Shooting is an Olympic sport, with over fifteen different categories. Standing Air Rifle and Pistol Shooting are among the most technical of these, with both disciplines requiring extreme precision for success. From a standing position, the shooter must aim at a target located 10 metres away which, in the case of rifle shooting, has a “ten ring”, or “bull’s eye”, 1mm wide. The bullet must touch this ring to score a ‘ten’, allowing for an angular movement of the gun of only 0.016° (Zatsiorski and Aktov, 1990). Not surprisingly then, the smallest of movements will significantly affect a shooter's score.

Although shooting has been scantly researched, studies have covered a number of psychological, physiological and biomechanical factors. The effects on performance of heart rate, respiration timing and respiration amplitude (eg. Tremayne et al., 1993), brain wave patterning (eg. Konttinen and Lyytinen, 1993) and arousal levels (eg. Mason and Bond, 1989) have been examined. The limited amount of biomechanical research in shooting has focused on the influence of body sway and aim point fluctuation on performance (eg. Mason et al., 1990; Niinimaa and McEvoy, 1983; Zatsiorski and Aktov, 1990).

The influence of body sway on shooting performance is a logical area of study, due to the very precise movements required in shooting and the potentially large gun movements that may be generated by body sway. Shooters have been found to produce smaller sway amplitudes than the general population (eg. Aalto et al., 1990).
with centre of pressure (COP) ranges of less than 1mm reported (eg. Viitasalo et al., 1997). The small amount of sway produced by shooters requires extremely accurate measurement. Commonly, this measurement has been performed using a force plate and a 12-bit analogue to digital converter (ADC). The three areas of error that may exist in force plate data collection that will influence the measurement of body sway are equipment error, noise and quantisation error. Although quantisation error is considered a type of noise, it will be treated separately in this study. Equipment errors include plate distortion and transducer cross talk. Noise, generated from sources external and internal to the system, such as amplifier noise or 50Hz main power noise, can be sensed by the system and recorded as part of the signal. The third area, quantisation error, refers to the difference between the analogue signal and the binary coded digital representation of that signal (Baher, 1992). Based on data obtained from a force plate using a 12-bit ADC system, Wisleder and McLean (1991) report that quantisation error is the major source of error in COP calculations when dealing with sports in which exceptional stability is required. Early experiments for this study also indicated that 12-bit ADC was inadequate for the measurement of some body sway parameters, particularly first derivative data such as COP velocity. It is quantisation error that will be the focus of stage 1 of this study- by comparing 12-bit ADC and 16-bit ADC in terms of the resolution provided and the error potential for body sway measures during shooting due to quantisation.

There have been conflicting results from the small number of studies examining body sway in pistol shooting. Mason et al. (1990) identified body sway as the major contributing factor to shooting performance in pistol shooting at the elite level. However, Aalto et al. (1990) suggest that body sway is unimportant in pistol shooting,
with other skill factors more influential to performance. This contention does not exist in rifle shooting. However, while rifle-shooting studies have shown that differences exist in body sway control between elite and non-elite rifle shooters (eg. Era et al., 1996), and that body sway is associated with performance when shooters from a wide range of skill levels are examined (eg. Viitasalo et al., 1997), no study has shown an association between body sway and performance at the elite level. Problems of insufficient measurement precision may have influenced these studies, with 12-bit ADC force plate measurement used to assess body sway. Another limitation of these studies was the within-group analysis method, with no within-individual analysis reported. With the small amount of variability that is likely to exist in elite shooting groups, this method of analysis may reduce the chance of finding significant associations between body sway and shooting performance. The examination of body sway, measured using a 16-bit ADC system, and its influence on shooting performance will be examined in stage 2 of this study, with this examination conducted on a group and individual basis.

Aim point refers to the location on the target that the gun aligns with, or put simply, where the gun is pointing. Aim point fluctuation refers to the movement of the aim point on the target. This is another logical research focus, as performance is dependent on the location of the aim point at the instant of shot. The relationship between aim point fluctuation and shooting performance has been explored and found to hold pertinent information for the competitor (eg. Zatsiorski and Aktov, 1990; Lu, 1989). However, while associations between aim point fluctuation and performance exist when shooters from a wide range of skill levels were examined (Viitasalo et al., 1997) and elite level shooters have been shown to produce less aim point fluctuation
than non-elite shooters (eg. Norvpalo et al., 1997), no studies have shown an
association between aim point fluctuation and performance at the elite level. The
same difficulties of finding statistical significance in an elite group when assessed on
a within group basis only exist for the relationship between aim point fluctuation and
performance. Stage 2 of this study will also correlate aim point fluctuation and
performance on a group and individual basis.

There are no reports examining the relationship between body sway and aim point
fluctuation during standing rifle shooting or standing pistol shooting. In running
target shooting, an association between body sway and aim point fluctuation has been
found when shooters with a wide range of skills were tested, but not when the elite
group was examined in isolation (Viitasalo et al., 1997). The examination of the
relationship between body sway and aim point fluctuation on a group and individual
basis will form a part of stage 2 of this study.

In summary, this study will be presented in 2 stages. Stage 1 will examine the
accuracy of 12-bit and 16-bit ADC data capture for measurement of body sway in
shooting. Stage 2 will examine the relationship between body sway, aim point
fluctuation and performance in elite pistol and rifle shooting with this examination
conducted on a group and an individual basis.
CHAPTER 2  REVIEW OF LITERATURE

2.1 Errors in force plate data collection

A force plate is used to measure the forces that are exerted at the ground. Briefly, it consists of a top plate and a bottom plate connected in each corner by a transducer (figure 2.1). Each transducer measures the force produced by the top plate on the bottom plate in three orthogonal axes, denoted by Fx, Fy and Fz.

Figure 2.1: A typical force plate with four transducers top and bottom plate and three orthogonal measurement axes.

Errors in measurement using force plates can be generated from three sources: equipment, noise and quantisation error.
2.1.1 Equipment

Equipment set-up is considered carefully during laboratory construction. Force plate manufacturers provide installation guidelines for plate mountings and surrounds (eg. AMTI, 1982). Briefly, these involve locating mountings on a concrete block on the ground floor of a building. This block should be isolated from the surrounding building to reduce the effects of building vibration and building movement on the signal output. Precise levelling of force plates is necessary for accurate alignment of axes to obtain true forces and torques. The choice of overlay on the force plates must also be given consideration to minimise force attenuation whilst maintaining the safety and integrity of ‘competition like’ settings, as well as remain level with the surrounding floor.

