# The association of osteopathic tests and diagnoses of sacroiliac joint dysfunction with ground reaction forces during gait

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## *ABSTRACT*

# The association of osteopathic tests and diagnoses of sacroiliac joint dysfunction with ground reaction forces during gait

### ***Summary***

This study compared the ground reaction forces during walking of 44 symptomatic patients who tested positive for somatic dysfunction of the sacroiliac joints with 25 normal subjects. 12 subjects returned in 1 week in order to test the reliability over time of the measures. The gait analysis showed significant differences in ground reaction forces between the two positive symptomatic groups, subjects with right anterior innominate (innominate group) and forward sacral torsion - left on left (sacral group), and between both these groups and the control (norm) group ($p < .05$). 15 of the 76 parameters measured proved to be highly variable from week to week.

The study has identified specific differences in the ground reaction forces in subjects with two of the most commonly diagnosed somatic dysfunctions of the pelvis from normal subjects, and therefore adds a possible objective measure to the theoretical models of sacroiliac joint dysfunction.

As the literature is confused regarding the definition and diagnostic criteria of Sacroiliac Joint Dysfunction, a comprehensive model of categorization is proposed.

## Background and purpose

The diagnoses of somatic dysfunction utilised by the osteopathic profession have not been validated by experimental data, and the aim of the study was to investigate whether ground reaction forces during gait might be associated with these dysfunctions.

## Introduction

The biomechanical role of the sacroiliac joint during gait is to absorb both ground reaction forces and shear forces during movement. Analysing the gait of patients with sacroiliac joint dysfunction is vital if there is to be an increase in the understanding of its role in low back and pelvic pain and related dysfunctions.

Force platforms are seen as a reliable, objective measure of gait, and have been used in the past in the analysis of clinical biomechanical dysfunctions.

## Materials and methods

102 adult males were recruited from the students, staff and patients of an osteopathic outpatient teaching clinic. A questionnaire was used to specify whether the applicant was symptomatic of low back and/or pelvic pain in the last six months, and to screen for the presence of the exclusion criteria of trauma and pathology of the low back, pelvis and lower limbs. Those who were not excluded but were symptomatic were interviewed to define the pain history. Of the 102 applicants, 93 were eligible to be examined for the presence of two specific somatic dysfunctions of the sacroiliac joint, with the one examiner using a modified osteopathic diagnostic procedure. Applicants with diagnoses other than these two were excluded. The

remaining 69 subjects were divided into three groups; the first were asymptomatic and normal on examination (control, n=25), the second were symptomatic with anteriorly rotated innominate (n=20), and the third were symptomatic with forward sacral torsion – left on left (n=24). Subjects performed an average of nine gait trials over an AMTI force platform with each leg, walking at a controlled speed of 1.5 m/s ± 10% in a biomechanics laboratory. A computer based software programme analysed 76 parameters divided amongst the three orthogonal components of the ground reaction forces; vertical, anteroposterior and mediolateral. These parameters included absolute and normalized (to body weight for forces and to total time for temporal measures) values, with force and temporal measurements of each foot throughout stance.

In order to examine the different sources of variance due to within subject and between subject variance, as well as the group by leg interactions (left to right leg differences between groups), a Multilevel statistical approach was used.

## Results

39 parameters had insignificant results. The significant results are presented in categories of the differences between groups.

The innominate group had significant ($p < 0.05$) asymmetry between legs compared to control in 13 parameters. These were:

1. The vertical heelstrike transient maximum value, the maximum value normalised to body weight and the slope to this maximum.
2. The timing of the second minimum, the minimum trough impulse and its normalised value.

3. The first vertical maximum peak of the typical bimodal pattern, this first peak normalised, the slope up to the first peak and the slope normalised.
4. The second vertical maximum peak of the bimodal pattern, and this peak normalised.
5. The average propulsive (anterior) force.

The results of the first maximal vertical peak slope demonstrated excessive variability between weeks, based on the measure being less than 1.96 its standard error and being the highest proportion of the variance.

The sacral group had significant ($p < 0.05$) asymmetry between legs compared to control in 14 parameters, which were:

1. The vertical heelstrike transient minimum, this minimum normalised, the slope to this minimum and the slope normalised.
2. The time of the first vertical minimum of the normal bimodal pattern, the time normalised, the slope up to this minimum, this slope normalised, the impulse of this minimum and the impulse normalised.
3. The second vertical maximum peak.
4. The maximum medial force and this force normalised.

The result in the second vertical peak is questionable, as the normalised result was insignificant, suggesting the influence of body weight.

The sacral group had significant ($p<0.05$) differences to the innominate group in 15 parameters, which were:

1. The slope of the heelstrike vertical transient and the slope normalised.
2. The slope of the minimum after the heelstrike transient, the timing of this minimum and this timing normalised.
3. The slope of the first maximum peak of the typical bimodal pattern, and this maximum normalised.
4. The slope of the first minimum trough of the typical bimodal pattern, and this slope normalized.
5. The second vertical peak in the bimodal pattern, and its slope.
6. The time of maximum braking, and this timing normalised.
7. The maximum medial force and this maximum normalised.

The slope results of the first vertical peak demonstrated excessive variability between weeks, based on the measure being less than 1.96 its standard error and being the highest proportion of the variance. The findings on the second vertical peak and its slope are not supported by the normalised findings, which suggest body weight is a significant influence on the result.

The control group had significant asymmetry between legs in 22 parameters, which were:

1. The heelstrike transient vertical trough, its slope, and these findings normalised.
2. The impulse of the first trough of the bimodal pattern, and the impulse normalized.
3. The second vertical peak of the bimodal pattern, the peak normalized, its slope and the slope normalized.
4. The total vertical impulse.
5. The timing of the maximum braking, this timing normalized.

6. The maximum propulsive (anterior) force; its timing, average and impulse, and all these findings normalised.
7. The maximum medial force, and this force normalised.

## Conclusions

The findings in this study appear to support the view that dysfunction of the sacroiliac joint effects gait. The results suggest that there is some validity to the diagnoses of anteriorly rotated innominate and forward sacral torsion, and that these are different to one another in their effect on ground reaction forces. These diagnoses have emerged from the osteopathic literature, but had not been demonstrated experimentally before this study.

This study also demonstrated that the normal asymptomatic group had significant asymmetry between legs in their ground reaction forces. This may reveal a leg dominance that was not investigated in this study. This finding is paradoxical to literature that presumes gait is symmetrical, and measures outcomes against increasing symmetry.

Further research following similar methodology, with an increased focus on inter-examiner reliability, is warranted. The proposed effect of the altered ground reaction forces on the clinical presentation of painful musculoskeletal conditions requires further study.

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## FIGURES

# 1 *Introduction*

Low back pain (LBP) is extremely common as a presenting symptom; 50% of the population will complain of LBP at some time (Stein, 1994). The sacroiliac joint (SIJ) is known to be one source of LBP and buttock pain in patients, accounting for up to 30% of low back and referred pain presentations (Schwarzer et al., 1995). The role the SIJ plays in the presentation of low back and buttock pain includes infection, arthritis, malignancy and sacroiliac joint dysfunction.

Sacroiliac Joint Dysfunction (SIJD) is a controversial diagnosis utilised in various professions as both a description of the joint that is producing pain, and as a biomechanical description of altered motion. This confusion over definition creates a lack of clarity in the debate over the existence of this condition, its diagnosis and the therapies that purport to treat it. The relationship between two of the most commonly used definitions, one of an articulation producing pain and the other of a mobility dysfunction, has not been established and has rarely been discussed in the literature (Lee, 1999, Ch 7).

This relationship of SIJ mobility to the diagnosis of SIJD is inconsistently reported in the literature, and has not been validated by experimental analysis. This is despite the fact that testing the mobility of the SIJ is an essential component in the diagnosis of SIJD, and continues as part of a normal routine in many professional practices around the world. Orthopaedic and sports physicians, physiotherapists, chiropractors and osteopaths commonly utilise motion testing in their diagnosis of SIJD, with resultant diagnostic labels such as dyskinesia, fixation, hypomobility and subluxation. No investigation, test or combinations of tests have been repeatedly proven to predict the diagnosis of SIJD when viewed in either mobility terms, pain provocation or the relationship between the two.

The mobility of the SIJ has been described as "minimal" after decades of controversy, and the specific characteristics of this movement have not been clarified experimentally. The biomechanical role of the SIJ in gait has been described as a triplanar shock absorber of ground reaction forces (GRF) and shear in the linking between the lower limbs and the lumbar spine and trunk (Greenman, 1990; Alderink, 1991; Hesch et al., 1992; Lee, 1999 Ch 5; Snijders et al., 1993a; Wilder et al., 1980). Biomechanical modeling has been presented which suggests that failed stabilisation of the pelvis resulting from SIJD during lifting and loading is connected to lumbar inter-vertebral disc herniation, a major cause of lower back and pelvic pain (Gracovetsky & Farfan, 1986; Gracovetsky et al., 1989). It has been stated that "understanding of the role of the pelvis in locomotion and the attendant dysfunctions is the third great landmark of orthopaedic medicine" (Dorman, 1997).

