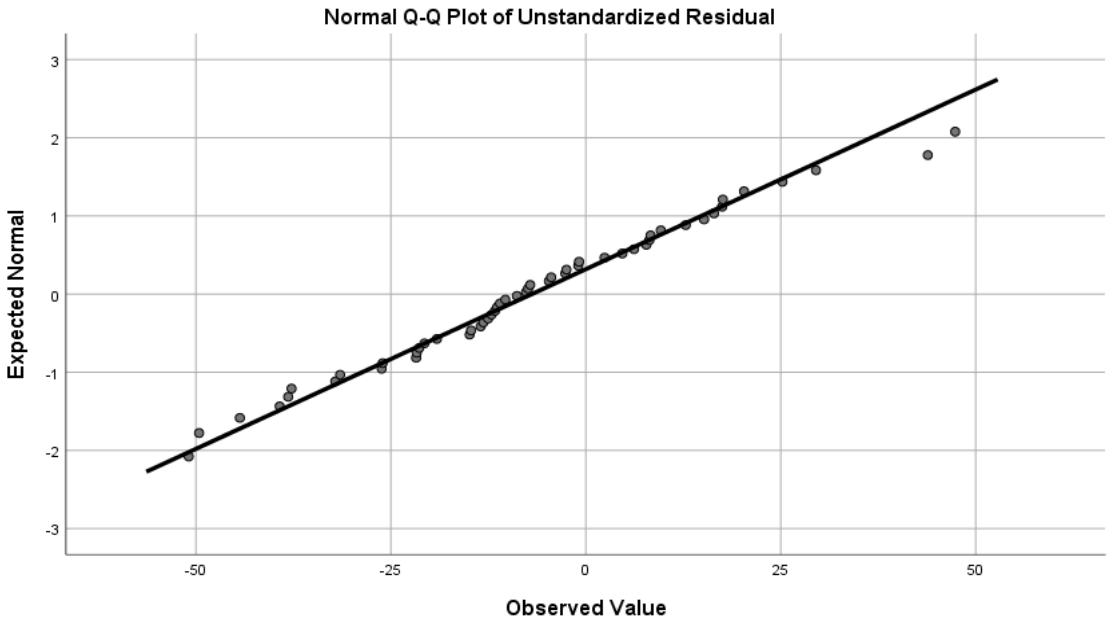


Figure C.31 Stage 2-4 driver body & GRF residual Q-Q plot

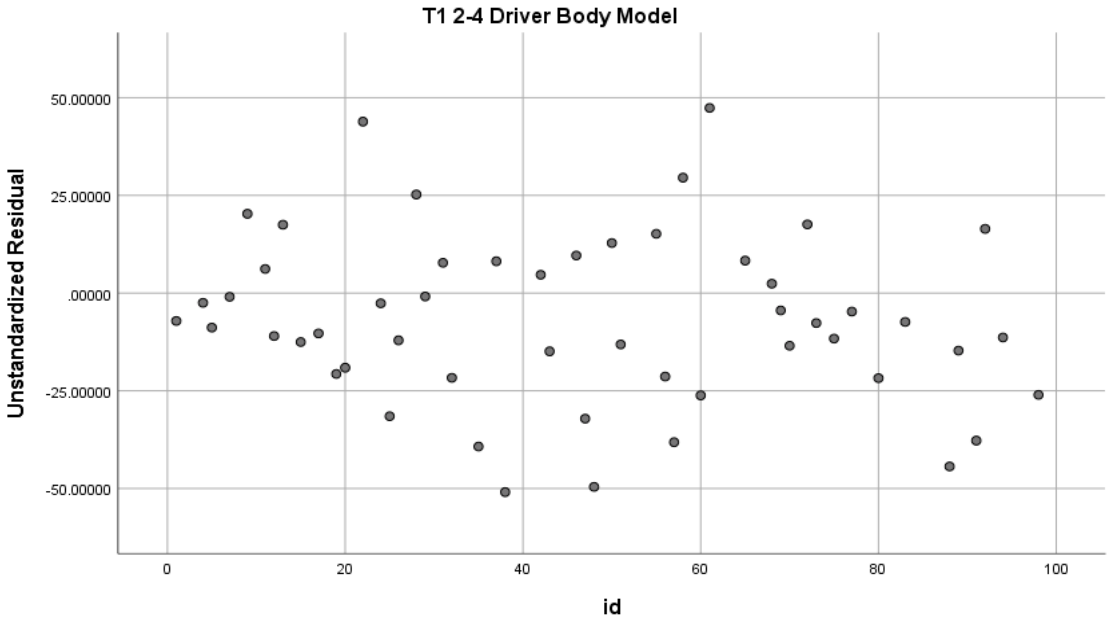


Figure C.32 Stage 2-4 driver body & GRF residual scatter plot

Table C.17 Stage 2-3 driver body & GRF regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		-2.0633301	1.02272911
	95% Confidence Interval for Mean	Lower Bound		
		Upper Bound		
	5% Trimmed Mean		-2.0816662	
	Median		-1.4930006	
	Variance		58.575	
	Std. Deviation		7.65340386	
	Minimum		-18.74714	
	Maximum		14.25550	
	Range		33.00265	
	Interquartile Range		9.09690	
	Skewness		-0.123	0.319
	Kurtosis		-0.163	0.628

Table C.18 Stage 2-3 driver body & GRF residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.103	56	.200*	0.976	56	0.327
*. This is a lower bound of the true significance.						
a. Lilliefors Significance Correction						