Bartlett (1992), in guidelines for force plate measurement, report that valid force measurement requires force transducers which exhibit adequate sensitivity, low threshold, high linearity, low hysteresis, low cross-talk and adequate temperature tolerance. Cabling needs to be considered also to reduce the generation of electrical noise from inductance and to minimise the environmental noise, which may be sensed by the cables, through adequate insulation. Calibration of the system can reduce the potential errors that any of these factors may introduce.

The centre of pressure (COP) is the point of application of the ground reaction force vector on the force plate surface. COP measurement, particularly during the measurement of quiet stance, requires extreme accuracy of all these components and tests the force plate set-up to its limits. Force plate manufacturers report COP errors of
up to 30mm (Kistler, 1997). While this is an upper limit for COP error, COP ranges during shooting have been reported as less than 4mm (eg. Mason et al., 1990; Viitasalo et al., 1997). Measurement of this magnitude of movement requires greater accuracy than the potential maximum error quoted above.

Bobbert and Schamhardt (1990) examined the COP accuracy produced by a Kistler force plate of dimensions 600mm in the X-axis and 900mm in the Y-axis. On the application of a point source of known force to 117 COP locations on the force plate, average COP displacement errors of 3.5mm in the X-axis and 6.3mm in the Y-axis were found to exist. The researchers eliminated likely sources of this error, such as cross talk between transducers and nonlinearity of individual transducers. Bobbert and Schamhardt concluded that distortion of the force plate itself caused this error. This plate distortion changed the angle of applied force on each transducer, which then generated a slightly different force value as a result. Further, the researchers found that the discrepancy between actual and measured COP position varied systematically at different plate locations. Based on these findings, a COP correction algorithm was developed, which reduced the average COP displacement error to from 3.5mm and 6.3mm to 1.3mm and 1.6mm in COPx and COPy respectively. Sommer et al. (1997) developed correction algorithms for a range of Kistler plates, which reduced mean COP errors from 14.1mm to 5.8mm for the same model force plate as used by Bobbert and Schamhardt. While slightly different methodologies were used, the difference in errors found in each study is unclear.

The algorithms presented by Bobbert and Schamhardt (1990) and Sommer et al. (1997) improve COP accuracy for point source applications of force. However, the
method of assessment of COP may not apply directly to situations where more than one point of force application or application areas exists. In the case of quiet stance, there are two areas of application of force—under each foot. Distortion of the force plate will probably differ due to the different loading pattern compared with a similar mass concentrated on a single point. This will reduce the algorithm’s effectiveness for reducing COP errors. The errors in COP measurement due to force platform distortion have been shown to be reduced when a known load is placed on a force plate at two areas, rather than at one point (Middleton et al., 1999). Further, Bobbert and Schamhardt used an aluminium plate on top of the force plate that would tend to alter the distorting effect of the applied force to the force plate. To this author’s knowledge, force plates built by other manufacturers have not been examined to improve COP measurement.

A number of factors will reduce the potential error due to plate distortion. First, as mentioned, Middleton et al. (1999) found smaller errors in COP measurement when a load was applied at two areas, rather than at a single point. During the shooting stance, a load is applied to the force plate at two areas (at each foot). As such, reduced error due to force plate distortion can be expected during this assessment, compared with the error reported by Bobbert and Schamhardt (1990). Second, shooters have been shown to move minimally. For example, COP ranges have been reported to be approximately 3mm for pistol shooters (Mason et al., 1990) and 2mm for rifle shooters (Viitasalo et al., 1996). While the plate may be distorted during body sway measurement, this distortion will remain relatively constant throughout the trial, particularly as the COP moves through only 2-3mm during measurement. As such, the error due to the distortion will also remain relatively constant throughout the
trial. As most body sway measures used in posture assessment and in this study depend on a change in COP position, at least part of this error due to distortion of the plate will be eliminated in calculations due to the distortion remaining fairly constant. Third, most parameters used in posture assessment are relative measures such as averages, areas and ranges where the absolute measures of COP are not important, only the change in COP position. These measures will, in themselves, reduce the effect of systematic and random COP inaccuracies.

2.1.2 Noise

All measurement involving electrical signals will be a combination of true signal and noise (Baher, 1990). Noise can be generated from sources both internal and external to the measurement. External noise exists in the surrounding environment and may be generated by mains power and building vibration. This noise can be sensed by the force plate or cabling between the plate and the computer. The force plate transducers, the amplifiers and the ADC board in the computer can generate internal noise.

While most studies deal with the issue of noise in the form of smoothing of data, there does not seem to be a large deal of literature reporting specifically on the issue of noise in force plates, presumably due to its largely system specific nature. As such, there is a limit to the applicability of the findings of research outside of the specific system on which the research was conducted. Granat et al. (1990) report that when using digital techniques for sampling measurement error is generated by small amounts of noise and quantisation effects. To examine this error source and assess
the effects of smoothing, a 100N weight was placed on a Kistler force plate and sampled using a 12-bit ADC system at 60Hz. Sample time was not reported. Prior to filtering, a speed of 1.7mm/s was found. Although not reported, it is assumed that this refers to COP movement. Filtering using a FIR (finite impulse response) low pass digital filter with a cut-off frequency of 7.5Hz reduced this speed to 0.05mm/s, which was considered suitable by the authors for most applications.

While smoothing can reduce error due to noise, as found by Granat et al. (1990) it cannot be completely eliminated. Noise of similar frequency to that of the true signal cannot be removed without removing true signal also. The selection of smoothing cut-off frequency is a compromise between the amount of signal and noise in the filtered data (Winter, 1990). As such, some amount of noise will always exist in a signal.

2.1.3 Quantisation

When a signal is measured as a voltage, it is quantified by passing through an analogue to digital converter (ADC). The finite number of points that can be used to measure a signal directly affects the level of precision that can be obtained. For example, a 12-bit ADC uses \(2^{12}\), or 4096 measurement steps, during conversion, usually across a ±10 Volt range. If the maximum measurement for a signal is ±2000N, then each step in measurement will equal approximately 1N. This means that any signal which lies at a fractional number will be rounded up or down and may fluctuate between the two values. The error generated by this process is a type of
noise and is termed quantisation error and is the difference between the analogue signal and the binary coded digital representation of that signal (Baher, 1992).