If the small movements of the sacroiliac joint are components of normal gait, and that SIJD includes a diagnosis of hypomobility, then it is reasonable to suggest that the GRF would be altered in those patients with symptoms and diagnosis of SIJD compared to normal controls.

This study will examine whether osteopathic tests and diagnoses of SIJD are associated with changes in gait as measured by ground reaction forces.

# *2 Sacroiliac Joint*

In order to describe and give support to the theory of diagnosis of SIJD described in this thesis, particularly with regard to the potential for the SIJ to have specific movements that are not experimentally proven, it is essential to first describe the articulation in detail in its anatomical, neurological and biomechanical aspects.

## *2.1 Anatomy*

### *2.1.1 Definition*

The sacroiliac joints consist of the articulations between the left and right articular surfaces on the sacrum and the left and right iliac bones, and are best described as true diarthrodial articulations of the lower limbs (Bowen & Cassidy, 1981; Warwick and Williams, 1973). There has been debate over the type of joint since it was first described as a true synovial articulation in the literature by Bernhard Siegfried Albinus (1697-1770) and William Hunter (1718-1783), and as a diarthrodial joint by Von Luschka in 1864 (Bowen & Cassidy, 1981). Weisl (1954) described each as two condyloid joints separated by a saddle joint. They are still referred to as part synovial and part syndesmosis (Walker, 1992). Syndesmoses are types of synarthroses that are connected by interosseous fibrous tissue, whereas diarthroses have indirect connection by a joint capsule; the sacroiliac joints have characteristics of both (Norkin & Levangie, 1992).

### *2.1.1 Osteology*

The articular surface of the sacrum is auricular (L-shaped) with a cephalad short arm lying in the vertical plane, and a caudad long arm lying in the antero-posterior plane. These coincide with the fused sacral vertebrae where S1 contains the short arm, and S2 and S3 contain the long arm (Lee, 1999, Ch 5). The three dimensional orientation of these articulations is variable. This variability and complexity creates difficulty in viewing the surfaces by conventional radiography. The sacral surface is commonly described as an inverted wedge with the middle third vertically inclined and the lower third flaring outward (Walker, 1992).

Fryette (1954) described three categories of sacrum in the 23 he examined; type A having coronal orientation of its superior articular processes and the sacral articular surface narrowing inferiorly at S1 and S2, type B having sagittal superior articular processes and narrowing superiorly at S1, and type C having bilateral asymmetry with type A on one side and type B on the other. The orientation of the sacroiliac articulations has also been described as propeller shaped (Vleeming et al., 1997), with a change in orientation occurring between the two arms.

Articular cartilage on the sacral surface is hyaline and is reported as three times the thickness of the fibrocartilage on the iliac surface (Bowen & Cassidy, 1981; Lee, 1999, Miller at al., 1987), this amount being comparable in proportion with an articular disc (Strachan et al., 1938).

These surfaces have ridges and depressions in the adult, with a high degree of individuality; they are thought to add stability to the joint and are greater in males (Bowen & Cassidy, 1981; Vleeming et al., 1990; Walker, 1992; Weisl, 1954). Accessory articulations occur in 8-40% of the population, with up to three reported at one sacroiliac joint site; they occur at the level of the sacral crest, at the first and second posterior foramina, on the ilium at the medial surface of the posterior superior iliac spine and on the tuberosity (Cole et al., 1996; Walker, 1992). They have been variously described as true synovial and syndesmoses, and there are no reports of their presence in children, and so are probably acquired (Walker, 1992), although cadaveric studies on children are not frequent (Lee, 1999, Ch 3).

### *2.1.3 Arthrology*

The sacroiliac joint capsule has an outer fibrous layer of collagen and fibroblasts, and an inner synovial layer. The posterior capsule blends with the interosseus ligament, whilst the anterior capsule is clearly differentiated from the ventral ligaments. The synovium thickens with age (Bowen & Cassidy, 1981; Lee, 1999, Ch 4). Schwarzer et al (1995) found evidence of ventral capsular tears in nineteen of the twenty three symptomatic patients who underwent sacroiliac joint injection fluoroscopy. Fortin et al (1994) found no evidence of ventral tears using the same procedure in ten asymptomatic subjects, although he noted some extravasation of contrast in nine of those ten.

In spite of the wedging of the sacrum and interlocking surface of the articulation (Weisl, 1954; Wilder et al., 1980), in vivo it is thought that the sacrum is dynamic (Fortin et al., 1994) and suspended by ligaments and muscles (Miller et al., 1987). It is important to consider the functional anatomy of these structures in order to facilitate the understanding of clinical biomechanics later in this thesis.

The interosseus sacroiliac ligament (Figures 3 and 5) is the largest and strongest bond between the ilium and sacrum, and fills the space between the lateral sacral crest and the iliac tuberosity, immediately superior and posterior to the joint itself. It can be divided into a superficial part which is a fibrous sheet which attaches to the superior articular process and lateral crest on S1 and S2 and to the medial aspect of the iliac crest, and a deep part which attaches to the three fossae on the lateral aspect of the dorsal sacral surface, and the adjacent iliac tuberosity (Warwick & Williams, 1973; Lee, 1999, Ch 4).

The ventral sacroiliac ligament (Figure 1 and 5) is a thickening of the anterior and inferior joint capsule and is relatively weak. It is thicker at the levels of the arcuate line and the posterior inferior iliac spine, where it connects S3 to the ilium (Warwick & Williams, 1973; Bowen & Cassidy, 1981). Posteriorly lies the dorsal sacroiliac ligament (Figure 4), which is separated from the interosseus ligament by the dorsal rami of the sacral spinal nerves and blood vessels, and attaches to the lateral sacral crest at S3 and S4 and to the posterior superior iliac spine and the inner lip of the iliac crest (Warwick & Williams, 1973; Bowen & Cassidy, 1981). Fibres that pass from S3 and S4 to the posterior superior iliac spine have been termed the long dorsal sacroiliac ligament, and medially these fibres attach to the deep lamina of the posterior layer of the thoracolumbar fascia and the aponeurosis of the erector spinae muscle. Laterally the fibres blend with the superior band of the sacrotuberous ligament (Vleeming et al., 1996). The dorsal rami of S1, S2 and S3 were frequently found to pass under the long dorsal ligament through flat tunnels in 10 cadavers (Willard et al., 1998).

The sacrotuberous ligament (Figure 1) is attached to the posterior iliac spines, to the lower transverse tubercles of the sacrum and to the lateral margin of the lower part of the sacrum and the upper part of the coccyx by three main bands; the lateral, medial and superior. The lateral band connects the ischial tuberosity to the posterior inferior iliac spine crossing the pyriformis muscle, from which it recieves some fibres. The medial band attaches to S3, S4, S5 and lateral margin of the sacrum and coccyx, the fibres spiralling whilst running inferomedially. The superior band connects the coccyx to the posterior superior iliac spine (Warwick & Williams, 1973; Lee, 1999, Ch 4). The gluteus medius attaches to the sacrutuberous ligament, and some fibres of the biceps femoris can bridge the ischial tuberosity to attach directly to the ligament as well (Vleeming, 1995).

The sacrospinous ligament (Figure 1) is a thin and triangular structure, attaching medially to the lower lateral aspect of the sacrum and coocyx and also to the spine of the ischium, blending with the capsule of the sacroiliac joint (Willard, 1997) and with the coccygeus muscle (Warwick and Wiliams, 1973).