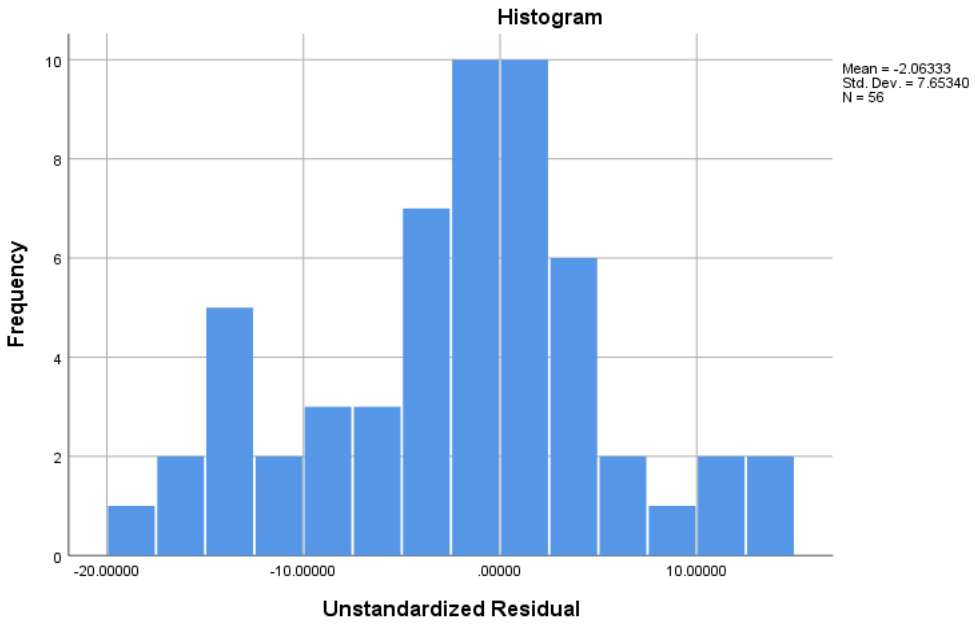


Figure C.33 Stage 2-3 driver body & GRF residual histogram

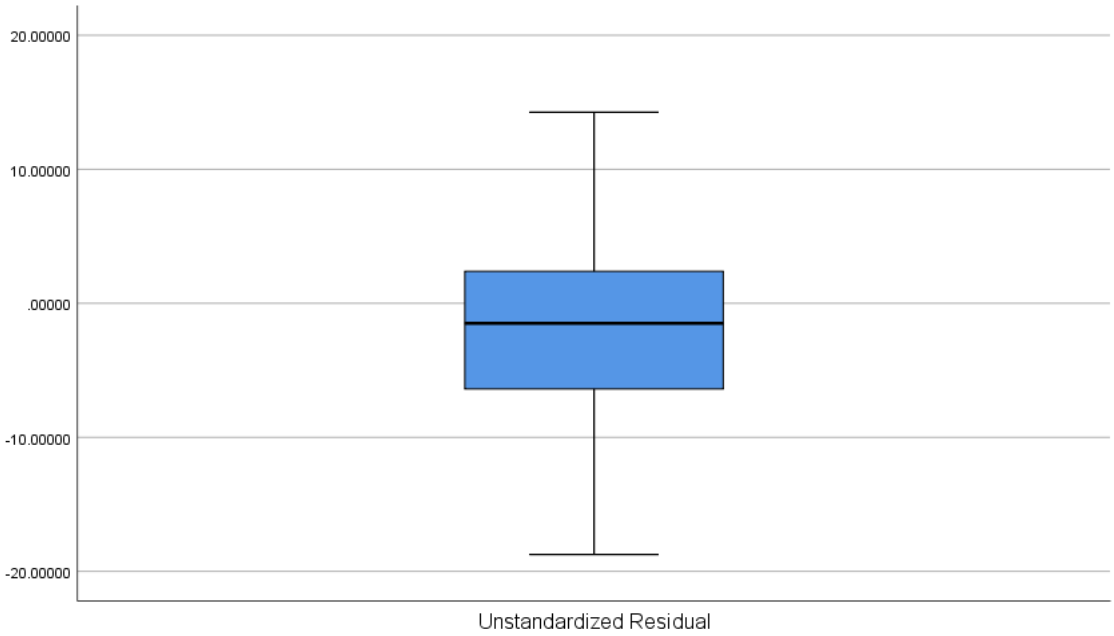


Figure C.34 Stage 2-3 driver body & GRF residual distribution box plot

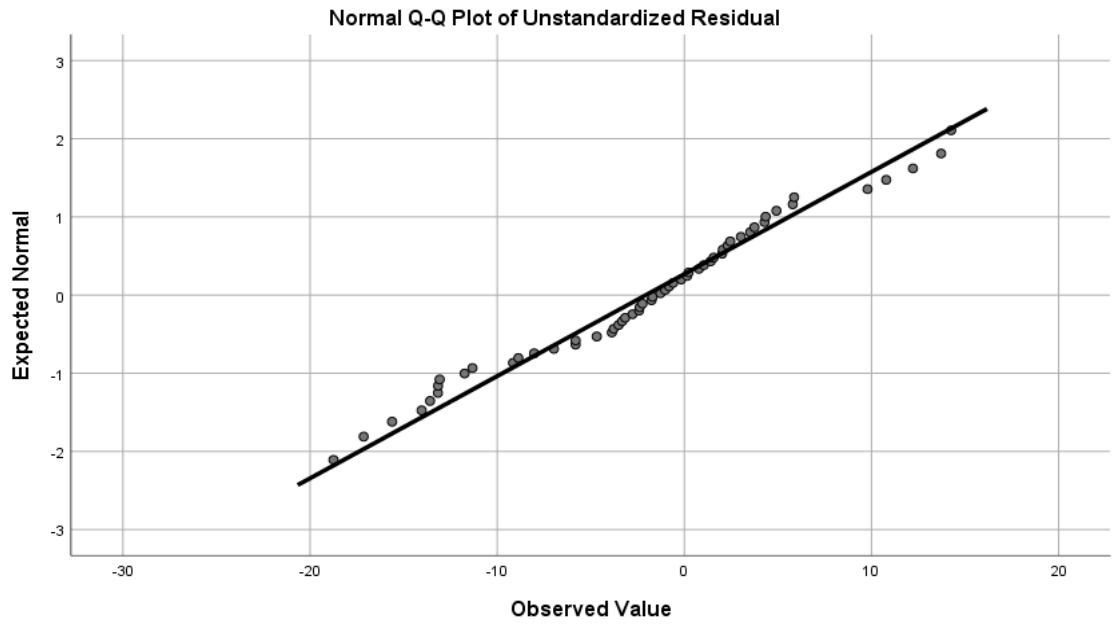


Figure C.35 Stage 2-3 driver body & GRF residual Q-Q plot

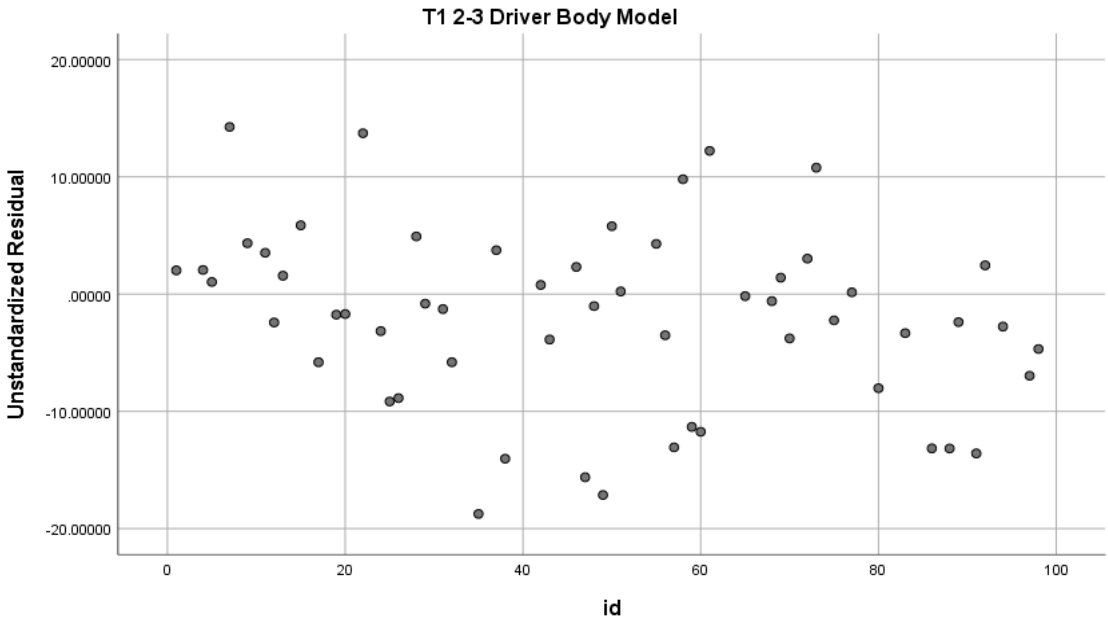


Figure C.36 Stage 2-3 driver body & GRF residual scatter plot

C.1.10 Stage 1-3 P-GPC Relationships: Physical – Driver CHS

Table C.19 Stage 1-3 driver physical regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		-0.1497451	0.90919812
	95% Confidence Interval for Mean	Lower Bound	-1.9733656	
		Upper Bound	1.6738754	
	5% Trimmed Mean		0.0820477	
	Median		-0.8036261	
	Variance		44.639	
	Std. Deviation		6.68121440	
	Minimum		-21.17769	
	Maximum		13.80261	
	Range		34.98030	
	Interquartile Range		10.22712	
	Skewness		-0.470	0.325
	Kurtosis		0.739	0.639

Table C.20 Stage 1-3 driver physical residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.079	54	.200*	0.975	54	0.322
*. This is a lower bound of the true significance.						
a. Lilliefors Significance Correction						