Research specific to quantisation in force plate data collection is scarce. Wisleder and McLean (1991) examined the COP output of a series of different stationary weights on a Kistler force plate, reporting COP ranges of 3.1mm in the X-axis and 4.8mm in the Y-axis. The researchers concluded that quantisation error was the cause of the weights ‘moving’. Further, this error was found to increase as the vertical force (Fz) decreased below 800N. Wisleder and McLean suggested that this error may become significant, particularly when the value of Fz is low and the movement being measured was small, as in the case of posture control and particularly in shooting analyses. While quantisation error would account for large incremental jumps in the measured signal, noise or limitations of the electronics in the system must also exist to cause the fluctuation of the values over more than two ADC units.

Aalto et al. (1988) presented a means of filtering force plate data to eliminate quantisation error. This involved applying a three point moving window across the complete dataset. In each window of three points, the median value was chosen to represent the data at the midpoint of the window. A moving point average was then applied to this adjusted data. A reduction of 65% in COP sway velocities was reported using this smoothing method. Unfortunately, the method was assessed only by comparing subject data obtained using this smoothing technique with data obtained by other authors, making it difficult to assess the quality of the process. No direct comparison with a known result, such as a weight placed on the force plate, was reported.
In summary, three sources of error exist in force plate data collection. Problems with equipment have been shown to affect COP measurement in Kistler plates. No studies have examined this problem in the AMTI force plates, which will be used in this study. Assessment of this type is beyond the scope of this study and remains a possible limitation of COP measurement. Noise will affect force plate measurement, but is largely system and environment specific. As such, this issue must be dealt with on a system specific basis. Noise in the COP signal is dealt with in the smoothing analysis (Appendix D). Quantisation is a problem that holds a general application, as hardware and software set the quantisation resolution available. The resolution that is offered by 12-bit ADC systems, used in previous shooting studies (eg. Mason et al., 1990; Niinimaa and McEvoy, 1983), may not be accurate enough to provide discerning information when dealing with elite shooters. This area is examined in stage 1 of this study.
2.2 Body sway

2.2.1 Centre of pressure (COP)

COP, calculated from force platform data, has been used to assess body sway in most biomechanics shooting research reviewed by the author (eg. Mason et al., 1990; Bozsik et al., 1995; Viitasalo et al., 1997). Inherent in this measure of body sway is the assumption that the larger COP movement indicates a less stable subject. In shooting competition settings, COP has been measured over different time periods prior to the shot (1s-7.5s). Table 2.1 summarises the COP parameters used in shooting studies.

<table>
<thead>
<tr>
<th>COP Parameter</th>
<th>Definition</th>
<th>Studies in which the parameter has been used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>Range</td>
<td>Mason et al., 1990</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Viitasalo et al., 1997</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>Deviation of COP location</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Norvapalo et al., 1997</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>total length, or distance, traced by the COP path</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Niinimaa and McEvoy, 1983</td>
</tr>
<tr>
<td></td>
<td>Area</td>
<td>percentage time spent within a given area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bozsik et al., 1995</td>
</tr>
<tr>
<td>Velocity/speed</td>
<td>Average</td>
<td>Wu et al., 1997</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>Wu et al., 1997</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>Norvapalo et al., 1997</td>
</tr>
</tbody>
</table>

While COP is the most commonly used measure to assess body sway for shooters, it should be noted that COP movement is not a direct measure of postural sway. Body sway refers to the oscillation of the centre of gravity (CG) about a mean point, while COP is the point of application of the resultant force generated by the shooter. The
two are related but not the same. Winter et al. (1993) reports that during upright stance, the COP movement in the Anterio-Posterior (AP) direction is proportional to the horizontal acceleration of the CG. However, while the COP movement in the AP direction was in phase with CG movement, it was larger in amplitude. Similarly in the Medio-Lateral (ML) direction, COP movement was greater in magnitude than the CG movement, although the movements were anti-phase (Winter et al.). Intuitively, the COP will move more than the CG during sustained upright stance to maintain the CG position within the base of support. However, in the case of quiet stance, horizontal plane movements of the COP and the CG are very similar (Davis and Grabiner, 1996). Further, given the smaller COP movements of shooters relative to non-shooters (eg. Aalto et al., 1990), CG and COP movement will be very closely related. As such, the use of COP would seem to be a reasonable measure of body sway for shooting research.

### 2.2.2 Rifle shooting and body sway

The effect of body sway on rifle shooting performance has been examined by a number of authors. This examination has taken the form of assessment during shooting in competition like conditions (eg. Era et al., 1996; Norvapalo et al., 1997) in rifle holding positions without shooting (eg. Bretz and Kaske, 1995; Niinimaa and McEvoy, 1983) and for quiet standing tasks (eg. Aalto et al., 1990; Wu et al., 1997).

In the only study to examine body sway during standing rifle shooting under competition conditions, Era et al. (1996) found that elite shooters produced
significantly less body sway than novice shooters. Further, a hierarchical progression existed for body sway between different skill levels, with the better skill levels exhibiting less body sway. Four groups of shooters were tested: 6 international level men, 3 international level women, 8 national level men and 7 controls, termed naive shooters. Each shooter performed 100-200 shots over a distance of 18m. As such, competition conditions were compromised, as 18m is not a competition distance and more shots were taken than in competition. Although the calculations were not fully detailed in the article, posture control was assessed using the horizontal centre of forces (COF), which was obtained from an algorithm that incorporated the COP, body mass and 0.55 times body height. COF total path and mean speed in the X-axis (parallel with the line of shot) and Y-axis (perpendicular to the line of shot), the moment of velocity and the length of a square which encompassed all COF movement were calculated for the time between 7.5s before shot to the point of shot. It was interesting that Era et al. used both length and mean speed measures of COF, as speed is directly measured from length and values will be very closely related. A one way ANOVA found COF to be significantly different between the naive shooters and all other groups in the 7.5s preceding the shot, with larger COF speeds in X and Y axes and higher maximal speeds than the other groups, although no statistical values were reported. The top level male shooters showed the lowest COF X and COF Y speeds and the smallest moment of velocity, while female top level shooters had significantly better values than the national level men in all parameters except in COF Y speed. It is unclear in the article exactly which relationships were statistically significant. While differences were found between shooters of different levels of skill and body sway related to performance for shooters of lower skill levels, Era et al. (1996) found no relationship between body sway and performance in the elite level group. This
relationship was examined by comparing the 20 best and 20 worst shots, as defined by the shot score and the coach’s evaluation of the quality of the shot, of the elite shooting group. Results were evaluated on an individual and group basis. Two tailed t-tests showed no significant differences between COF measures during good shots and COF measures during bad shots for the group, nor individuals.