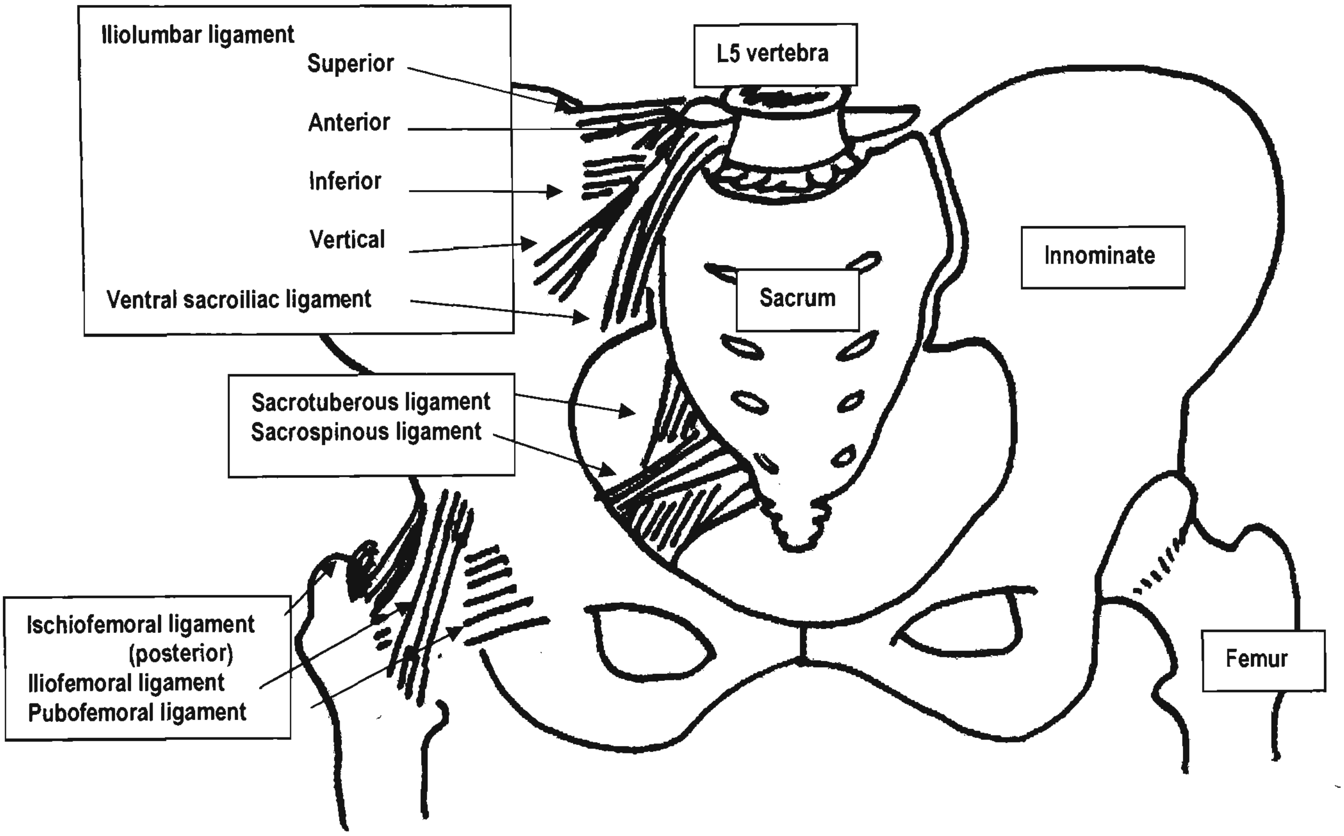


Figure 1

Anterior view of pelvis

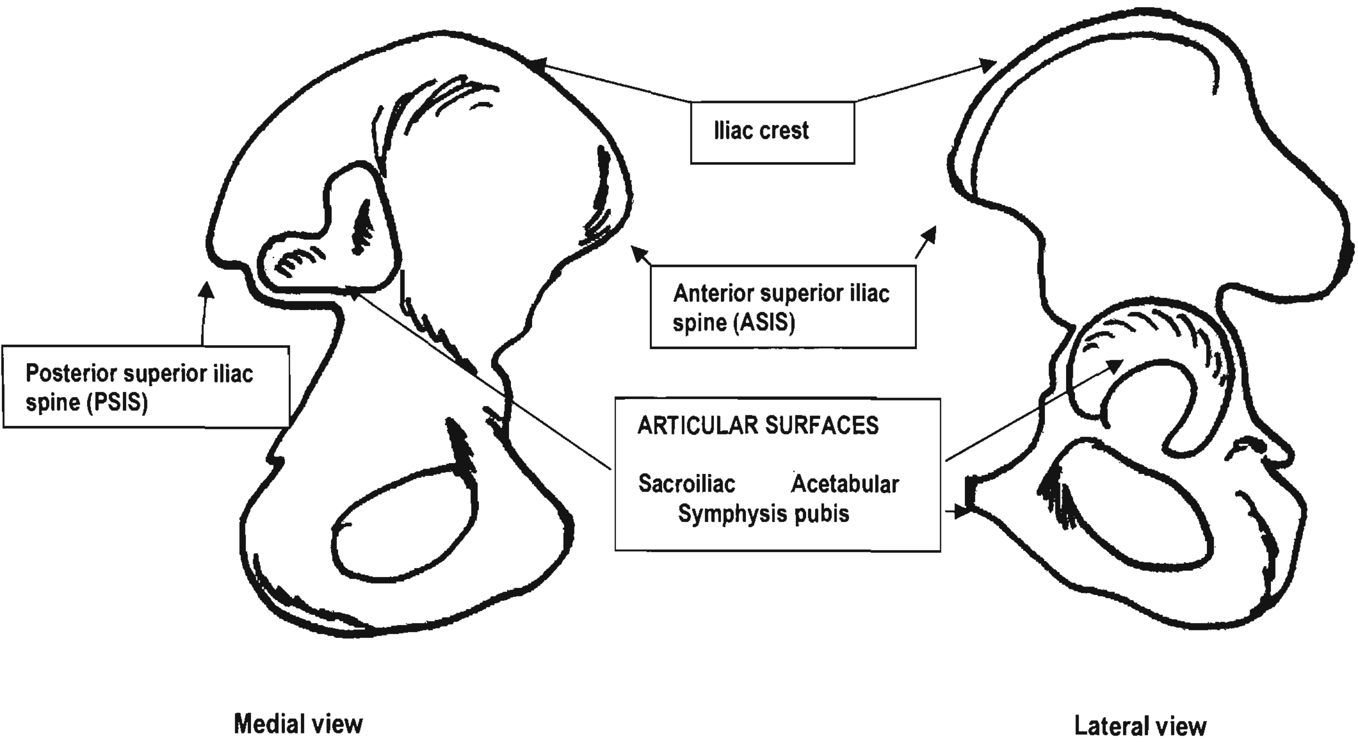
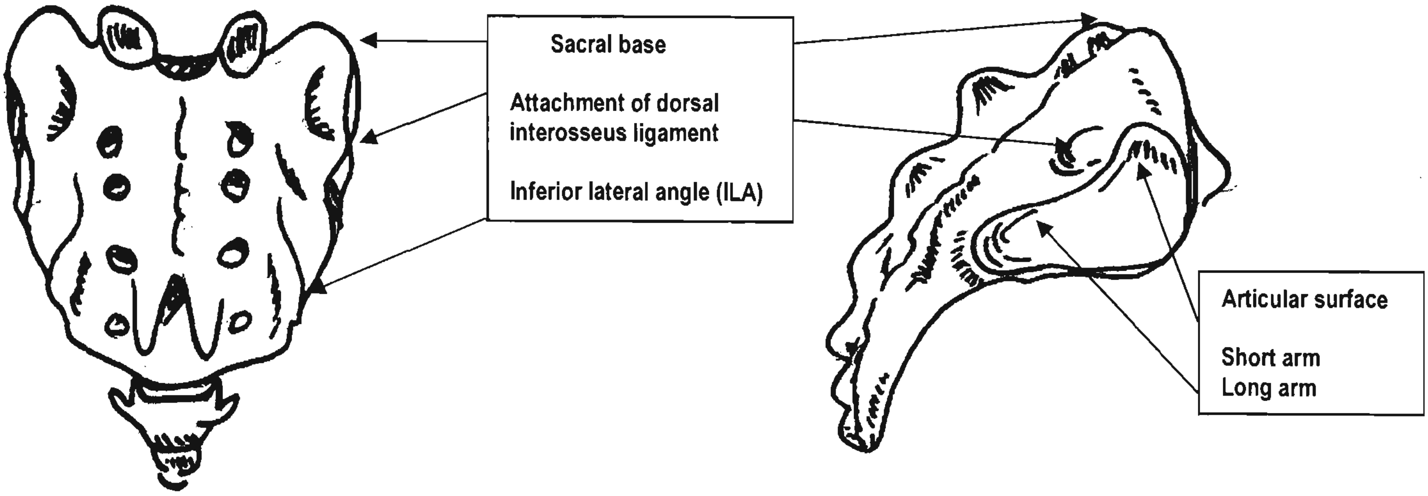