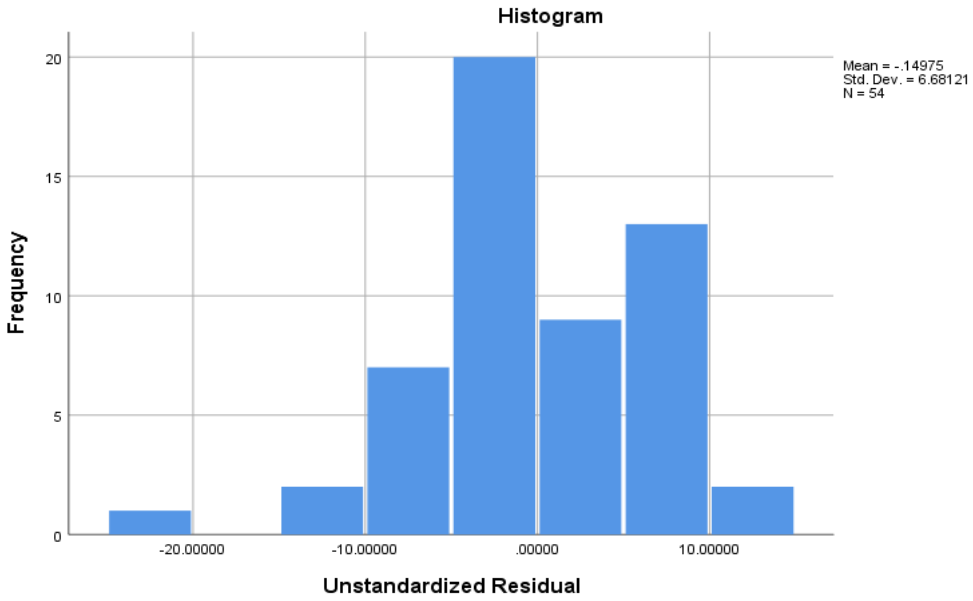


Figure C.37 Stage 1-3 driver physical residual histogram

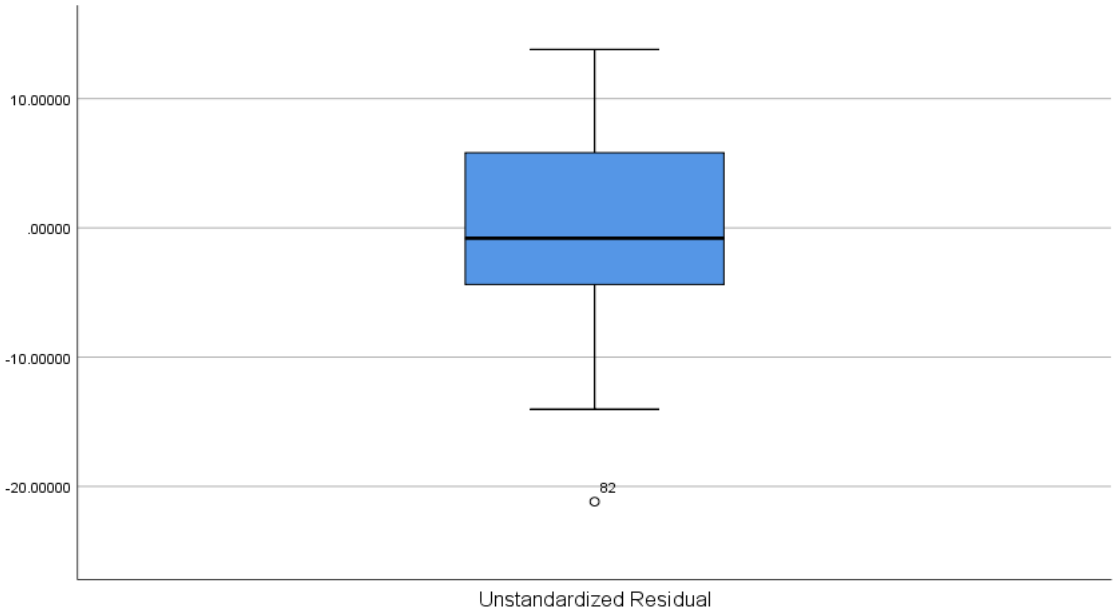


Figure C.38 Stage 1-3 driver physical residual distribution box plot

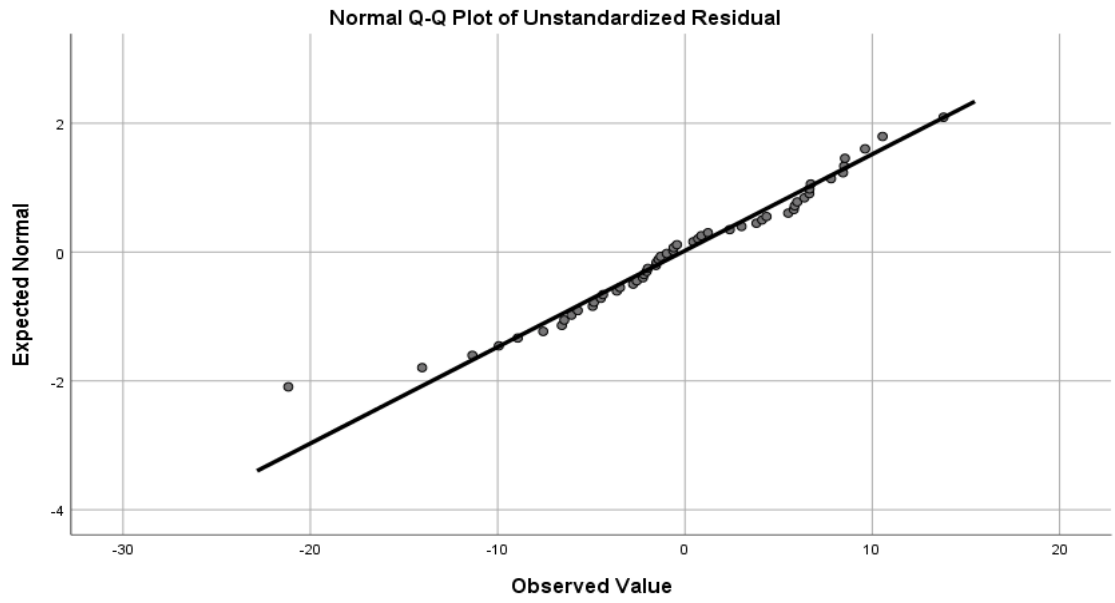


Figure C.39 Stage 1-3 driver physical residual Q-Q plot

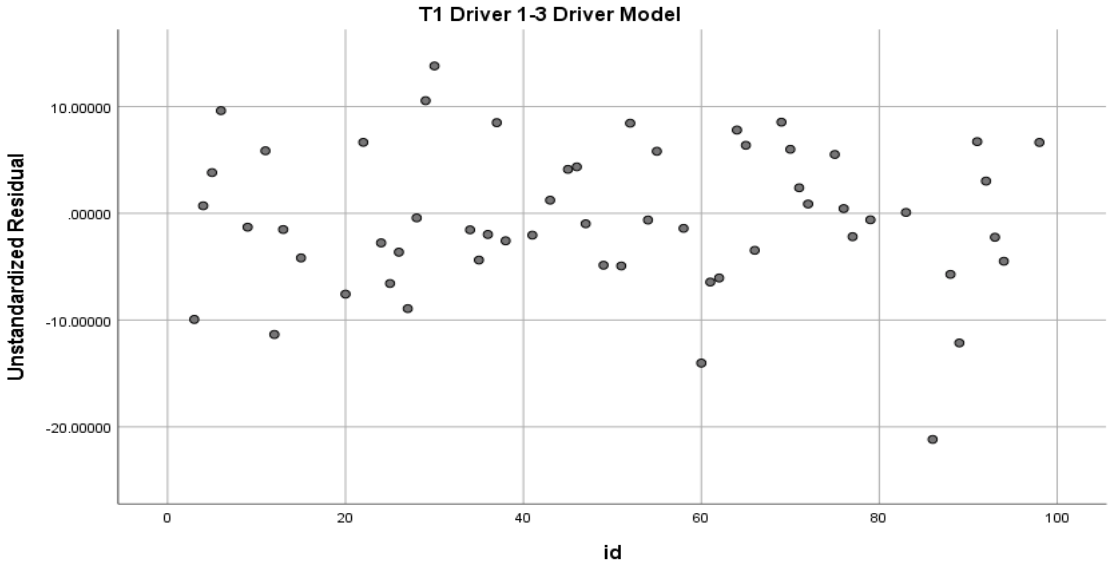


Figure C.40 Stage 1-3 driver physical residual scatter plot

C.1.11 Stage 1-3 P-GPC Relationships: Physical – 120m Spin Rate

Table C.21 Stage 1-3 120 m physical regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		12.6986895	162.35421015
	95% Confidence Interval for Mean	Lower Bound	-310.8727847	
		Upper Bound	336.2701637	
	5% Trimmed Mean		-4.6669227	
	Median		108.9435164	
	Variance		1950557.827	
	Std. Deviation		1396.62372422	
	Minimum		-2559.54613	
	Maximum		3338.81742	
	Range		5898.36355	
	Interquartile Range		2275.40138	
	Skewness		0.068	0.279
	Kurtosis		-0.728	0.552

Table C.22 Stage 1-3 120 m physical residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.055	74	.200*	0.980	74	0.300
*. This is a lower bound of the true significance.						
a. Lilliefors Significance Correction						