Changes in body sway during the aiming process were also examined by Era et al. (1996). COF measures were quantified for five 1.5s windows (from 7.5s prior to shot until the point of shot) for elite and non-elite standing rifle shooters. Era et al. report finding significant reduction in COF velocity in the AP direction as the moment of shot approached (p<0.05 for a paired t-test) for the elite male and female shooters. This was not the case for the national level men or novice shooters. Novices were of particular note in that the COF velocity remained similar for all windows.

A number of factors may have affected the findings of Era et al. (1996). The elite group exhibited very little within group variability, minimising the likelihood of a correlation between body sway and shooting performance. This is a problem that exists in most research into elite level sports. Further, group numbers were low, reducing the statistical power of the study. Era et al. also reports using a 16-bit ADC board, the DT2821. However, according to the Data Translation (1996) catalogue the DT2821 board offers only 12-bit ADC. Given the minimal COP ranges of movement that are produced by rifle shooters, 12-bit ADC may not be precise enough to measure any differences in movement that may occur between shots in the elite group. An analysis of 12-bit and 16-bit ADC will be conducted as part of this study.
While no other studies have examined standing rifle shooting during competition, Norvapalo et al. (1997), examining running target shooters, found a similar tendency for novices to sway more than top level shooters. Total displacement and speed of the COP in the X-axis (parallel to the line of shot) and Z-axis (perpendicular to the line of shot) were calculated for the aiming phase (between 2 and 4s in length) of 30 slow running target shots from 10m. Three groups were tested: top level (international) shooters, national level shooters and novice shooters. A one way ANOVA showed that national and international level shooters had significantly lower COP velocities than novices in both X (F=8.42, p<0.05) and Z (F=12.97, p<0.05) axes. However, unlike Era et al. (1996), there was no difference between national and international level shooters. No data values were reported. Norvapalo et al. suggested this may be due to the use of only slow moving targets. Also, the national level group was older and therefore more experienced. Both factors may have served to minimise the difference between the groups.

Viitasalo et al. (1997) also failed to find significant correlations between body sway and shot performance for elite running target rifle shooters. Viitasalo et al. examined three groups of shooters in running target rifle shooting: international level rifle target shooters, regional level rifle target shooters and moose hunters. A definition of moose hunters was not provided. Each subject performed 30 slow run target shots while COP was calculated in the X-axis (parallel to the line of shot) and Z-axis (perpendicular to the line of shot) axis. When all shooters were analysed as one group, shooting performance was significantly correlated with COP amplitude, or range (X-axis, r=-0.620, p<0.01 and Z-axis, r=-0.819, p<0.001), indicating that as COP amplitude increased, shot score decreased. However, as for Norvapalo et al.
(1997), when groups were treated separately, no within group significant relationships were found. Viitasalo et al. (1997) suggest that there are factors other than body sway, such as unstable trigger squeezes, that influence shooting performance at the elite level. These factors will affect the strength of the relationship between body sway and performance. In both studies, the elite group comprised only six subjects, providing poor statistical power, with an r value in excess of 0.81 required for significance at p<0.05.

Similar to results found in rifle shooting research, differences in COP measures have been found between elite and non-elite archers but not between the elite archers themselves, nor between good and bad shots (Mason and Pelgrim, 1986; Squadrone and Rodano, 1995). Archery is a sport that holds strong similarities with shooting, with participants maintaining an upright, stationary position and shooting at a target, which requires extreme precision for good performance. Mason and Pelgrim (1986) tested elite level archers during simulated competition conditions while standing on a force plate. Body sway in the last second before shot, as measured by COP displacement range, COP standard deviation, and velocity in COPX and COPY, was compared with performance. Mason and Pelgrim found a significant relationship existed between these parameters. Specifically, body sway parallel to the line of shot (COPy) was related to the position of the arrow shot on target in the horizontal axis. However, this relationship was more significant for junior archers and not as apparent in senior archers. Mason and Pelgrim suggested that control of body sway was a prerequisite in becoming an elite archer, although once achieved, was not a discriminating factor of performance. Squadrone and Rodano (1995) also concluded that COP movement was not able to discriminate between elite level archers.
Rifle shooters have been found to not only be more stable than untrained shooters during shooting, but also during quiet standing (e.g. Wu et al., 1997; Viitasalo et al., 1997; Aalto et al., 1990). Norvapalo et al. (1997) compared competition (national and international level) and novice running target rifle shooters. COP amplitude (range) and average COP speed were calculated in the X and Z-axis (defined previously) from force plate data during normal standing for 30s. A one way ANOVA showed that COP amplitude was significantly smaller for competition shooters compared with novice shooters in the Z-axis (F=8.60, p<0.05) but not the X-axis in both shooting and free standing tasks. As mentioned previously, no body sway data was reported in this article.

Aalto et al. (1990) found that both rifle and pistol shooters swayed less than untrained subjects during quiet stance over a period of 27s. These tasks performed by shooters and controls (non shooters) involved standing on a custom built force plate for 180s, the first 90s with the eyes open and the second 90s with eyes closed. Average COP velocity was calculated from six 27s periods within this time, three in each 90s period. Using Wilcoxon’s rank sum test, significantly reduced average COP velocities were found in the shooter group compared to the control group. Aalto et al. suggest that this was due to specific training of postural control in these shooters.

Conversely, Niinimaa and McEvoy (1983) found no difference between the COP excursions (total distance the COP travels) for shooters and untrained subjects during a 60s standing task. Four groups, comprising elite rifle shooters, elite biathletes, intermediate level rifle shooters and a group of non-shooters were tested. Subjects
stood on a force plate, while holding a rifle in a shooting position, both before and immediately after exercise. COP excursions tended to decrease with an increase in shooting experience but were not found to be significantly different between groups.