Figure 2

Left innominate



Posterior view

Lateral view

Figure 3

Sacrum

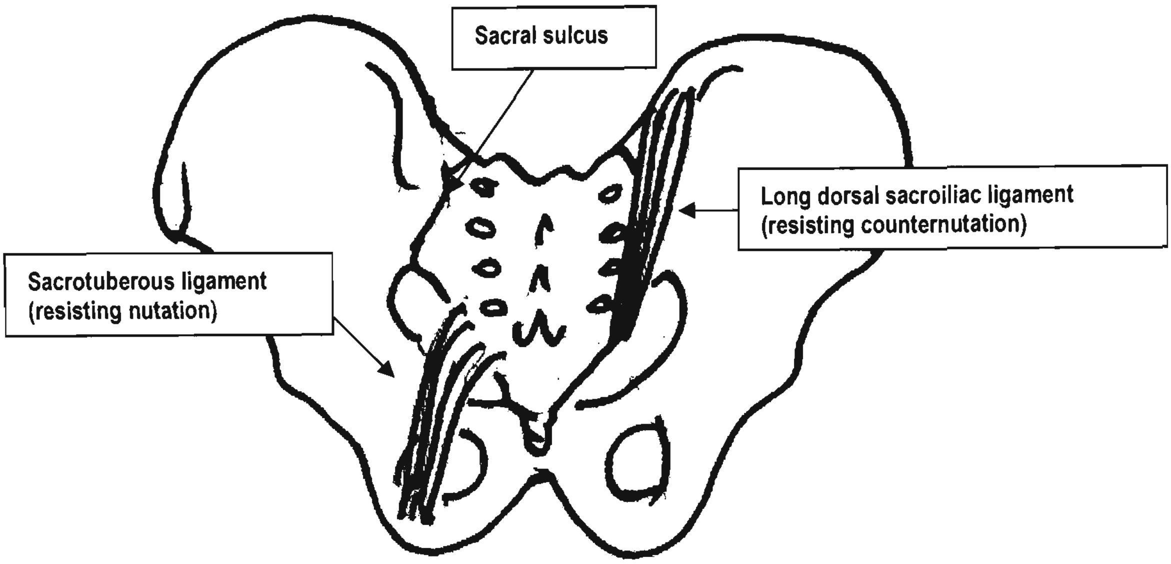


**Figure 4**

Posterior pelvic ligaments

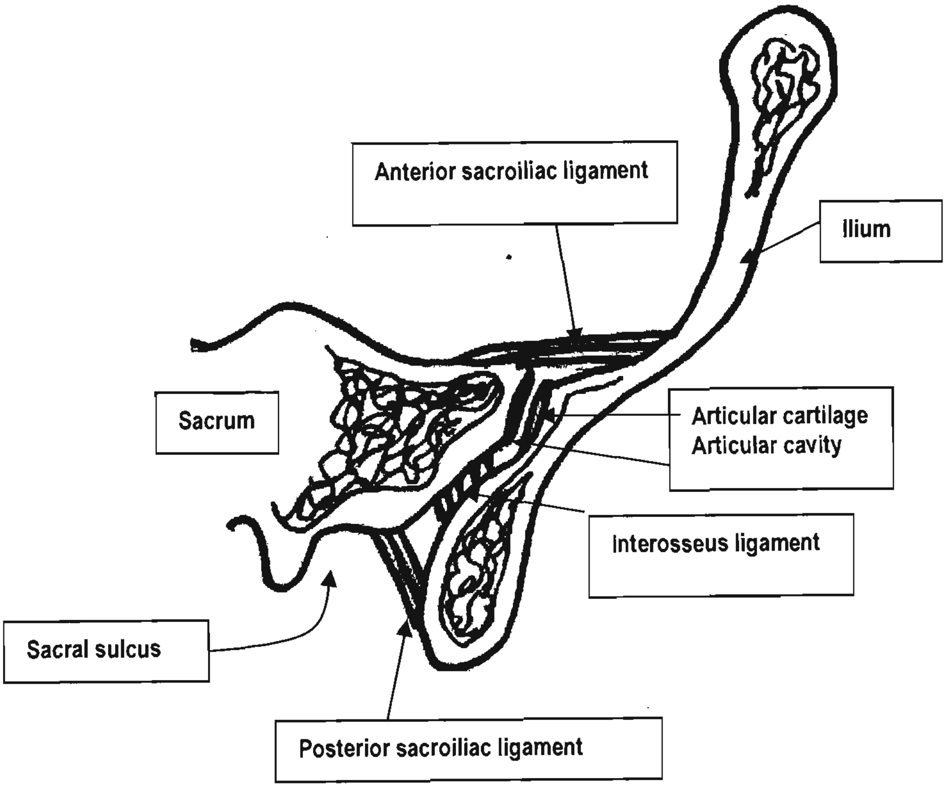


**Figure 5**

**Sacroiliac joint transverse section**

### 2.1.4 Myology

There are 35 muscles which attach to the sacrum and/or the innominate, producing motion and assisting the ligamentous structures in stabilising function of the trunk and extremities. These are (Lee, 1999, Ch 4; Bogduk, 1997):

1 Quadratus lumborum, with attachment to the anterior and superior iliolumbar ligament.

2 Rectus abdominis, attaching to the pubic symphysis and contributing to its stability (Warwick and Williams, 1973).

3 Pyramidalis, also attaching to the pubic symphysis.

4 External oblique,

5 Internal oblique, and

6 Transversus abdominis, all attaching to the superior anterior pelvic surface and thoracodorsal fascia.

7 Levator ani,

8 Sphincter urethrae,

9 Transverse perineal and ischiocavernosus, and

10 Coccygeus, making up the pelvic floor with portions attaching to the coccyx and pubis.

11 Latissimus Dorsi, which attaches directly to the iliac crest, and indirectly to the sacrum through the thoracodorsal fascia.

12 Multifidus, with attachments to the mamillary processes and the spinous processes of the lumbar and sacral spine, and to the iliac crest and posterior superior iliac spine (PSIS) of the ilium.

13 Erector Spinae (lumbar and thoracic longissimi, lumbar and thoracic iliocostalis) attaching to the PSIS, iliac crest and/or sacrum.

14 Quadratus femoris,

15 Superior gemellus,

16 Inferior gemellus,

17 Obturator internus and

18 Obturator externus, all hip rotators with attachments to the pelvis.

19 Tensor fascia lata and the iliotibial band as part of the fascia of the thigh, has strong attachment to the lateral innominate.

20 Gluteus medius, and

21 Gluteus minimus have attachments on the lateral surface of the ilium and abduct the hip joint.

22 Semimembranosus,

23 Semitendinosus, and

24 Biceps femoris, all attach commonly to the ischial tuberosity.

25 Adductor brevis,

26 Adductor longus,

27 Adductor magnus,

28 Pectineus, and

29 Gracilis all adduct the hip and attach along the pubic rami.

30 Rectus femoris, and

31 Sartorius, attach on the anterior superior iliac spines and act as hip flexors.

32 Psoas minor is absent in 40% of the population and attaches onto the iliopectineal eminence.

The following muscles are highly relevant to the discussion of sacroiliac joint function:

33 Iliacus attaches to the iliac fossa and the ventral sacroiliac ligament, and combined with the major hip flexor, psoas major, becomes the iliopsoas.

35 Gluteus maximus attaches in part on the sacrum, dorsal sacroiliac ligaments and the sacrotuberous liagament, acting mainly as a hip extensor.

36 Piriformis which attaches directly to the anterolateral sacrum, the joint capsule and often the sacrotuberous ligament and acts as an external hip rotator.

These muscles that blend with the ligaments and joint capsule of the sacroliliac joint contribute to its strength and stability (Walker, 1992), and are highly likely to be involved in any dysfunction of the joint (Lee, 1999, Ch 4).

### *2.1.5 Development and Ageing*

The sacroiliac joints begin to develop embryologically at 10-12 weeks gestation (Cole et al., 1996), and for the first decade after birth the surfaces remains flat (Bowen & Cassidy, 1981). During the second and third decades there is a difficulty to obtain fresh cadavers, and based on the few studied it appears that a convex ridge develops on the ilium apposed to a sacral groove. The superficial cartilage demonstrates fibrillation, and there appears some crevices and erosions by the end of the third decade (Bowen & Cassidy, 1981; Lee, 1999, Ch 3; Vleeming et al., 1990a).

The changes noted during the period between 31 and 50 years of age are increased fibrillation and ridging on the iliac side with erosions progressing to subchondral sclerosis. Marginal lipping is demonstrated by the end of the 5th decade in some specimens. Males appear to develop these changes earlier and they appear degenerative to some authors (Bowen & Cassidy, 1981; Walker, 1992), whilst others see the changes as an asymptomatic adaptive response designed to increase friction and result in greater stability (Vleeming et al., 1990b).

The years between 51 and 70 show an increase in irregularity with deeper erosions and some bridging osteophytes on the anterior and inferior margins, as well as fibrous tissue between the joint surfaces (Bowen & Cassidy, 1981). Ankylosis has been reported in males over 50 years of age (Cole et al., 1996), and found in up to 60% of cadavers (Alderink, 1991). There is evidence demonstrating joint motion despite erosions and plaque formation and marked reduction of joint space up into the eighth decade (Bowen & Cassidy, 1981; Lee, 1999, Ch 3).

### *2.1.6 Related regions*

#### *2.1.6.1 Lumbosacral spine*

The structure of L5 is different to the normal lumbar vertebrae in that it is more wedge shaped. The superior discal surface is 5 % greater and the inferior discal surface smaller than at the other lumbar levels (Norkin & Levangie, 1992). The inferior zygapophyseal joints are adapted for articulating with the sacrum by being widely spaced, and are normally oriented in the coronal plane. Facet asymmetry, when one is oriented in the sagittal plane, is reported as one of the most common radiological abnormalities in the low back (Ravin, 1997).

#### *2.1.6.2 Symphysis pubis*

The pubic symphysis is lined by a thin layer of hyaline cartilage, and contains a fibrocartilagenous disc. This often contains a cavity, more developed in the female and not seen before ten years of age. It has no lining of synovial membrane. The ligamentous support of the articulation comes from the superior, anterior and posterior pubic and the inferior arcuate ligaments. Anteriorly, the structure is also supported by a lacework of fibres from the external oblique aponeurosis and the medial tendons of origin of the recti abdominis (Warwick and Williams, 1973; Lee, 1999, Ch 4).