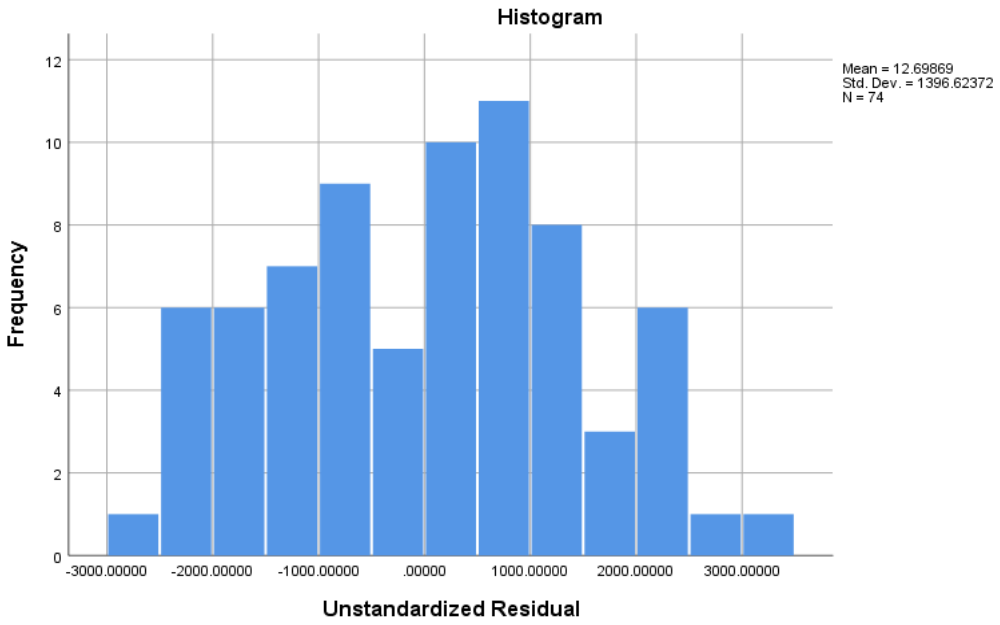


Figure C.41 Stage 1-3 120 m physical residual histogram

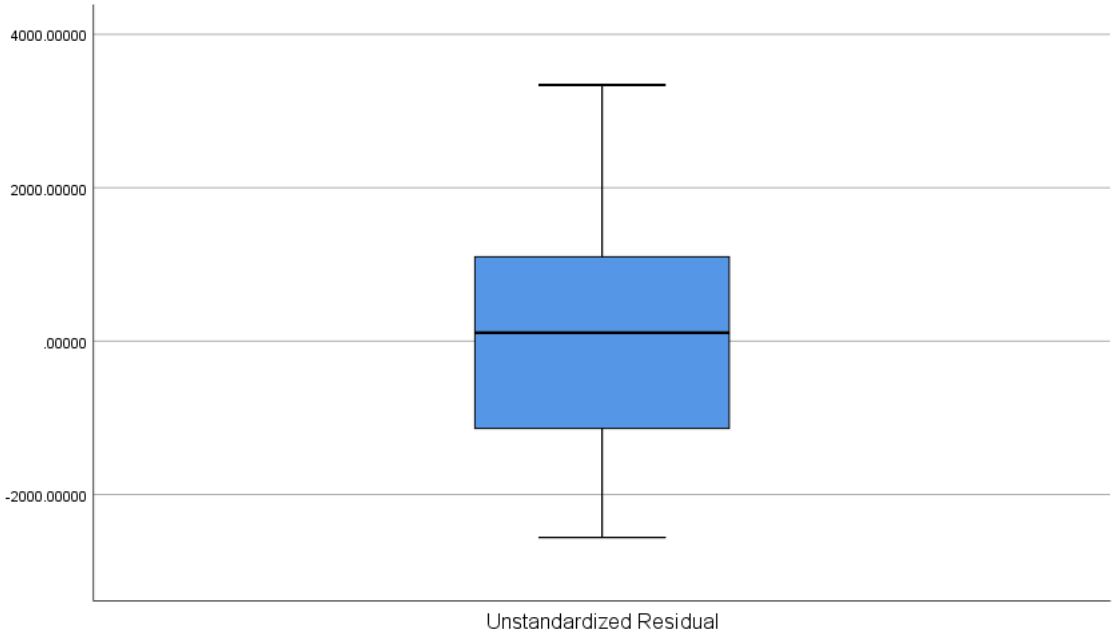


Figure C.42 Stage 1-3 120 m physical residual distribution box plot

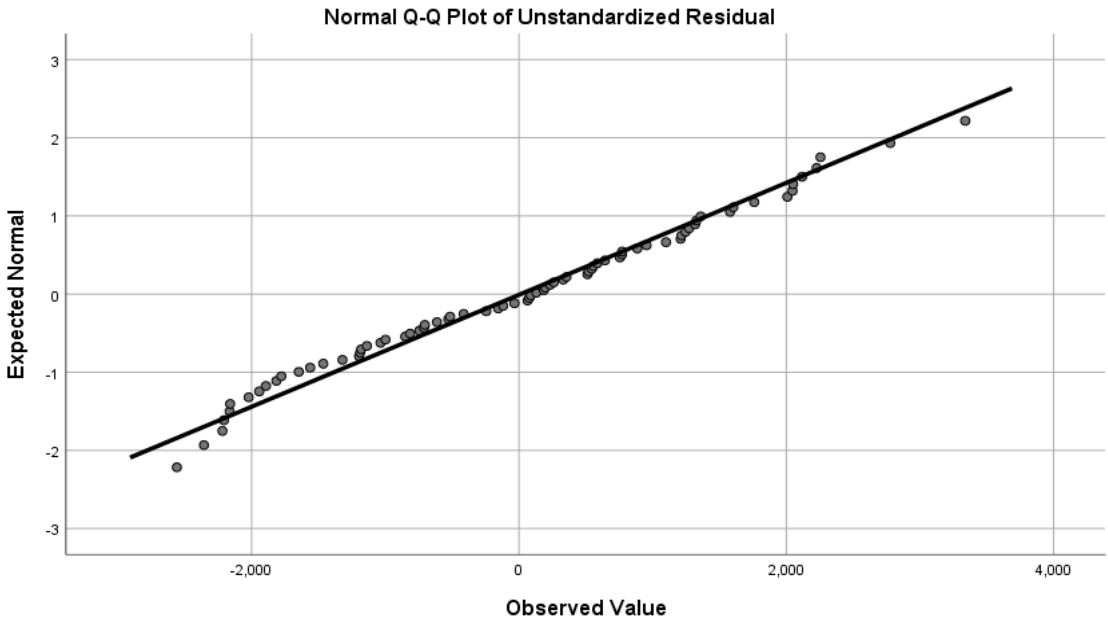


Figure C.43 Stage 1-3 120 m physical residual Q-Q plot

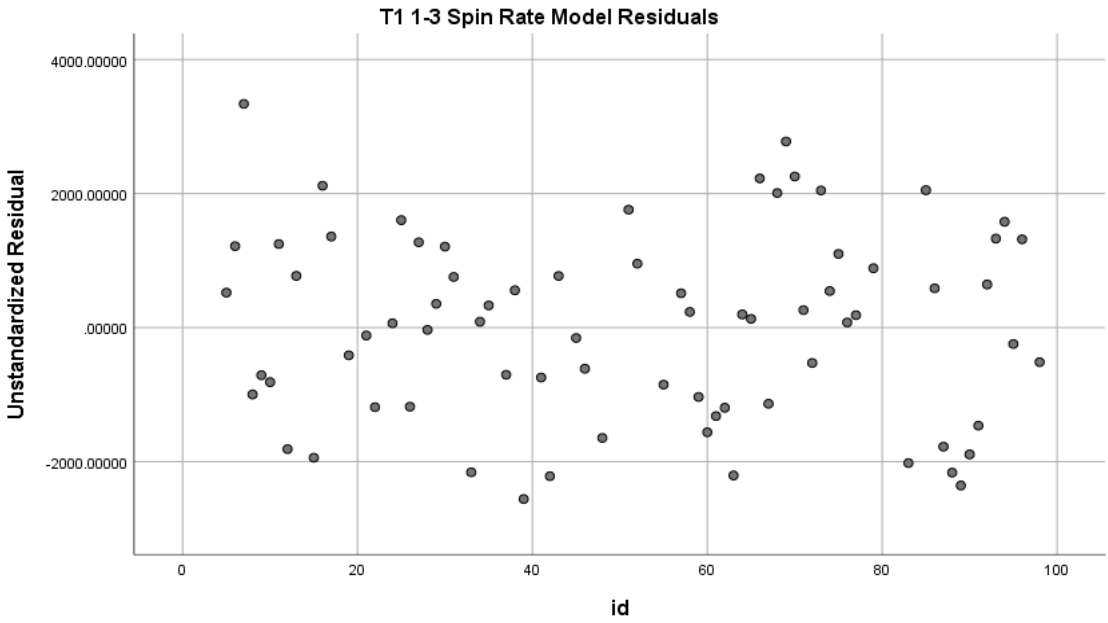


Figure C.44 Stage 1-3 120 m physical residual scatter plot

C.1.12 Stage 1-2 P-GPC Relationships: Physical – Driver Lead Shoulder Speed

Table C.23 Stage 1-2 driver physical regression residual descriptives

Descriptives				
			Statistic	Std. Error
Unstandardized Residual	Mean		10.5475728	14.53747539
	95% Confidence Interval for Mean	Lower Bound	-18.6819805	
		Upper Bound	39.7771261	
	5% Trimmed Mean		9.9295499	
	Median		13.1523761	
	Variance		10355.571	
	Std. Deviation		101.76232772	
	Minimum		-230.97077	
	Maximum		240.44155	
	Range		471.41232	
	Interquartile Range		136.38288	
	Skewness		-0.019	0.340
	Kurtosis		-0.216	0.668

Table C.24 Stage 1-2 driver physical residual normality tests

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	0.056	49	.200*	0.992	49	0.984
*. This is a lower bound of the true significance.						
a. Lilliefors Significance Correction						