However, a number of major limitations existed in the Niinimaa and McEvoy (1983) study. Subject numbers in each group were very small (N=4 to 6) reducing statistical power. Force plate measurement was performed using a 12-bit ADC system, which increases the potential error due to quantisation in the measure. Further, while COP length measures can be influenced considerably by noise, particularly over long measurement periods (Granat et al., 1990), no smoothing seems to have been used. These factors cast doubts over the reliability and usefulness of this finding.

The premise in assessing postural sway by using these tasks is that they relate to performance, or body sway during performance. This was also specifically examined by Viitasalo et al. (1997), who measured COP amplitude (range) for three groups of shooters (international level, national level and moose hunters) during a 30s standing trial with eyes open and a 30s trial with eyes closed and correlated these parameters with shooting performance. When all shooters were analysed as one group, shooting performance was significantly correlated with COP amplitude during standing with eyes open (X-axis r=-0.630, p<0.01, Z-axis r=-0.692, p<0.01) and standing with eyes closed (Z-axis only r=-0.536, p<0.05). These results indicated that lower COP amplitudes were associated with better performance. Also, in the Z-axis, COP amplitude during shooting was significantly correlated with COP amplitude during standing with eyes open (r=0.828, p<0.001) and standing with eyes closed (r=0.739, p<0.001). When groups were analysed separately, no significant relationships existed
between performance and COP amplitude for any task. However, COP amplitude in
the Z-axis during shooting was related to COP amplitude during eyes open stance
\( r=0.775, p<0.05 \) and eyes closed \( r=0.830, p<0.05 \). Viitasalo et al. suggested that
the ability to maintain stable posture in eyes open and eyes closed conditions was a
good predictor of stability during shooting.

In summary, the influence of body sway on rifle shooting performance has been
shown to be significant when shooters from a wide range of skill levels were used (eg.
Norvapalo et al., 1997). Further, elite level shooters have been shown to be more
stable than novice shooters (eg. Era et al., 1996). However, the link between
performance and body sway for elite shooters has not been found to be significant (eg.
Viitasalo et al., 1997). Low subject numbers and poor measurement resolution may
have affected these findings. As mentioned, stage 1 of this study will address the
issue of resolution. The examination of the relationship between body sway and
performance using greater measurement resolution than used in these studies will be
the focus of section two.

2.2.3 Pistol shooting and body sway

In the few studies examining body sway and pistol shooting performance, results and
conclusions have been conflicting. Mason et al. (1990) found significant associations
between body sway and pistol shooting performance at the elite level. 16 elite level
pistol shooters performed 25 shots under simulated competition conditions. A large
number of parameters were measured and calculated relating to body sway, aim point
fluctuation, pistol movement and grip pressure. In multiple regression analysis
including all parameters, body sway, as measured by COP range, was found to be the
factor most influential to shot result, contributing 30% (R=0.55, p<0.02) to errors of shot on target, with total pistol movement accounting for the next largest variance of 13%. On examination of the influence of these variables to errors of shot in horizontal and vertical axes, it was found that COP range parallel to the line of shot was correlated with the vertical fall of shot on the target (above and below the target centre, r=0.63, p<0.01).

A limitation of the Mason et al. (1990) study was the use of 12-bit ADC for force plate data collection for body sway assessment, a limitation also present in rifle shooting research as mentioned in section 2.2.2. The measurement resolution and error due to quantisation using 12-bit ADC may be a limitation of measure of body sway for pistol shooters. Given the elite nature of the group tested by Mason et al., it is likely that the difference in body sway values for different shooters was small. The poor resolution and potentially large error due to quantisation in body sway measures will limit the ability to discern between shooters on this basis. As such, it could be expected that statistical analyses would be influenced by this data, potentially masking relationships that exist or finding relationships where they do not exist.

However, Iskra et al. (1988) also concluded that body stabilisation is the most important factor in pistol shooting performance, supporting the findings of Mason et al. (1990). Spectral analyses were performed on signals recorded from accelerometers fixed to the gun barrel and gun butt. Seventeen shooters performed a number of shots on target. These subjects included one shooter who was described as an expert (not well defined by the researcher). The level of skill of the remaining 16 was not reported. A mean power spectrum, obtained by averaging individual shot power
spectra across all trials for each shooter, showed three resonance peaks (figure 2.2). The first peak (0.7Hz) correlated with the shot result, although it is unclear from the article how this correlation was obtained. Iskra et al. attributed this frequency to body sway. A number of authors have shown that the majority of power in COP movement during quiet stance exists below 1.2Hz (eg. Soames and Atha, 1982; Lucy and Hayes, 1985; Powell and Dzendolet, 1984), with peaks below 1Hz during quiet stance. Given that the pistol-shooting stance is an example of quiet stance, these peaks could be expected to exist in shooters also. As such, the conclusion of Iskra et al. seems reasonable. A second peak was found reported at the 7Hz mark, although the example frequency graph presented indicated this peak was between 4Hz and 5Hz. The authors could not explain this peak. While slightly lower than the value reported by Iskra et al., peaks between 4 and 5Hz have been found in force plate data during quiet stance that were attributed to the ballistocardiogram (Goldie, 1985) and may be a contributing factor to this 7Hz peak. Alternatively, it could be associated with muscle tremor. Thomas and Whitney (1959) report that muscle tremor existed in force plate signals between 5Hz and 10Hz. However, Iskra attributed the third peak (12Hz) to muscle tremor. The generating mechanisms of these peaks at higher frequencies are unclear but would seem to be too high to be associated with body sway, and will be of less interest to this study.
Iskra et al. (1990) also reports that the finding that body sway is the most influential factor to shooting performance supported a number of previous studies (Losel, 1976; Radowksi, 1975; Rudina and Bik, 1978). These articles could not be obtained and translated in the time span of this study. It should be mentioned that, while correlations performed by Iskra et al. indicated that body sway and shot result were associated, the conclusions of Iskra et al. were not well developed. Body stabilisation would seem to be a factor affecting performance in this study, although the measurement of body sway using accelerometers on the gun is somewhat indirect.