#### *2.1.6.3 Coxofemoral joint*

The coxofemoral or hip joint, is the articulation between the head of the femur and the acetabular socket of the innominate, which is made up of portions of the ischium, ilium and pubic bones. It is a diathrodial ball and socket joint, lined with hyaline cartilage. The acetabulum has an articular lunate portion projecting in an anterolateral and inferior direction, and is surrounded by the fossa which is filled with loose areolar tissue and covered with synovium. The acetabulum is deepened by a fibrocartilagenous labrum, which has a deficiency in its inferior portion bridged by the transverse acetabular ligament. The capsule attaches to the base of the labrum and extends over the whole neck to attach on the trochanteric line of the femur. The iliofemoral, pubofemoral and ischiofemoral ligaments blend with the capsule providing strong support. This is further strengthened by the intra-articular ligamentum teres which attaches the femoral head to either end of the lunate surface of the acetabulum, and also the tendon of the psoas major passing closely over the anterior part of the joint and seperated from the joint by a bursa (Warwick and Williams, 1973; Lee, 1999, Ch 4).

## 2.2 Neurology

The sacroliac joint has a nerve supply, though the specific contribution of various nerves has been described as variable (Bernard, 1997). Posteriorly, the joint is supplied by the posterior primary rami of L4 to S3, anteriorly by the anterior primary rami of L2 to S2 (Solonen, 1957). Solonen studied 18 joints from 9 cadavers in his landmark study, and proposed that the anterior aspect was supplied by the ventral rami which was present in all specimens from at least one level (L5) and with the superior gluteal nerve in a majority from levels L4 and S1; Kissling and Jacob (1997) could not confirm any anterior supply in 7 cadavers. The dorsal nerve trunks pass between the layers of the sacrotuberous ligament and pierce the origin of the gluteus maximus muscle to reach the skin as the nervi clunium medii (Kissling & Jacob, 1997). There are numerous thick myelinated axons in the nerve branches to the joint indicating special encapsulated mechanoreceptors and nociceptors Kissling & Jacob, 1997). The mechanoreceptors supply information on position, motion and stability, whilst the nociceptors respond to mechanical deformation and/or chemical irritation with the sensation of pain (Rowinski, 1997). The nerve supply to the muscles that may influence pelvic motion are listed in table 1.

| MUSCLE | PERIPHERAL NERVE | ROOTS |
|---|---|---|
| Abdominals | Ventral rami | T12, L1 |
| Pyramidalis | Subcostal nerve | T12 |
| Gluteus medius | Superior gluteal | L5, S1 |
| Gluteus minimus | Superior gluteal | L5, S1 |
| Gluteus maximus | Inferior gluteal | L5, S1, S2 |
| Piriformis | Ventral rami | L5, S1, S2 |
| Superior gemellus | Nerve to obturator internus | L5, S1 |
| Inferior gemellus | Nerve to quadratus femoris | L5, S1 |
| Obturator externus | Obturator | L5, S1 |
| Obturator internus | Nerve to obturator internus | L5, S1 |
| Quadratus femoris | Nerve to quadratus femoris | L5, S1 |
| Semimembranosus | Tibial | L5, S1, S2 |
| Semitendinosus | Tibial | L5, S1, S2 |
| Biceps femoris | Tibial, common peroneal | L5, S1, S2 |
| Adductor brevis | Obturator | L2, L3, L4 |
| Adductor longus | Obturator | L2, L3, L4 |
| Adductor magnus | Obturator, tibial | L2, L3, L4 |
| Pectineus | Femoral, accessory obturator | L2, L3 |
| Gracilus | Obturator | L2, L3 |
| Rectus femoris | Femoral | L2, L3, L4 |
| Sartorius | Femoral | L2, L3 |
| Tensor fascia lata | Superior gluteal | L4, L5 |
| Erector spinae | Lateral and intermediate branches of the segmental dorsal rami | |
| Quadratus lumborum | Ventral rami | T12-L3(4) |
| Iliacus | Femoral | L2, L3, L4 |
| Psoas minor | Ventral rami | L1 |
| Levator ani | Inferior rectal, pudendal | S4 |
| Sphincter urethra | Perineal branch pudendal | S2, S3, S4 |
| Coccygeus | Ventral rami | S4, S5 |
| Multifidus | Medial branch of segmental dorsal ramus | |
| Psoas major | Ventral rami | L1, L2, L3 |

**Table 1**

**The peripheral nerves and their spinal root derivatives which innervate the muscles of the pelvic girdle (Lee, 1999 Ch 4)**

## 2.3 *Biomechanics*

The biomechanics of the sacroiliac joints cannot be complete without consideration of the synergistic functions of the pelvis of which they are a part (Greenman, 1989, Mitchell et al., 1979). It has been stated that the motion of the SIJ is affected by motions in the lumbar spine, hip joint and the symphysis pubis (Bernard & Cassidy, 1991). In order to underpin later clinical sections, some information will be presented regarding the whole pelvis.

### *2.3.1 Kinematics*

#### *2.3.1.1 Sacroiliac joint*

Kinematics is the study of motion of rigid bodies without consideration of the forces involved (Warwick & Williams, 1973). Sacroiliac joint motion has been studied empirically and analytically in cadavers and living subjects dating back to the late nineteenth century, and has only recently been widely accepted to exist (Alderink, 1991; Egund et al., 1978, Kissling & Jacob, 1997; Miller et al., 1987; Pitkin & Pheasant, 1936; Simkins, 1950; Smidt, 1997; Strachan et al., 1938; Sturesson et al., 1989; Weisl, 1955). There is less agreement over the nature and extent of that movement.

The topography of the joint was measured in order to establish the possible axes of motion, with a conclusion that translation must occur for any sagittal innominate rotation to be possible because of the irregular surfaces and taut ligament structure, and that the axis for this rotation was variable (Weisl, 1954; Wilder et al., 1980). 4.8-6.2 degrees of antagonistic motion between the ilia was found using an inclinometer in vivo, when subjects stood with one foot on a 1.5 inch block, and then flat on the floor (Pitkin & Pheasant, 1936). A ventral translation of the sacral promontory of 2-3mm was found in cadavers, which approximated the iliac crests and separated the ischial tuberosities (Weisl, 1954). Weisl (1955) also found motion in normal subjects of ages 17-28 by comparative radiology, with the maximum quantity (5.6 ± 1.4mm) occurring in ventral movement of the sacral base when changing posture from supine to standing erect. He placed the axis of this rotation at 10cm inferior to and in front of the sacral promontory.

Video based motion analysis systems have been used to analyse pelvic motion in vivo, finding means of 4.1 degrees in sagittal plane motion, 7 degrees in coronal and 10.1 in the transverse plane during walking with an error reported at 8%; these figures correlated negatively with age (Thurston & Harris, 1983).

Miller et al (1987) measured a mean 2.74 mm anterior translation and 6.21 degrees of torsion (axial rotation) in 8 fresh cadavers using mechanical loading devices. In another cadaveric study, a load of 1000 N produced 1.8 mm of translatory motion in an anterior direction and 1.5 mm in the superior and inferior directions, whilst 50 N.m of torque load to the sacrum produced 1.6 degrees of axial rotation, 1 degree of flexion or extension and 1.1 degrees of lateral bending (Zheng et al, 1995).

SIJ motion has also been examined by stereoradiography, also termed roentgen stereophotogrammetry, where two x-ray tubes project beams to plates orthogonal to one another in order to locate a point, and its movement, in three dimensional space. When markers are placed on the skin (Grieve, 1981) the results may be affected by skin movement over the bony placement (Drerup & Hierholzer, 1987; Pearcy & Tibrewal, 1984). Frigerio et al (1974) used stereoradiography on both a cadaver and a single in vivo specimen, and using mathematical methods calculated changes in pelvic landmarks when the legs were parallel compared to when one leg was in a position of flexion and abduction. The findings ranged from 0.3-15 mm of movement between the bony landmarks of the pelvis for the cadaver and up to 40 mm in vivo. These measurements are larger than others in the literature; the movements are not clearly defined, and with the relatively vague landmarks (eg "superior aspect iliac crest") and the limited subject number the results are questionable. Lavignolle (1983) used a stereoradiographical procedure to examine SIJ motion in five non-weight bearing young people, and reported 12 degrees of posterior innominate rotation with 6mm of anterior translation, and 2 degrees of anterior rotation with 8 mm anterior translation; this coupled motion was thought to demonstrate an unlocking mechanism of the joint. The authors calculated that the instantaneous centres of rotation of the iliac bones lay adjacent to the pubic symphysis on variable oblique axes, although they also stated that the small population studied would decrease the statistical significance of this finding.