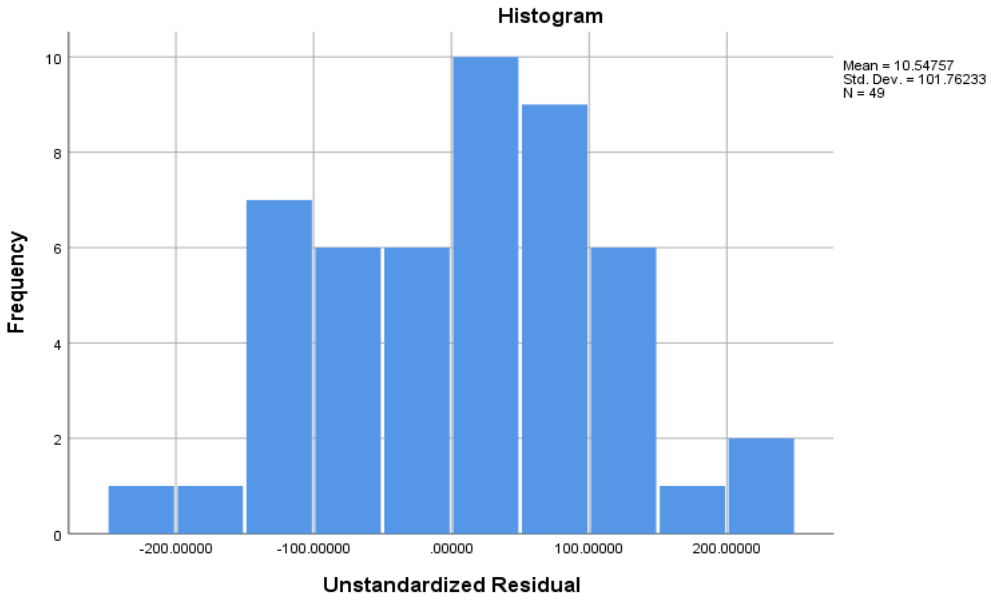


Figure C.45 Stage 1-2 driver physical residual histogram

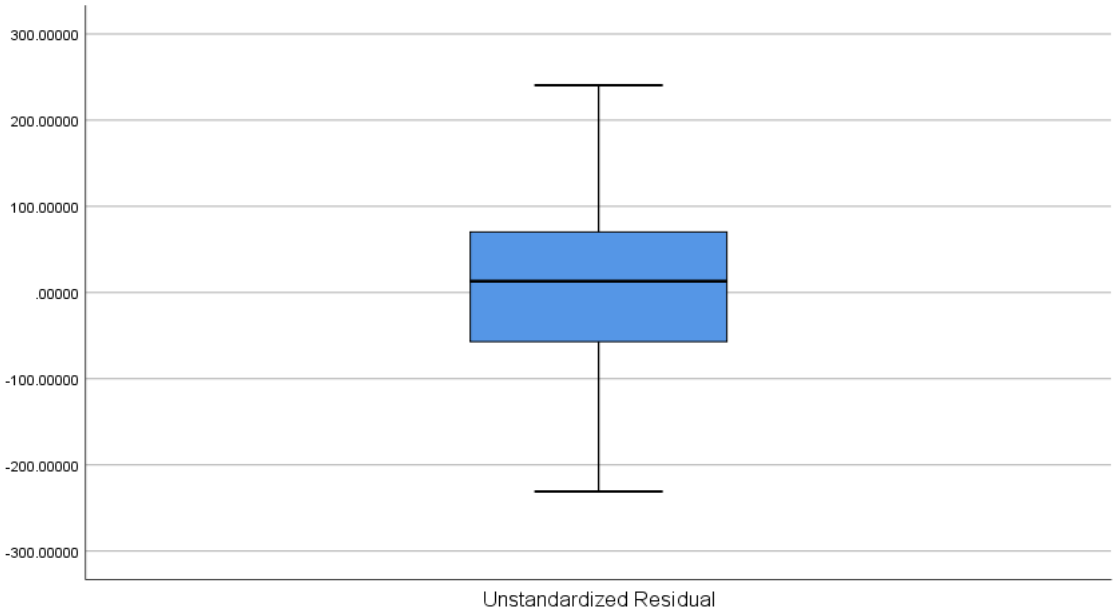


Figure C.46 Stage 1-2 driver physical residual distribution box plot

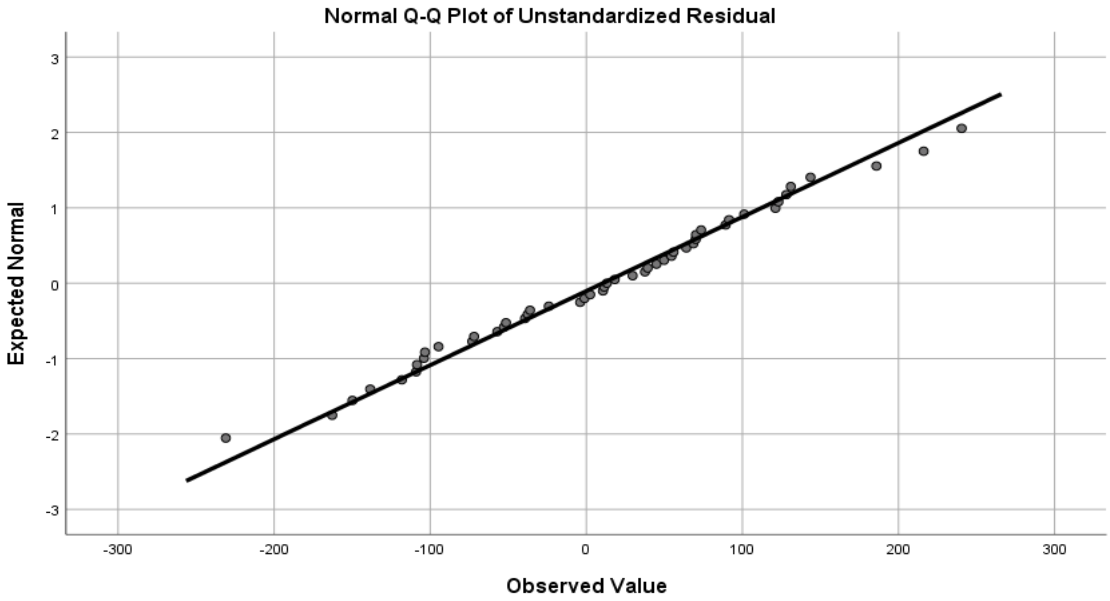


Figure C.47 Stage 1-2 driver physical residual Q-Q plot

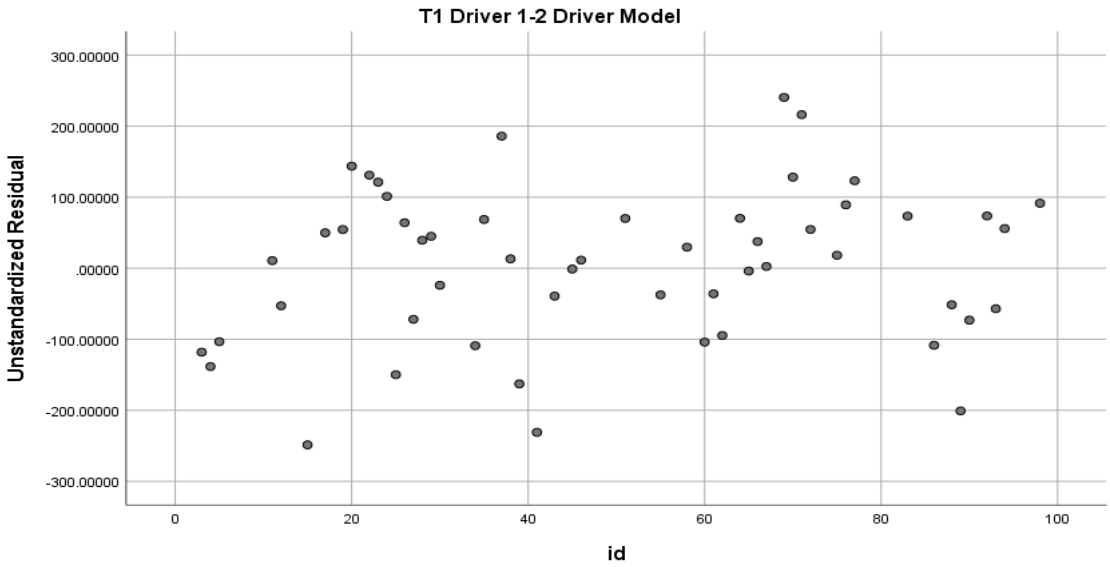


Figure C.48 Stage 1-2 driver physical residual scatter plot

Appendix D: MODEL DIMENSION REDUCTION

Dimension reduction for Study IV and V models followed step-by-step process. Table D.1 provides a description and abbreviation for each measure removal criteria, categorised as 'pre-full-model-fit' and 'post-full-model-fit'. Table D.2 through to Table D.12 detail how predictor sets were reduced for each model until model adequacy was achieved. Full initial predictor sets and alternate names are provided for measures.

Table D.1 Measure removal criteria and abbreviations for regression and linear mixed models

Measure removal criteria*	Abbreviation
Dimension reduction to allow full model fit	
Measure belongs to a different predictor set	None
Non-significant correlation to the dependent variable	NS
Weakest correlate to dependent variable of derived metrics from same measure	WCD
The weaker correlate of two measures that were more than .9 correlated with each other	COL
Similar metric, e.g. same measure on left and right side of body, where more correlated to each other than the dependent variable	SIM
Predictors removed after full model fit	
Variance inflation factor > 5 therefore collinear with another predictor	VIF
Beta coefficient lower than maximum predictors fit to n > 15 cases per predictor rule, OR, the measure did not improve the model R^2 or RMSE	MA
Included in the model	INC
The dependent variable	DV

*In order used in model construction

Table D.2 Stage 3-5 Driver club & ball models' removed measures and alternate names

Full Predictor Set: Driver Club & Ball Measures - Handicap	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
Handicap standardised	Handicap, HCP	DV	DV
Driver club head speed mph	Driver CHS	INC	INC
Driver club head speed relative to height mph/cm	Driver CHS/height	WCD	WCD
Driver club head speed relative to weight mph/kg	Driver CHS/weight	NS	NS
Driver club head speed relative arm span mph/cm	Driver CHS/arm span	WCD	WCD
Driver attack angle°	Driver angle of attack	VIF	INC
Driver club path°	N/A	NS	NS
Driver low point cm	N/A	COL (attack angle)	COL (attack angle)
Driver swing plane°	N/A	NS	NS
Driver swing direction°	N/A	VIF	VIF
Driver dynamic loft°	N/A	NS	NS
Driver face angle°	N/A	VIF	VIF
Driver face to path°	N/A	VIF	INC
Driver ball speed mph	N/A	SIM (CHS)	SIM (CHS)
Driver smash factor	N/A	INC	INC
Driver launch angle°	N/A	INC	NS
Driver launch direction°	N/A	COL (face angle)	COL (face angle)
Driver spin rate rpm	N/A	NS	NS
Driver spin axis°	N/A	NS	NS
Driver maximum height distance m	Max height distance	VIF	VIF
Driver maximum height m	Max height	COL (carry time)	COL (carry time)
Driver maximum height side m	Max height side	NS	NS
Driver carry flat length m	Driver carry length	Stage 4 skill measure	Stage 4 skill measure
Driver carry flat side m	Driver carry side	NS	NS
Driver carry flat land angle°	Driver land angle	INC	COL (carry time)
Driver carry flat ball speed mph	Driver land ball speed	INC	NS
Driver carry flat time s	Driver carry time	COL (land angle)	INC

Table D.3 Stage 3-5 120 m Shot club & ball models' removed measures and alternate names

Full Predictor Set: 120 m Club & Ball Measures - Handicap	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
Handicap standardised	Handicap, HCP	DV	DV
120 m club head speed mph	120m CHS	VIF	INC
120 m attack angle°	Driver angle of attack	COL (low point)	COL (low point)
120 m club path°	N/A	NS	NS
120 m low point cm	N/A	INC	INC
120 m swing plane°	N/A	NS	NS
120 m swing direction°	N/A	NS	NS
120 m dynamic loft°	N/A	COL (spin rate)	COL (spin rate)
120 m face angle°	N/A	INC	COL (launch direction)
120 m face to path°	N/A	NS	NS
120 m ball speed mph	N/A	COL (carry flat time)	SIM (CHS)
120 m smash factor	N/A	VIF	INC
120 m launch angle°	N/A	COL (carry flat angle)	COL (carry flat angle)
120 m launch direction°	N/A	COL (launch direction)	INC
120 m spin rate rpm	N/A	INC	INC
120 m spin axis°	N/A	NS	NS
120 m max height distance m	120m maximum height distance	COL (carry flat time)	COL (carry flat time)
120 m max height m	120m maximum height	COL (carry flat time)	COL (carry flat time)
120 m max height side m	120m maximum height side	NS	NS
120 m carry flat length m	120m carry length	COL (carry flat time)	COL (carry flat time)
120 m carry flat side m	120m carry side	NS	NS
120 m carry flat land angle	120m land angle	VIF	VIF
120 m carry flat ball speed mph	120m land ball speed	NS	NS
120 m carry flat time s	120m carry time	VIF	VIF

Table D.4 Stage 3-4 Driver club measure models' removed measures and alternate names

Full Predictor Set: Club Measures - Driver Distance	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
Driver est. total flat length m	Driver total distance	DV	DV
Driver club head speed mph	Driver CHS	INC	INC
Driver club head speed relative to height mph/cm	Driver CHS/height	WCD	WCD
Driver club head speed relative to weight mph/kg	Driver CHS/weight	NS	NS
Driver club head speed relative arm span mph/cm	Driver CHS/arm span	WCD	WCD
Driver attack angle°	Driver angle of attack	MA	INC
Driver club path°	N/A	NS	NS
Driver low point cm	N/A	COL	COL (attack angle)
Driver swing plane°	N/A	NS	NS
Driver swing direction°	N/A	SIM (face angle)	SIM (face angle)
Driver dynamic loft°	N/A	NS	NS
Driver face angle°	N/A	NS	INC
Driver face to path°	N/A	NS	INC
Driver smash factor	N/A	INC	INC