In contrast to the findings and conclusions of these studies, Aalto et al. (1990) suggested that body sway is unimportant for pistol shooting. Aalto et al., examined posture control of two pistol shooters, eight rifle shooters and 27 control subjects during 27s stability tasks. Results indicated that the rifle shooters were more stable than pistol shooters. Aalto et al. report that this difference was statistically
significant, although no statistical values were reported. Based on these results, Aalto et al. suggested that this result supported the ‘commonly held notion’ that body sway was not important to pistol shooting performance. Given only two pistol shooters were used, this conclusion seemed a little presumptuous. Further, the stability test used was not specific to shooting and no link between stability tasks and posture control during shooting was made. Certainly, this notion does not appear to hold up based on the research by Mason et al. (1990) and Iskra et al. (1988).

2.2.4 General posture control

There is a large body of literature associated with human postural control covering a large number of sub topics. This next section will briefly review a selection of these topics.

Research in posture control has covered a wide range of issues, including normal stance (eg. Stevens and Tomlinson, 1971; Murray et al., 1975; Ekdahl et al., 1989), sites of posture control (eg. Horak and Nashner, 1986; Nakagawa et al., 1993; Teasdale et al., 1993), modelling of stance (eg. O’Riley et al., 1990; Davis and Grabiner, 1996) and clinical applications (eg. Lucy and Hayes, 1985; Simoneau, 1992; Bauer, 1993).

Measurement of sway and postural control has been performed using both kinetic and kinematic methods. Early kinematic methods included direct attachment of wires between the upper and lower back of a subject and a recording device to monitor the
amount of movement experienced at these two sites (Stevens and Tomlinson, 1971). Studies have digitised body landmarks from film or video to quantify sway (eg. Brown and Frank, 1997). However, the most common method used to measure postural control has involved locating the subject on a single force plate and monitoring COP movement during a specified time. This is the method almost exclusively used in shooting research to measure posture control.

Different researchers have used a number of parameters to quantify posture control and stability. COP movement is most often quantified in terms of displacement, velocity, area covered per unit of time and variability in the AP and ML axes (eg. Gianikellis et al., 1995; Landin et al., 1993). Other forms of measurement, such as the variability of force in the ML and AP directions (Goldie et al., 1994) and Fourier analysis have also been used (eg. Powell and Dzendolet, 1984; Liu and Lawson, 1995).

There is contention as to the most valid and reliable measure for posture control, with advantages existing for each measurement type. Goldie et al. (1989) performed a reliability study using 28 subjects, found that the variance in the horizontal force signals (ML and AP directions) was a more reliable measure than variance in COP, particular for one-legged stance. Simoneau (1992) reported finding that COP measurement was unreliable in posture assessment. Samson and Crowe (1996) found inconsistencies across trials for the length of the COP trace, as well as poor COP repeatability between stability trials. Despite these concerns, COP remains the most widely used measure of posture assessment. Possible reasons for this lack of reliability of COP parameters, a focus of this study, is the use of 12-bit ADC systems.
Numerous researchers have examined the posture control strategies used to maintain upright stance. Horak and Nashner (1986) suggested that sway in the AP and ML directions was regulated by different mechanisms. Sway in the AP direction is controlled by an ankle strategy, while sway in the ML direction was controlled by a hip strategy. Using the ankle strategy, body position is controlled by alternately activating and deactivating the musculature on the anterior and posterior aspects of the ankle and leg. Sway in this direction has been modelled as an inverted pendulum (Nashner and McCollum, 1985). Pivoting about the ankle joints, the body acts as a single segment and sways back and forth similar to a pendulum. This inverted pendulum has been included in models of quiet stance (eg. O’Riley et al., 1990; Davis and Grabiner, 1996). The hip strategy used in ML sway control involves the hip musculature working to keep the CG at or about the centre of balance (COB) by loading or unloading each hip. Winter et al. (1993) examined the different strategies more closely using two force plates, one for each foot. Winter et al. report that AP and ML sway control are independent of each other. Confirming previous research, Winter et al. also suggested that musculature about the ankle controlled only the AP sway, while hip adductors/abductors were the main muscles used in the control of ML sway.

Winter (1995) suggested that balance and posture are controlled by three systems in the body.

1. Vision provides information on the position of the body relative to the external environment, the position of body parts relative to each other, and spatial orientation of the body and environment.
(2) The vestibular system acts as a level balance mechanism, providing information on head position and acceleration, and assisting with the provision of a stable visual image.

(3) Afferent information, provided by the somatosensory system, monitors body segment orientation, joint position and joint angular movement.

In addition, Deitz et al. (1992) suggest the golgi tendon organs may also be involved in posture control by way of assisting with body weight and gravity, possibly locating the body’s CG.

Cavanagh et al. (1993) report that, while these three mechanisms are complimentary to each other, they each have a specific role. The afferent information from the somatosensory system is highly redundant, but useful in a number of different environments or where the effectiveness of the other systems is reduced or eliminated. Such a situation exists in shooting, where much of the visual system is associated with the aiming process. Nakagawa et al. (1993) suggested that the somatosensory system contributed little to the control of body sway. Simoneau (1992), however, reports that somatosensory input is the most important of the three, contributing 40% to the control of balance, followed by vision (29-34%) and vestibular apparatus (3%).

Balance in normal, healthy individuals has been examined by a number of authors. Murray et al. (1975) in one of the earliest posture assessment studies using a force plate, noted that the COP is constantly moving and traces a long path while remaining within a small radius. During double limb stance over 30 seconds, COP ranges of 3.8mm in the AP direction and 3.3 mm in the ML direction were reported. These
values are similar to the COP ranges reported by Ekdahl et al. (1989) of 3-4mm for 20 - 29 year old subjects. However, Simoneau et al. (1992) reports finding very large COP ranges of up to 16mm for normal subjects using a similar protocol and force plate system to that used by Ekdahl et al.. It is unclear what has caused this large discrepancy between studies.

The effects of changed conditions on posture, such as eliminating visual feedback by closing the eyes or altering the support base by balancing on one leg have shown consistent results with increases in postural sway always found under these conditions. Bretz and Kaske (1995) found an increase in the area of the COP trace during eyes closed conditions when compared with eyes open for a double stance stability test. Goldie et al. (1989) found an increase in the variability of horizontal forces and COP, as measured by a force plate, under similar conditions. These results support the theory that visual cues form a major role in stability.