Measurement is made more accurate when radiopaque balls are embedded into bony landmarks and measured by radiographs (Egund et al., 1978; Reynolds, 1980; Sturesson et al., 1989). Using these techniques, the sacrum of a non-embalmed cadaver had 2.33 degrees of flexion (Reynolds, 1980). Egund et al (1978) quantified 2 mm of undefined translation and 2 degrees of rotation around a transverse axis located adjacent to S2 in 4 symptomatic patients who moved from supine to standing, with maximal rotation around this axis occurring with manual pressure on the sacral apex; there was no change in distance between the posterior iliac spines. Sturesson et al (1989) found that 25 symptomatic subjects diagnosed with sacroiliac joint dysfunction had innominate rotation of 2.5 ± 0.5 degrees (range 1.6-3.9 degrees) around an undefined transverse axis when standing from being supine, with a maximal total translation along the three axes of 0.7 mm (0.1-1.6 mm); the symptomatic subjects' motions were no different to controls.

Measurement by analysing the movement of Kirschner wires attached to the PSIS's was used to reveal a unspecified translation of up to 10 mm when subjects performed forward flexion from the erect position (Colachis et al., 1963). Jacob & Kissling (1995) also used percutaneous Kirschner wires attached rigidly to the bones of 21 normal and one symptomatic subject. Using inclinometry they found that following changes of position from erect to lumbar spine anteflexion and retroflexion, the rotation movement around a anteroposterior axis was the greatest at 1 degree. The one symptomatic subject had high levels of motion, up to 8 degrees, and women tended to have greater rotation than men. However, the Kirschner wire method has been criticised, as the base of the pins may move under the influence of the subcutaneous, muscular and ligamentous tissues overlaying the bone (Sturesson, 1997).

The Metrocom Skeletal Analysis System, a computerised goniometer, has been used to examine inter-innominate motion during extreme static positions, revealing 20-36 degrees of oblique sagittal plane motion, presumed to divide equally between the two sacroiliac joints which would allow this motion (Smidt, 1997). However, this system had nil to weak agreement with results from radiographic examination of the lumbar curve and sacral base angle in 17 asymptomatic subjects (Walsh & Breen, 1995).

Vleeming et al (1992) demonstrated that there was a total of 4 degrees of sagittal plane rotation of the sacroiliac joints using digital displacement meters, and applying a cranial and ventral force through the acetabula to test nutation, plus a caudal and dorsal force to test contranutation. This motion was found in cadavers of age 73-83, and except for one joint that was significantly immobile and demonstrated arthrosis radiographically, these findings appear to suggest that this motion is present throughout life. The authors also found asymmetry of motion within and between specimens.

Most authors agree that the primary motion of the sacrum, variously described as nutation (or anterior rotation or flexion) and counternutation (or posterior rotation or extension), occurs around a transverse axis. This is hypothesised to pass through the sacroiliac joint in the region of S2 (Figures 6 and 7) (DeRosa & Porterfield, 1997; Greenman, 1989; Kapandji, 1974; Mitchell et al., 1979; Simkins, 1950). Various clinical theories have been proposed regarding the details of these motions. Lee (1999, Ch 5) stated that nutation seems to occur bilaterally when moving from supine to standing, and unilaterally with flexion of the hip joint. Counternutation occurs bilaterally whilst lying supine and sometimes near the end of trunk flexion, and unilaterally during hip extension. The coronal axis is believed to be anchored by the interosseus ligament. These motions are hypothetically coupled with accessory or secondary motions – nutation with inferoposterior glide, and counternutation with anterosuperior glide (Figure 7) (Greenman, 1989; Lee, 1999, Ch 5; Mitchell et al., 1979).

It has been suggested that the innominate rotates anteriorly with extension of the hip, and posteriorly during hip flexion around a transverse axis (DonTigny, 1990; Greenman, 1989; Greenman, 1990; Grieve, 1981). Lee (1999, Ch 5) placed this transverse axis through the same S2 location as sacral motion. Others put the axis adjacent to the symphysis pubis (Greenman, 1990; Lavignolle et al., 1983; Pitkin & Pheasant, 1936. Lee (1999, Ch 5) stated that this is the same as the arthrokinematic motion of the nutation of the sacrum, in that the innominate is proposed to glide inferiorly down the short arm and posteriorly down the long arm of the joint during anterior rotation, with the opposite occurring in posterior rotation as in sacral nutation. All of these are speculative theories, and have not been experimentally proven. Wilder et al (1980), using anatomical contour mapping and statistical geometry, concluded that the separation and translation of the sacroiliac joint required for rotation to occur in the innominate bone would not exist owing to the ligamentous structure, although their studies were done on cadaveric material.

Grieve (1981) criticised the use of cadavers in motion studies, and used skin markers on the posterior superior iliac spines, the sacrum, the hip, and L4 and L5 bony landmarks whilst 21 subjects performed knee raising motions. The motions were found to be similar side to side, and a positive relationship was reported between mobility of the SIJ and symptoms. In vivo, the sacrum was found to move between 4-12 degrees around an assumed transverse axis on erect normal subjects in “complete” trunk flexion and extension, based on plain radiographs and measurements on vertical and horizontal coordinates (Simkins, 1950).

The combination of movements of rotation and translation leads to the concept of the helical or screw axis, which is a line in space around which a rigid body rotates and translates (Alderink, 1991). Reynolds (1980) used this method to characterise the motion of the sacrum with different hip positions, and found the axes changed and were not oriented to the conventional cardinal planes. This was also noted by Lavignolle et al (1982), who located the instantaneous axis of rotation in cadavers and living athletes near to the pubic symphysis.

Osteopathic authors (Greenman, 1989; Mitchell et al., 1979) have suggested the existence of multiple axes, based on clinical observation. Four transverse horizontal axes are utilised for various combinations of sacral nutation and counternutation, anterior and posterior innominate rotation, pubic symphysis motion and motion of the sacrum resulting from respiration. The first axis is proposed to be passing through the upper pole of the SIJ, the second through the lower pole, a third through S2 and a fourth one through the pubic symphysis – see Figure 6. The motions are divided into iliosacral and sacroiliac, depending on where the loading originates – spinal for sacroiliac motion and lower extremities for iliosacral motion. Mitchell et al (1979) also proposed oblique sacroiliac axes generated by the unilateral pull of the piriformis muscle creating a pivot point on the lower pole of the SIJ. The authors stated that this would rotate the sacrum around a vertical axis, and cause a degree of sidebending or inferior translation contralaterally. This "torsional" movement of the sacrum has not been experimentally demonstrated to occur in isolation, but sidebending and axial rotation has been demonstrated using roentgenography and an inclinometer as correlated to, or following, ilium motion (Pitkin & Pheasant, 1936).