Table D.5 Stage 3-4 Driver ball measure models' removed measures and alternate names

Full Predictor Set: Ball Measures - Driver Distance	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
Driver est. total flat length m	Driver total distance	DV	DV
Driver spin rate rpm	N/A	INC	VIF
Driver spin axis°	N/A	NS	NS
Driver maximum height distance m	Max height distance	SIM (ball speed)	SIM (ball speed)
Driver maximum height m	Max height	COL (carry flat time)	COL (carry flat time)
Driver maximum height side m	Max height side	SIM (launch direction)	SIM (launch direction)
Driver carry flat length m	Driver carry length	Stage 4 skill measure	Stage 4 skill measure
Driver carry flat side m	Driver carry side	NS	NS
Driver carry flat land angle°	Driver land angle	COL (carry flat time)	COL (carry flat time)
Driver carry flat ball speed mph	Driver land ball speed	NS	NS
Driver carry flat time s	Driver carry time	INC	INC
Driver launch angle°	N/A	NS	NS
Driver launch direction°	N/A	INC	INC
Driver ball speed mph	N/A	INC	INC

Table D.6 Stage 3-4 120 m Shot ball measure models' removed measures and alternate names

Full Predictor Set: 120 m Ball Measures - Distance to Target	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
120 m distance to target m	120 m accuracy	DV	DV
120 m ball speed mph	N/A	SIM (carry flat time)	SIM (carry flat time)
120 m launch angle°	N/A	COL (carry flat time)	COL (carry flat time)
120 m launch direction°	N/A	NS	INC
120 m spin rate rpm	N/A	INC	INC
120 m spin axis°	N/A	MA	INC
120 m max height distance m	120m maximum height distance	COL (carry flat time)	COL (carry flat time)
120 m max height m	120m maximum height	COL (carry flat time)	COL (carry flat time)
120 m max height side m	120m maximum height side	SIM (launch direction)	SIM (launch direction)
120 m carry flat length m	120m carry length	Stage 4 skill measure	Stage 4 skill measure
120 m carry flat side m	120m carry side	Stage 4 skill measure	Stage 4 skill measure
120 m carry flat land angle	120m land angle	MA	VIF
120 m carry flat ball speed mph	120m land ball speed	INC	NS
120 m carry flat time s	120m carry time	MA	COL (carry land angle)

Table D.7 Stage 3-4 120 m Shot club measure models' removed measures and alternate names

Full Predictor Set: 120 m Club Measures - Distance to Target	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
120 m distance to target m	120 m accuracy	DV	DV
120 m club head speed mph	120m CHS	MA	INC
120 m attack angle°	120m angle of attack	NS	INC
120 m club path°	N/A	INC	NS
120 m low point cm	N/A	NS	VIF
120 m swing plane°	N/A	NS	NS
120 m swing direction°	N/A	NS	NS
120 m dynamic loft°	N/A	INC	INC
120 m face angle°	N/A	INC	INC
120 m face to path°	N/A	NS	INC
120 m smash factor	N/A	NS	NS

Table D.8 Stage 2-4 Driver body & GRF measure models' removed measures and alternate names

Full Predictor Set: 3D Body & GRF - Driver Distance	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
Driver est. total flat length m	Driver total distance	DV	DV
Pelvis peak velocity s	Pelvis speed, Pelvis peak speed	SIM (lead shoulder speed)	SIM (lead shoulder speed)
Thorax peak velocity s	Thorax speed, Thorax peak speed	SIM (lead shoulder speed)	SIM (lead shoulder speed)
Lead shoulder peak velocity s	Lead shoulder speed, Lead shoulder peak speed	INC	INC
Lead hand peak velocity s	Lead shoulder speed, Lead shoulder peak speed	MA	INC
Pelvis-thorax peak velocity ratio	Pelvis-thorax peak speed ratio	NS	NS
Thorax-lead shoulder peak velocity ratio	Thorax-lead shoulder peak speed ratio, Thorax-lead shoulder speed ratio	SIM (lead shoulder speed)	SIM (lead shoulder speed)
Lead shoulder-hand peak velocity ratio	Lead shoulder-hand peak speed ratio, Lead shoulder-hand speed ratio	SIM (lead shoulder speed)	SIM (lead shoulder speed)
Pelvis turn top of backswing°	N/A	NS	NS
Thorax turn top backswing°	N/A	NS	NS
X-factor top backswing°	N/A	NS	NS
Pelvis turn at impact°	N/A	NS	NS
Thorax turn impact°	N/A	NS	NS
X-factor at impact°	N/A	NS	NS
GRFmax fx rear N	GRFpeak Fx rear	NS	NS
GRFmax relative fx rear N/kg	GRF rel Fx rear	NS	NS
GRFmin fx lead N	GRFmin Fx lead	NS	NS
GRFmin relative fx lead N/kg	GRFmin rel Fx lead	MA	INC
GRF time between Fx peaks s	GRF time btn Fx peaks	NS	NS
GRFmax fy rear N	GRFpeak Fy rear	INC	INC
GRFmax relative fy rear N/kg	GRFpeak rel Fy rear	WCD (GRFmax Fy rear)	SIM (GRFmax Fy rear)
GRFmin fy lead N	GRFmin Fy lead	NS	NS
GRFmin relative fy lead N/kg	GRFmin rel Fy lead	NS	NS
GRF time between Fy peaks s	GRF time btn Fy peaks	NS	NS
GRFmax fz lead N	GRFpeak Fz rear	INC	SIM (GRFmax Fz lead)
GRFmax relative fz rear N/kg	GRFpeak rel Fz rear	NS	NS
GRFmax fz rear N	GRFpeak Fz lead	VIF	INC

GRFmax relative fz lead N/kg	GRFpeak rel Fz lead	WCD (GRFmax Fz lead)	NS
GRF time between Fz peaks s	GRF time btn Fz peaks	NS	NS

Table D.9 Stage 2-3 Driver body & GRF measure models' removed measures and alternate names

Full Predictor Set: 3D Body & GRF Measure - Driver CHS	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
Driver club head speed mph	Driver CHS	DV	DV
Pelvis peak velocity s	Pelvis speed, Pelvis peak speed	NS	NS
Thorax peak velocity s	Thorax speed, Thorax peak speed	VIF	SIM (lead shoulder speed)
Lead shoulder peak velocity s	Lead shoulder speed, Lead shoulder peak speed	INC	INC
Lead hand peak velocity s	Lead shoulder speed, Lead shoulder peak speed	VIF	MA
Pelvis-thorax peak velocity ratio	Pelvis-thorax peak speed ratio	NS	NS
Thorax-lead shoulder peak velocity ratio	Thorax-lead shoulder peak speed ratio, Thorax-lead shoulder speed ratio	VIF	SIM (lead shoulder speed)
Lead shoulder-hand peak velocity ratio	Lead shoulder-hand peak speed ratio, Lead shoulder-hand speed ratio	NS	NS
Pelvis turn top of backswing°	N/A	Model Adequacy	MA
Thorax turn top backswing°	N/A	NS	NS
X-factor top backswing°	N/A	NS	NS
Pelvis turn at impact°	N/A	NS	NS
Thorax turn impact°	N/A	NS	NS
X-factor at impact°	N/A	NS	NS
GRFmax fx rear N	GRFpeak Fx rear	MA	INC
GRFmax relative fx rear N/kg	GRF rel Fx rear	NS	NS
GRFmin fx lead N	GRFmin Fx lead	NS	NS
GRFmin relative fx lead N/kg	GRFmin rel Fx lead	NS	NS
GRF time between Fx peaks s	GRF time btn Fx peaks	NS	NS
GRFmax fy rear N	GRFpeak Fy rear	INC	MA
GRFmax relative fy rear N/kg	GRFpeak rel Fy rear	COL	COL
GRFmin fy lead N	GRFmin Fy lead	SIM (GRF max Fz lead)	SIM (GRF max Fz lead)
GRFmin relative fy lead N/kg	GRFmin rel Fy lead	NS	NS
GRF time between Fy peaks s	GRF time btn Fy peaks	NS	NS

GRFmax fz rear N	GRFpeak Fz rear	SIM (GRFmax Fy rear)	MA
GRFmax relative fz rear N/kg	GRFpeak rel Fz rear	NS	NS
GRFmax fz lead N	GRFpeak Fz lead	INC	INC
GRFmax relative fz lead N/kg	GRFpeak rel Fz lead	SIM (GRFmax Fz lead)	NS
GRF time between Fz peaks s	GRF time btn Fz peaks	NS	NS

Table D.10 Stage 1-3 Physical - Driver measure models' removed measures and alternate names

Full Predictor Set: Physical Measures - Driver CHS	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
Driver club head speed mph	Driver CHS	DV	DV
Sit and reach cm	Sit reach	NS	NS
Hip internal rotation rear°	Hip internal rotation rear	NS	NS
Hip internal rotation lead°	Hip internal rotation lead	NS	NS
Hip external rotation rear°	Hip external rotation rear	NS	NS
Hip external rotation lead°	Hip external rotation lead	NS	NS
Modified Thomas test rear°	Hip extension rear	NS	NS
Modified Thomas test lead°	Hip extension lead	NS	NS
Shoulder external rotation rear°	Shoulder external rotation rear	NS	NS
Shoulder external rotation lead°	Shoulder external rotation lead	INC	NS
Thorax seated rotation rear°	Thorax seated rotation rear	MA	MA
Thorax seated rotation lead°	Thorax seated rotation lead	SIM (Thorax seated rotation rear)	SIM (Thorax seated rotation rear)
SB anterior-medial rear reach cm	MSEBT, Rear leg SB anterior-medial	NS	NS
SB relative anterior-medial rear reach cm/m	MSEBT, Rear leg SB relative anterior-medial	SIM (SB posterior-medial reach lead)	SIM (SB posterior-medial reach lead)
SB medial-rear reach cm	MSEBT, Rear leg SB medial	MA	SIM (SB posterior-medial reach lead)
SB relative medial rear reach cm/m	MSEBT, Rear leg SB relative medial	NS	NS
SB posterior-medial rear reach cm	MSEBT, Rear leg SB posterior-medial	MA	SIM (SB posterior-medial reach lead)
SB relative posterior-medial rear reach cm/m	MSEBT, Rear leg SB relative posterior-medial	NS	NS
SB anterior-medial lead reach cm	MSEBT, Lead leg SB anterior-medial	NS	NS
SB relative anterior-medial lead reach cm/m	MSEBT, Lead leg SB relative anterior-medial	NS	NS
SB medial lead reach cm	MSEBT, Lead leg SB medial	SIM (SB posterior-medial reach lead)	SIM (SB posterior-medial reach lead)