It is unclear from the literature how anthropological factors affect stability. Powell and Dzendolet (1984) examined the influence of height, weight, a number of foot dimensions, height of the ankle and height of the umbilicus of 80 adult male subjects on body sway. No link was found. Ekdahl et al. (1989) also found no relationship between subject height, weight and COP excursion. However, Chia et al. (1993) found height to influence stability results for both experimental and control group. This area needs more research to define the relationship between anthropological measures and body sway. Although not examined in this study, these factors may also have implications for shooters as the body gun system will be different between subjects of different anthropology. However, this is beyond the scope of this study.
Spectral analyses of body sway measures have been performed by a number of researchers. The majority of these studies have calculated the COP in AP and ML directions and used a fast Fourier transform (FFT) analysis to obtain a mean power spectrum of the COP signal. Most power during quiet stance seems to be less than 3Hz, with peak power at approximately 0.1-0.3Hz (Scott and Dzendolet, 1992; Liu and Lawson, 1995; Soames and Atha, 1982). Bretz and Kaske (1995) found dominant frequency of sway in both the ML and AP direction was 0.45Hz, although there were higher frequencies observed in the AP direction. Lucy and Hayes (1985) report finding the principal power of COP less than 1Hz in both AP and ML directions, with peak power less than 0.2Hz. Mean power was higher for subjects with cerebral ataxia, with peaks above 1Hz. Lucy and Hayes also noted some higher frequency components (1-3Hz) for some of the older subjects, suggesting that this result was linked to the degradation of the peripheral sensory system. Simoneau (1992) also reported an increase in the mean frequency of COP movement in patients with diabetic neuropathy compared with healthy subjects. No frequency analysis of force plate data has been performed in shooting.

To adapt some of these findings to shooting and summarise this section, body sway during shooting may originate from a number of sources. The natural tendency of the body to sway while standing as well as the requirements of movement generated from the aiming process will affect the amount of movement generated by body sway during shooting. Muscle cannot, by its nature, maintain a totally constant tension (Lees, 1986). As such, reliance on musculature to maintain posture will cause at least a small amount of movement. Patla (1997), reported that the threshold for excitation
of the kinaesthetic receptors is not reached during quiet standing, suggesting that body stiffness, controlled actively by muscles surrounding a joint and passively by other structures, is ‘set’ which provides the necessary stability to remain still. It is possible, then, that inaccurate settings of this ‘body stiffness’ may allow for more body sway. Physiological tremor, such as breathing and heartbeat, also influences overall body movement (Mason and Bond, 1990). Although respiration has been shown to influence body stability (Takata, Kakeno et al., 1983), shooters hold their breath in the preceding seconds before shot to eliminate this influence on stability.

A number of aspects of the shooting skill may influence where and how posture is controlled during shooting. Era et al. (1996) suggested that the visual system is almost exclusively involved in the aiming process and would contribute little to balance, as did Aalto et al. (1990). Cavanagh et al. (1993), as mentioned previously, reported that the somatosensory system information is useful where the effectiveness of the other systems is reduced. Aalto et al. (1990) found that the ratio between stability with eyes open and eyes closed was smaller for shooters than for control subjects. Aalto et al. concluded that shooters rely less on vision for postural control, and compensates with proprioceptive and vestibular feedback. However, as mentioned, Patla (1997) reported that the threshold for excitation of the kinaesthetic receptors is not reached during quiet standing. This being the case, the contribution from the somatosensory (proprioceptive) system may be limited. More accurate settings of body stiffness, as proposed by Patla as controlling sway in quiet standing, may be the mechanism that has been trained to a high level by elite shooters, which contributes to the highly stable stances.
2.3 Aiming

2.3.1 Rifle shooting and aim point fluctuation

Aim point fluctuation refers to the movement of the point of aim of the gun on the target and relates directly to shooting performance. There are a number of commercial laser or infrared based systems available that perform the task of monitoring the aim point of the gun on the target. These systems consist of an instrumented target that outputs beams, which are detected by a directional sensor located on the barrel of the gun. The sensor is aligned such that the direction of the sensor corresponds with the point of aim of the gun on the target. This aim point measurement is calibrated and quantified in terms of the vertical plane XY coordinates of the target and fed into a computer. The vibration of the gun at the point of shot is detected to locate the moment in time that the shot is fired. Figure 2.3 shows the aim point fluctuation on a target as recorded by the laser-based SCATT system.
2.1.1 Training Window

Figure 2.3: SCATT (aim point fluctuation) output. The fluctuating line represents the aim point (measured every 1/128 s), the large dots represent the aim point at the instant the shot was fired.

The aiming process during shooting has been examined with the use of these laser-based systems (Zatsiorski and Aktov, 1990; Lenart, 1992; Mason et al., 1990). Zatsiorski and Aktov (1990) monitored the aim point of elite rifle shooters during the five seconds preceding the shot. The researchers found that general fluctuations of this aim point, quantified by measuring the size of a rectangle fitted around all aim point positions recorded, decreased as the instant of shot approached. Further, in the last second before shot, the aim point always remained within the ‘9’ ring.

Interestingly, while the vertical fluctuations of the aim point decreased as the point of shot approached, the horizontal deviations remained fairly constant. Due to small subject numbers, no statistical analysis between aim point fluctuation and shooting performance was reported in the Zatsiorski and Aktov study.
Zatsiorski and Aktov (1990), in further examination of the aim point fluctuation in elite rifle shooters, found that a ‘fixation strategy’ was used by elite shooters in preference to an ‘interception’ technique when aiming at a target. This fixation strategy involved stabilising the aim point at a single point or number of points on the target, finally centring on the target centre. The interception technique involved moving the aim point across the target. Shooters would attempt to ‘time’ the point of shot such that the aim point coincided with the point of intersection with the target centre. It is not clear from the study if any shooters used the interception technique.