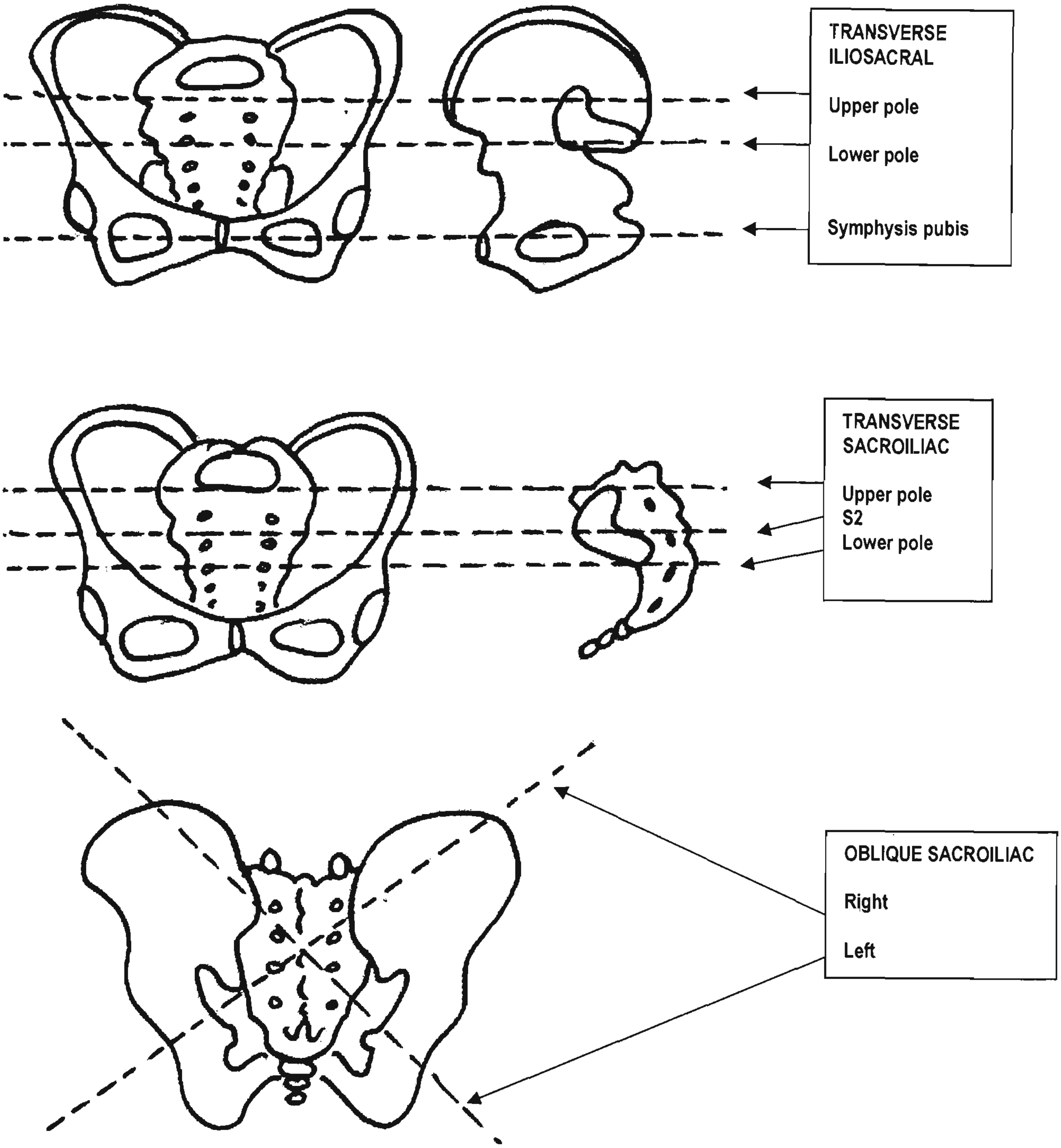
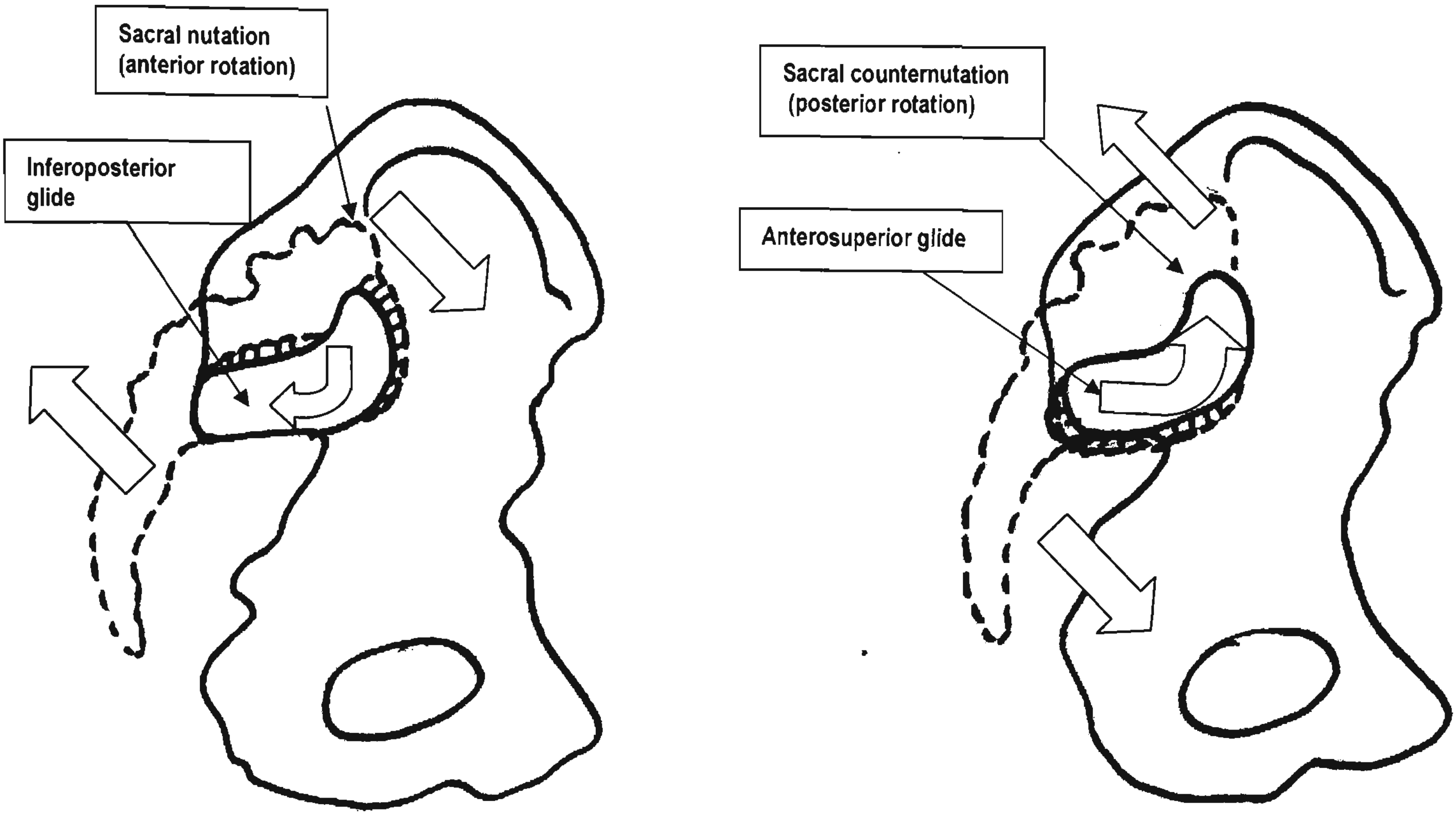


**Figure 6**

**Proposed sacroiliac joint rotation axes**

(adapted from Mitchell et al, 1979)



Anterior rotation

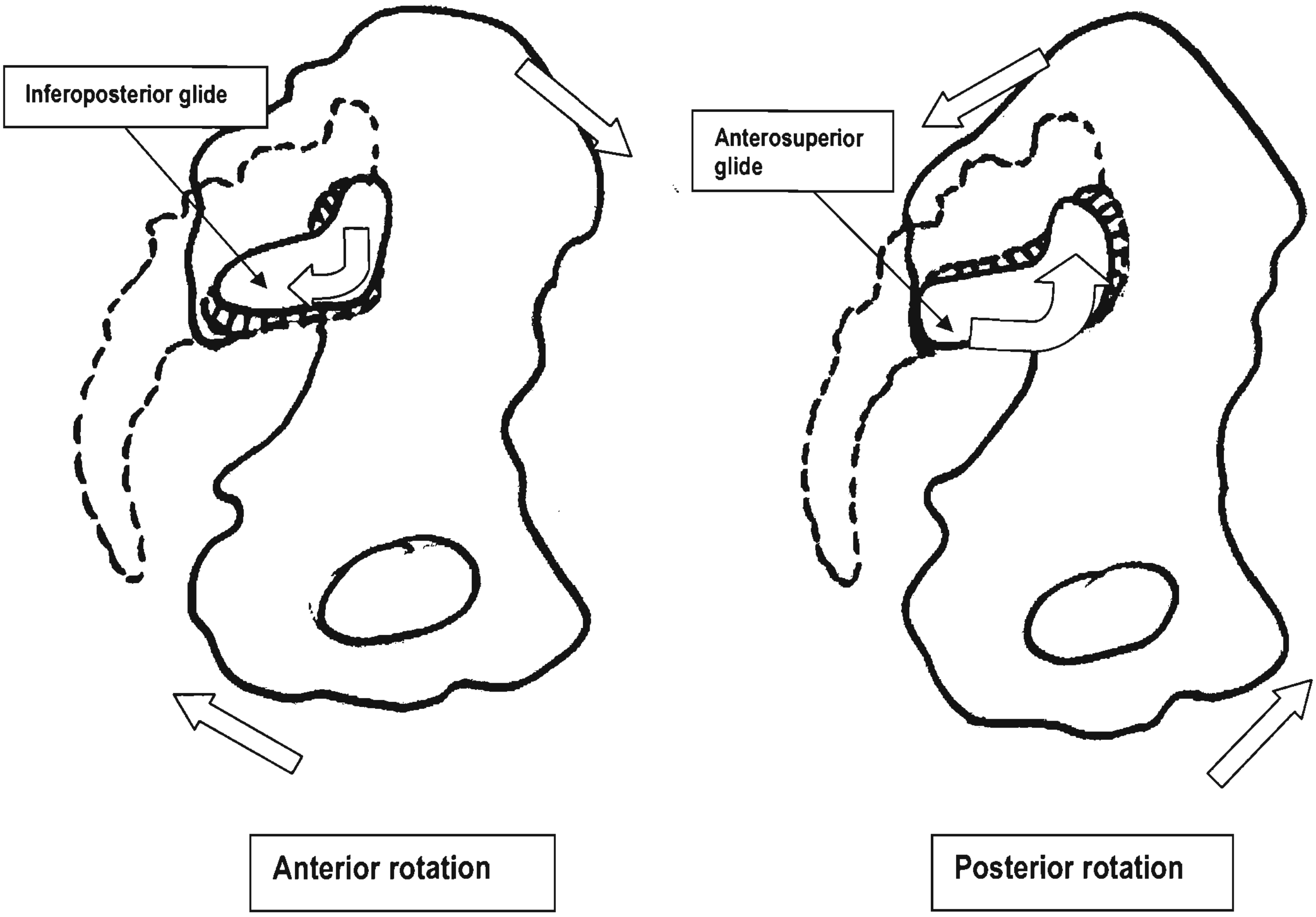
Posterior rotation

**Figure 7**

Sacral sagittal rotations

The glides of the sacroiliac articulation in response to sacral rotations

(Adapted from Lee, 1999, Ch 5)