SB relative medial lead reach cm/m	MSEBT, Lead leg SB relative medial	NS	NS
SB posterior-medial lead reach cm	MSEBT, Lead leg SB postero-medial	MA	MA
SB relative posterior-medial lead reach cm/m	MSEBT, Lead leg SB relative posterior-medial	NS	NS
SB sum reach rear cm	MSEBT, Rear leg SB sum score	SIM (SB posterior-medial reach lead)	SIM (SB posterior-medial reach lead)
SB relative sum reach rear cm/m	MSEBT, Rear leg SB relative sum score	NS	NS
SB sum reach lead cm	MSEBT, Lead leg SB sum score	SIM (SB posterior-medial reach lead)	SIM (SB posterior-medial reach lead)
SB relative sum reach lead cm/m	MSEBT, Lead leg SB relative sum score	NS	NS
YMCA step test HRR at 45 sec	YMCA step test recovery heart rate at 45 s	NS	NS
Grip lead kg	Grip lead	COL (Grip rear)	COL (Grip rear)
Grip rear kg	Grip rear	MA	INC
Trunk isometric rotation lead kg	Trunk rot lead	WCD	WCD
Trunk isometric rotation lead torque kg/m	Trunk rot lead torque	MA	MA
Trunk isometric rotation lead relative torque kg/m/kg	Trunk rot lead rel torque	WCD	WCD
Trunk isometric rotation rear kg	Trunk rot rear	SIM (trunk rot rear torque)	SIM (trunk rot rear torque)
Trunk isometric rotation rear torque kg/m	Trunk rot rear torque	SIM (trunk rot rear torque)	SIM (trunk rot rear torque)
Trunk isometric rotation rear relative torque kg/m/kg	Trunk rot rear rel torque	SIM (trunk rot rear torque)	SIM (trunk rot rear torque)
Hip isometric adduction lead kg	Hip adduction lead	WCD	WCD
Hip isometric adduction lead torque kg/m	Hip adduction lead torque	MA	MA
Hip isometric adduction lead relative torque kg/m/kg	Hip add lead rel torque	WCD	WCD
Hip isometric adduction rear kg	Hip add rear	SIM (hip rear adduction torque)	SIM (hip rear adduction torque)
Hip isometric adduction rear torque kg/m	Hip add rear torque	SIM (hip rear adduction torque)	SIM (hip rear adduction torque)
Hip isometric adduction rear relative torque kg/m/kg	Hip add rear rel torque	SIM (hip rear adduction torque)	SIM (hip rear adduction torque)
Hip isometric abduction lead kg	Hip abduction lead	SIM (hip rear abduction torque)	SIM (hip rear abduction torque)
Hip isometric abduction lead torque kg/m	Hip abduction lead torque	SIM (hip rear abduction torque)	SIM (hip rear abduction torque)
Hip isometric abduction lead relative torque kg/m/kg	Hip abduction lead rel torque	SIM (hip rear abduction torque)	SIM (hip rear abduction torque)
Hip isometric abduction rear kg	Hip abduction rear	WCD	WCD

Hip isometric abduction rear torque kg/m	Hip abduction rear torque	MA	INC
Hip isometric abduction rear relative torque kg/m/kg	Hip abduction rear rel torque	WCD	WCD
Hip isometric external rotation lead kg	Hip ext rot lead	WCD	WCD
Hip isometric external rotation lead torque kg/m	Hip ext rot lead torque	MA	MA
Hip isometric external rotation lead relative torque kg/m/kg	Hip ext rotation lead rel torque	WCD	WCD
Hip isometric external rotation rear kg	Hip external rot rear	SIM (hip lead ext rot torque)	SIM (hip lead ext rot torque)
Hip isometric external rotation rear torque kg/m	Hip ext rot rear torque	SIM (hip lead ext rot torque)	SIM (hip lead ext rot torque)
Hip isometric external rotation rear relative torque kg/m/kg	Hip ext rot rear rel torque	SIM (hip lead ext rot torque)	SIM (hip lead ext rot torque)
Lateral jump lead m	Lateral jump lead	MA	MA
Lateral jump lead relative to weight m/kg	Lateral jump lead rel. weight	NS	NS
Lateral jump lead relative to leg length m/m	Lateral jump lead rel. leg length	COL	COL
Lateral jump rear m	Lateral jump rear	COL	COL
Lateral jump rear relative to weight m/kg	Lateral jump rear rel. weight	WCD	WCD
Lateral jump rear relative to leg length m/m	Lateral jump rear rel. leg length	WCD	WCD
Vertical CMJ reach cm	Vertical jump and reach	INC	WCD
Estimated peak leg power W	Estimated peak power	VIF	VIF
Chest pass3 kg m	MB seated chest pass 3 kg	SIM (sit throw)	SIM (sit throw)
Sit Throw 3 kg m	MB sit up throw 3 kg	INC	INC
Lateral throw 3 kg m	MB lateral throw 3 kg	SIM (sit throw)	SIM (sit throw)
Counter movement jump max Fz N	CMJ peak Fz	SIM (estimated leg power)	SIM (estimated leg power)
Counter movement jump relative max Fz N/kg	CMJ rel peak Fz	NS	NS

Table D.11 Stage 1-3 Physical – 120 m Shot measure models' removed measures and alternate names

Full Predictor Set: Physical Measures - 120 m Spin Rate	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
120 m spin rate rpm	N/A	DV	DV
Sit and reach cm	Sit reach	NS	NS
Hip internal rotation rear°	Hip internal rotation rear	NS	NS
Hip internal rotation lead°	Hip internal rotation lead	INC	NS
Hip external rotation rear°	Hip external rotation rear	NS	NS
Hip external rotation lead°	Hip external rotation lead	NS	NS
Modified Thomas test rear°	Hip extension rear	NS	NS
Modified Thomas test lead°	Hip extension lead	NS	NS
Shoulder external rotation rear°	Shoulder external rotation rear	NS	NS
Shoulder external rotation lead°	Shoulder external rotation lead	NS	NS
Thorax seated rotation rear°	Thorax seated rotation rear	MA	MA
Thorax seated rotation lead°	Thorax seated rotation lead	NS	NS
SB anterior-medial rear reach cm	MSEBT, Rear leg SB anterior-medial	NS	NS
SB relative anterior-medial rear reach cm/m	MSEBT, Rear leg SB relative anterior-medial	NS	NS
SB medial-rear reach cm	MSEBT, Rear leg SB medial	MA	INC
SB relative medial rear reach cm/m	MSEBT, Rear leg SB relative medial	WCD	WCD
SB posterior-medial rear reach cm	MSEBT, Rear leg SB posterior-medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB relative posterior-medial rear reach cm/m	MSEBT, Rear leg SB relative posterior-medial	NS	NS
SB anterior-medial lead reach cm	MSEBT, Lead leg SB anterior-medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB relative anterior-medial lead reach cm/m	MSEBT, Lead leg SB relative anterior-medial	NS	NS
SB medial lead reach cm	MSEBT, Lead leg SB medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB relative medial lead reach cm/m	MSEBT, Lead leg SB relative medial	NS	NS
SB posterior-medial lead reach cm	MSEBT, Lead leg SB postero-medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)

SB relative posterior-medial lead reach cm/m	MSEBT, Lead leg SB relative posterior-medial	NS	NS
SB sum reach rear cm	MSEBT, Rear leg SB sum score	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB relative sum reach rear cm/m	MSEBT, Rear leg SB relative sum score	NS	NS
SB sum reach lead cm	MSEBT, Lead leg SB sum score	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB relative sum reach lead cm/m	MSEBT, Lead leg SB relative sum score	NS	NS
YMCA step test HRR at 45 sec	YMCA step test recovery heart rate at 45 s	NS	NS
Grip lead kg	Grip lead	COL	COL
Grip rear kg	Grip rear	MA	INC
Trunk isometric rotation lead kg	Trunk rot lead	WCD	WCD
Trunk isometric rotation lead torque kg/m	Trunk rot lead torque	MA	MA
Trunk isometric rotation lead relative torque kg/m/kg	Trunk rot lead rel torque	WCD	WCD
Trunk isometric rotation rear kg	Trunk rot rear	SIM (trunk rot rear torque)	SIM (trunk rot rear torque)
Trunk isometric rotation rear torque kg/m	Trunk rot rear torque	SIM (trunk rot rear torque)	SIM (trunk rot rear torque)
Trunk isometric rotation rear relative torque kg/m/kg	Trunk rot rear rel torque	SIM (trunk rot rear torque)	SIM (trunk rot rear torque)
Hip isometric adduction lead kg	Hip adduction lead	SIM (hip lead adduction torque)	SIM (hip lead adduction torque)
Hip isometric adduction lead torque kg/m	Hip adduction lead torque	SIM (hip lead adduction torque)	SIM (hip lead adduction torque)
Hip isometric adduction lead relative torque kg/m/kg	Hip add lead rel torque	SIM (hip lead adduction torque)	SIM (hip lead adduction torque)
Hip isometric adduction rear kg	Hip add rear	WCD	WCD
Hip isometric adduction rear torque kg/m	Hip add rear torque	MA	INC
Hip isometric adduction rear relative torque kg/m/kg	Hip add rear rel torque	WCD	WCD
Hip isometric abduction lead kg	Hip abduction lead	SIM (hip rear abduction torque)	SIM (hip rear abduction torque)
Hip isometric abduction lead torque kg/m	Hip abduction lead torque	SIM (hip rear abduction torque)	SIM (hip rear abduction torque)
Hip isometric abduction lead relative torque kg/m/kg	Hip abduction lead rel torque	SIM (hip rear abduction torque)	SIM (hip rear abduction torque)
Hip isometric abduction rear kg	Hip abduction rear	WCD	WCD
Hip isometric abduction rear torque kg/m	Hip abduction rear torque	MA	MA
Hip isometric abduction rear relative torque kg/m/kg	Hip abduction rear rel torque	WCD	WCD
Hip isometric external rotation lead kg	Hip ext rot lead	WCD	WCD