The fixation and interception techniques were also recognised by Heinula (1996), although different terms were used to describe them. In a technical report on aim point fluctuation, Heinula collected a large amount of aim point data on over 100 shooters over three years. Shooter skill levels included international, national, club and untrained shooters. Based on the stability of the aim point hold, Heinula formulated three aim point categories for shooters; hold shooters, reaction shooters and optimised shooters. Hold shooters were the same as fixation shooters and reaction shooters were the same as interception shooters defined by Zatsiorski and Aktov (1990). Optimised shooters lay between the hold and the reaction shooters, exhibiting some stability of aim point hold, but still requiring timing of the shot as the aim point passed across the target centre. Heinula reports that most shooters employed the hold technique, although many alternated between the three categories presented.

Zatsiorski and Aktov (1990) noted that the fixation strategy used by elite shooters when aiming could be broken down into two categories, although no cluster or other
statistical analysis was performed on the data. As shown in figure 2.4, one cluster of shooters stabilised around a point, which was not necessarily the centre of the target, as the instant of shot approaches. This would then be repeated 2 to 5 times, with the shooter stabilising on one point for a period, then moving to another and stabilising again. The second technique evident was a single stage aiming process, where the shooter would stabilise on one point only. Also, a consistent approach on the target was noted for each shooter, with six of the ten shooters tested levelling their rifles predominantly up and down while four levelled right to left.

![Figure 2.4: Representation of the two aim variants during the aiming process found by Zatsiorski and Aktov, 1990.](image)

(i) Series of small areas of aim   (ii) One aim area only

Heinula (1996), from the large body of data the researcher collected, formulated an aim point model and a regression equation of both pistol and rifle shooting performance. This was based on three aiming factors: the hold, the aim and trigger control. The hold was defined as the steadiness of the aim point about a central point, the aim was defined as the proximity of the aim point to the centre of the target, and the trigger control was defined as the ability to press the trigger without the aim point moving. It was reported that the quality of the hold was the major contributing factor
to shooting performance, accounting for 83% of the variation in scores for a given shooter. Unfortunately, Heinula does not define the exact method of calculation of these factors in the research paper.

As for body sway, researchers have found significant relationships between aim point fluctuation and shooting performance when examining groups with a range of skill levels, but not within the elite level shooting groups. Viitasalo et al. (1997) tested 22 subjects from three groups, international shooters, regional shooters and moose hunters, during the performance 30-60 shots on slow running targets while aim point fluctuations were monitored. Aim point amplitude, interpreted by this researcher as range, and result of shot on target was quantified. Shooting performance and aim point fluctuation was significantly correlated in the X, or horizontal, axis ($r=-0.636$, $p<0.01$) and Y, or vertical, axis ($r=-0.712$, $p<0.001$) when all shooters were analysed together. However, when the group analysed was separated into the individual groups tested, statistical analyses were not significant, although only six elite shooters made up this group, providing very low statistical power, with a value of $r>0.81$ required for significance at $p<0.05$. Norvapalo et al. (1997), in a similar study, found a progression from novice shooters to national shooters to international shooters for aim point fluctuations, with the novices producing the most fluctuation and the international shooter the least. This was found for both horizontal and vertical aim point fluctuations. However, as for the Viitasalo et al. study, no statistical significance was found between performance and aim point fluctuation when the elite level group was treated separately. Once again, only six elite shooters made up this group, reducing statistical power.
A limitation of the quantification of aim point fluctuation in both the Viitasalo et al. (1997) and Norvapalo et al. (1997) study did not take into account different aim point strategies that may have existed in the data. Range measures alone will not be sensitive to the aim point strategies detailed by Zatsiorski and Aktov (1990) and Heinula (1996). As such, these strategies will influence any statistical analysis of the relationship between aim point movement, as measured by range, and performance. Further, Heinula reports shooters that used a range of strategies, which will further cloud any statistical analysis on a group basis.

### 2.3.2 Pistol shooting and aim point fluctuation

Pistol shooting performance and aim point fluctuation was examined by Mason et al. (1990) with a weak linear relationship between the two reported ($r=0.2$, $p<0.05$). The quantification of aim point fluctuation in the Mason et al. study was limited to length of movement and shot position in horizontal and vertical directions. A more thorough analysis of the aim point movement, including quantification of areas of movement, may have assisted in defining this relationship better. Further, the different aim point strategies found by Heinula (1992) in both rifle and pistol shooters would have influenced this result, largely negating any statistical analysis that was conducted across the group.

There are no other studies examining performance and aim point fluctuation in pistol shooting.

### 2.4 Body sway and aim point fluctuation
2.4.1 Body sway and aim point fluctuation in rifle shooting

No studies have examined the relationship between body sway and aim point fluctuation in standing rifle shooting.

Aim point fluctuation and body sway have been found to be related in running target rifle shooting. Viitasalo et al. (1997) compared body sway and aim point oscillations. Aim point length in the vertical direction was correlated with COP amplitude in the X-axis (parallel with the line of shot, r=0.534, p<0.05) and Z-axis (perpendicular to the line of shot, r=0.536, p<0.05). It was interesting that body sway in both axes related to an increase in aim point movement in the vertical axis only. This relationship did not exist for the elite level shooters when they were examined as a sub group. As mentioned previously, with only six shooters, statistical power was low. Further, the description of aim point fluctuation was limited to ranges and no account for aim point strategies was made. Norvapalo et al. (1997) found that elite level shooters were more stable and exhibited less aim point fluctuation than national level or novice shooters during running target rifle shooting. However, these parameters were not directly compared in the report nor was the data presented, and only discussed in general terms.

2.4.2 Body sway and aim point fluctuation in pistol shooting

No studies have examined the relationship between body sway and aim point fluctuation in pistol shooting. A broad link might be indicated in the comparison of
COP and aim point movement in their respective axes. Mason et al. (1990) reported more aim point fluctuation in the horizontal direction (108.9mm) as compared with the vertical direction (89.2mm), while body sway across the line of shot (3.3mm) was larger than parallel to the line of shot (3.0mm). Body sway perpendicular to the line of shot (as measured by COPx), without compensation from body parts, will cause a horizontal movement of the aim point across the target. Hence the larger amount of sway perpendicular compared to parallel to the line of shot may be linked to greater horizontal compared with vertical aim point movement. With more accurate body sway data and a larger number of aim point parameters, the relationship would be better defined.

This study will examine more closely, the relationship between aim point fluctuations and body sway, as well as the relationship each has to shooting performance in standing rifle and pistol shooting.