Hip isometric external rotation lead torque kg/m	Hip ext rot lead torque	MA	MA
Hip isometric external rotation lead relative torque kg/m/kg	Hip ext rotation lead rel torque	WCD	WCD
Hip isometric external rotation rear kg	Hip external rot rear	SIM (hip lead ext rot torque)	SIM (hip lead ext rot torque)
Hip isometric external rotation rear torque kg/m	Hip ext rot rear torque	SIM (hip lead ext rot torque)	SIM (hip lead ext rot torque)
Hip isometric external rotation rear relative torque kg/m/kg	Hip ext rot rear rel torque	SIM (hip lead ext rot torque)	SIM (hip lead ext rot torque)
Lateral jump lead m	Lateral jump lead	MA	MA
Lateral jump lead relative to weight m/kg	Lateral jump lead rel. weight	NS	NS
Lateral jump lead relative to leg length m/m	Lateral jump lead rel. leg length	NS	NS
Lateral jump rear m	Lateral jump rear	COL	COL
Lateral jump rear relative to weight m/kg	Lateral jump rear rel. weight	WCD	WCD
Lateral jump rear relative to leg length m/m	Lateral jump rear rel. leg length	NS	NS
Vertical CMJ reach cm	Vertical jump and reach	WCD	WCD
Estimated peak leg power W	Estimated peak power	COL (sit throw)	COL (sit throw)
Chest pass3 kg m	MB seated chest pass 3 kg	SIM (sit throw)	SIM (sit throw)
Sit Throw 3 kg m	MB sit up throw 3 kg	INC	INC
Lateral throw 3 kg m	MB lateral throw 3 kg	SIM (sit throw)	SIM (sit throw)
Counter movement jump max Fz N	CMJ peak Fz	SIM (estimated leg power)	SIM (estimated leg power)
Counter movement jump relative max Fz N/kg	CMJ rel peak Fz	NS	NS

Table D.12 Stage 1-2 Physical - Driver measure models' removed measures and alternate names

Full Predictor Set: Physical Measures - Lead Shoulder Peak Speed	Alternate Name/s	Removal criteria applied - regression	Removal criteria applied - LMM
Lead shoulder peak velocity s	Lead shoulder speed, Lead shoulder peak speed	DV	DV
Sit and reach cm	Sit reach	NS	NS
Hip internal rotation rear°	Hip internal rotation rear	MA	MA
Hip internal rotation lead°	Hip internal rotation lead	MA	MA
Hip external rotation rear°	Hip external rotation rear	NS	NS
Hip external rotation lead°	Hip external rotation lead	NS	NS
Modified Thomas test rear°	Hip extension rear	MA	NS
Modified Thomas test lead°	Hip extension lead	NS	NS
Shoulder external rotation rear°	Shoulder external rotation rear	NS	NS
Shoulder external rotation lead°	Shoulder external rotation lead	INC	VIF
Thorax seated rotation rear°	Thorax seated rotation rear	VIF	SIM (Shoulder external rotation rear)
Thorax seated rotation lead°	Thorax seated rotation lead	MA	INC
SB anterior-medial rear reach cm	MSEBT, Rear leg SB anterior-medial	MA	MA
SB relative anterior-medial rear reach cm/m	MSEBT, Rear leg SB relative anterior-medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB medial-rear reach cm	MSEBT, Rear leg SB medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB relative medial rear reach cm/m	MSEBT, Rear leg SB relative medial	MA	Model Adequacy
SB posterior-medial rear reach cm	MSEBT, Rear leg SB posterior-medial	WCD	WCD
SB relative posterior-medial rear reach cm/m	MSEBT, Rear leg SB relative posterior-medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB anterior-medial lead reach cm	MSEBT, Lead leg SB anterior-medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB relative anterior-medial lead reach cm/m	MSEBT, Lead leg SB relative anterior-medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB medial lead reach cm	MSEBT, Lead leg SB medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB relative medial lead reach cm/m	MSEBT, Lead leg SB relative medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)

SB posterior-medial lead reach cm	MSEBT, Lead leg SB postero-medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB relative posterior-medial lead reach cm/m	MSEBT, Lead leg SB relative posterior-medial	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB sum reach rear cm	MSEBT, Rear leg SB sum score	MA	SIM (SB medial reach rear)
SB relative sum reach rear cm/m	MSEBT, Rear leg SB relative sum score	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB sum reach lead cm	MSEBT, Lead leg SB sum score	SIM (SB medial reach rear)	SIM (SB medial reach rear)
SB relative sum reach lead cm/m	MSEBT, Lead leg SB relative sum score	SIM (SB medial reach rear)	SIM (SB medial reach rear)
YMCA step test HRR at 45 sec	YMCA step test recovery heart rate at 45 s	SIM (SB medial reach rear)	SIM (SB medial reach rear)
Grip lead kg	Grip lead	COL (Grip rear)	SIM (lateral jump rel leg length)
Grip rear kg	Grip rear	INC	NS
Trunk isometric rotation lead kg	Trunk rot lead	NS	NS
Trunk isometric rotation lead torque kg/m	Trunk rot lead torque	NS	NS
Trunk isometric rotation lead relative torque kg/m/kg	Trunk rot lead rel torque	NS	NS
Trunk isometric rotation rear kg	Trunk rot rear	MA	MA
Trunk isometric rotation rear torque kg/m	Trunk rot rear torque	NS	NS
Trunk isometric rotation rear relative torque kg/m/kg	Trunk rot rear rel torque	NS	NS
Hip isometric adduction lead kg	Hip adduction lead	SIM (trunk rot lead rel torque)	SIM (trunk rot lead rel torque)
Hip isometric adduction lead torque kg/m	Hip adduction lead torque	NS	NS
Hip isometric adduction lead relative torque kg/m/kg	Hip add lead rel torque	NS	NS
Hip isometric adduction rear kg	Hip add rear	MA	MA
Hip isometric adduction rear torque kg/m	Hip add rear torque	NS	NS
Hip isometric adduction rear relative torque kg/m/kg	Hip add rear rel torque	NS	NS
Hip isometric abduction lead kg	Hip abduction lead	SIM (hip lead adduction rel torque)	SIM (hip lead adduction rel torque)
Hip isometric abduction lead torque kg/m	Hip abduction lead torque	NS	NS
Hip isometric abduction lead relative torque kg/m/kg	Hip abduction lead rel torque	NS	NS
Hip isometric abduction rear kg	Hip abduction rear	NS	NS
Hip isometric abduction rear torque kg/m	Hip abduction rear torque	NS	NS
Hip isometric abduction rear relative torque kg/m/kg	Hip abduction rear rel torque	NS	NS
Hip isometric external rotation lead kg	Hip ext rot lead	NS	NS
Hip isometric external rotation lead torque kg/m	Hip ext rot lead torque	WCD	WCD
Hip isometric external rotation lead relative torque kg/m/kg	Hip ext rotation lead rel torque	WCD	WCD

Hip isometric external rotation rear kg	Hip external rot rear	MA	MA
Hip isometric external rotation rear torque kg/m	Hip ext rot rear torque	SIM (hip lead ext rot torque)	SIM (hip lead ext rot torque)
Hip isometric external rotation rear relative torque kg/m/kg	Hip ext rot rear rel torque	SIM (hip lead ext rot torque)	SIM (hip lead ext rot torque)
Lateral jump lead m	Lateral jump lead	SIM (hip lead ext rot torque)	SIM (hip lead ext rot torque)
Lateral jump lead relative to weight m/kg	Lateral jump lead rel. weight	WCD	WCD
Lateral jump lead relative to leg length m/m	Lateral jump lead rel. leg length	INC	VIF
Lateral jump rear m	Lateral jump rear	MA	MA
Lateral jump rear relative to weight m/kg	Lateral jump rear rel. weight	SIM (lat jump lead rel leg length)	SIM (lat jump lead rel leg length)
Lateral jump rear relative to leg length m/m	Lateral jump rear rel. leg length	SIM (lat jump lead rel leg length)	SIM (lat jump lead rel leg length)
Vertical CMJ reach cm	Vertical jump and reach	SIM (lat jump lead rel leg length)	INC
Estimated peak leg power W	Estimated peak power	INC	WCD (Vertical CMJ reach)
Chest pass3 kg m	MB seated chest pass 3 kg	NS	NS
Sit Throw 3 kg m	MB sit up throw 3 kg	SIM (vertical CMJ jump)	SIM (vertical CMJ jump)
Lateral throw 3 kg m	MB lateral throw 3 kg	SIM (vertical CMJ jump)	SIM (vertical CMJ jump)
Counter movement jump max Fz N	CMJ peak Fz	SIM (vertical CMJ jump)	SIM (vertical CMJ jump)
Counter movement jump relative max Fz N/kg	CMJ rel peak Fz	NS	NS
Sit and reach cm	Sit reach	SIM (vertical CMJ jump)	SIM (vertical CMJ jump)

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