Anterior rotation

Posterior rotation

Figure 8

Innominate sagittal rotations

The glides of the sacroiliac articulation in response to innominate rotations

(adapted from Lee, 1999, Ch 5)

### 2.3.1.2 Lumbo-sacral spine

The arthrokinematics of the lumbo-sacral junction has a direct influence on sacral motion, and therefore a brief discussion in this context is warranted. The lumbosacral junction at L5/S1 has sagittal plane motion of flexion and extension around a dynamic transverse axis coupled with anterior and posterior translation similar to the rest of the lumbar spine, although this segment behaves differently with the coupling of rotations around the AP (sidebending) and vertical axes (rotation). When the fifth lumbar vertebra is rotated, coupled sidebending has been found to occur to the same side, in contrast to the levels of L1-4 which occur to opposite sides, and L4/5 which is variable and termed transitional. The axis is vertical during early rotation, but shifts to pivot around the impacted zygapophyseal joint that has reached is motion limit. Added to the fact that these patterns are complex, they also change with age and degeneration; therefore the potential for altered biomechanics is large (Bogduk, 1997; Fryette, 1954; Gracovetsky & Farfan, 1986; Lee, 1999, Ch 5).

### 2.3.1.3 Symphysis pubis

The study of sacroiliac joint motion involves whole pelvic motion and therefore the third articulation in the chain, the symphysis pubis (Reynolds, 1980). These joints are linked in a closed kinematic chain, and any motion occurring at one will affect the other. The pubic symphysis has a small oblique inferior/superior translatory motion measuring 1 mm in the male, 1.3 mm in the female, and up to 3.1 mm in a multiparous woman (Walheim et al., 1984). There is also evidence of an alternating anterior and posterior rotation during gait (LaBan et al., 1978) and during hip flexion and abduction (Frigerio et al., 1974). This articulation has been reported to be the centre of rotations of the innominate bones (Pitkin & Pheasant, 1936; Greenman, 1990). It has been stated that the symphysis must be deformable to allow for small SIJ movement (Snijders et al., 1997). The articulation becomes hypermobile during pregnancy (Norkin & Levangie, 1992; Greenman, 1990).

#### *2.3.1.4 Coxofemoral joint*

The hip joint has 3 degrees of rotational osteokinematic freedom around three axes: flexion/extension in the sagittal plane, abduction/adduction in the frontal plane and medial/lateral rotation in the transverse plane (Norkin & Levangie, 1992). Another 3 translatory degrees may be described for the arthrokinematic translatory or gliding motion; medial and lateral, anterior and posterior and superior (compression) and inferior (distraction) (Lee, 1999, Ch 5). The range of motion for flexion is 90 degrees with the knee extended and 120-135 degrees with the knee flexed. For extension the range of motion is 10-30 degrees, for abduction 30-50 degrees and for adduction 10-30 degrees. When the hip is at 90 degrees of flexion, medial rotation has 30-45 degrees of motion and lateral rotation has 45-60 degrees (Norkin & Levangie, 1992). In normal gait on level ground, the hip is required to move to 30 degrees of flexion, 10 degrees of extension, 5 degrees of abduction and adduction and also 5 degrees of both medial and lateral rotation (Inman et al, 1981). Pure spin occurs in neutral positioning, though when the femur is in other positions gliding occurs. In weight bearing, the femur becomes relatively fixed, and the pelvis moves on the femur. The habitual pattern in normal gait is impure swings of combination movements; with flexion, abduction and medial rotation occurring together and extension, adduction and lateral rotation occurring together (Norkin & Levangie, 1992). More details of specific gait stages are described in Section 4.

### *2.3.1.5 Lumbopelvic rhythm*

The relationship between the lumbar spine, hip and pelvis in trunk flexion is referred to as lumbopelvic rhythm. In the first stages the hip extensors contract and lock the pelvis bilaterally whilst the lumbar lordosis flattens. The pelvis begins to rotate anteriorly around the hips after 60 degrees of flexion, and most authors believe the sacrum follows the lumbar spine. Some authors state that the innominates flare outward (external rotation) during trunk flexion, approximating the PSISs (Lee, 1999, Ch 5; Vleeming et al., 1997). Mitchell et al (1979) proposed, based on clinical observation, that at the extreme limit of trunk flexion a counternutation occurs, and a converse nutation at the end of upright extension. Lee (1999, Ch 5) stated that the counternutation is relative, and is actually a continuation of anterior innominate rotation around a transverse axis through the hip joints. These motions have not been demonstrated experimentally (Alderink, 1991; Mitchell et al., 1979).

In summary, the motion of the SIJ is relatively small, and can be described osteokinematically as sacral nutation and counternutation, and innominate anterior and posterior rotation. These are linked arthrokinematically, with unilateral sacral nutation apparently equivalent to posterior innominate rotation, and unilateral sacral counter nutation equivalent to anterior innominate rotation. Because these motions occur with concurrent translation or gliding, anteroposteriorly related to nutation and counternutation, and inferiorly related to side bending, they can be described as impure swings. The rotations take place around transverse and vertical dynamic screw axes, and are affected by lumbar spine, hip and pubic symphysis motion.

### 2.3.2 *Kinetics*

#### 2.3.2.1 *Sacroiliac joint*

The sacroiliac joint appears to function as a stabiliser of the pelvis, absorbing ground reaction forces during gait and shear forces during movement (Alderink, 1991; DeRosa & Porterfield, 1997; Greenman, 1990; Lee, 1999, Ch 5; Snijders et al., 1993; Wilder et al., 1980). It has also been described as a multidirectional force transducer, because of the sensitivity of the mechanoreceptors present (Snijders et al., 1993). De Rosa and Porterfield (1997) described the main influences as the force of gravity acting downwards through the spine creating the flexion moment of the sacrum on the ilium, and the ground reaction force traversing upwards through the lower extremity from heel strike creating a posterior rotational (termed "torsional") moment of the ilium on the sacrum; they termed these motions sacroiliac and iliosacral respectively, agreeing with the osteopathic authors mentioned above (Greenman, 1989; Mitchell et al., 1979).

A full discussion of SIJ and pelvic function in gait will be found in Section 4.

In the first two decades of life, before ossification and wedging is complete, the sacroiliac joints are planar and vulnerable to shear forces (Lee, 1999, Ch 2). In the adult, the sacrum is wedge shaped both superoinferiorly and anteroposteriorly, factors which enable it to provide resistance to vertical and horizontal translation (Fortin, 1993; Lee, 1995). The cadaveric SIJ resists loads from 500 – 1440 N and from 42-160 Nm without failure (Miller et al, 1987). Unilateral loading of one ilia with the other fixed, resulted in an average three to five times more motion in 8 adult cadaveric SIJs, and this was considered to replicate one-legged stance in vivo. In the same study, Miller and colleagues also tested the stiffness of the SIJ compared to the lumbar spine motion segments in eight adult cadavers, and found that the SIJ had 5% of lumbar stiffness with inferior (axial compression) force, 624% of medial (lateral shear) force, 64% of axial rotation and 700% of lateral flexion (sidebending) forces.

The ridged and depressed surfaces create high friction coefficients (Vleeming et al.,1990b), and it is speculated that the variability in these irregularities between and within people would result in highly individual responses to shear forces in terms of stability and vulnerability (Hoek van Dijke et al, 1999). The iliac cartilage is coarse, and this increases through ageing (Bowen & Cassidy, 1981). Vertical weight bearing causes the sacrum to nutate, essentially locking the pelvis (Kapandji, 1974; Warwick and Williams, 1973). These articular characteristics contribute to the self locking mechanism of the pelvis, and have been termed "form closure" (Figure 9)(Snijders et al., 1993; Vleeming et al., 1990a; Vleeming et al., 1990b).
Stability by self bracing is also supplied by myofascial and ligamentous elements, called "force closure" (Figure 9) (Snijders et al., 1993; Vleeming et al., 1990a; Vleeming et al., 1990b). Nutation is resisted by the integrity of the interosseus and sacrotuberous ligaments (Vleeming et al., 1990a; Vleeming et al., 1990b), which are supported by the pelvic floor muscles, particularly coccygeus (Snijders et al., 1993; Lee, 1999, Ch 5), and biceps femoris through its role in tensing the sacrotuberous ligament (Van Wingerden et al., 1992). Sacral counter nutation is limited by tension in the long dorsal sacroiliac ligament (Vleeming et al., 1996). The tension generated in the ligament complex seems to create compression of the joint surfaces, further stabilising the articulation by force closure (Vleeming et al., 1997). The pelvic structure has been compared to a Roman arch, where the ends are secured by the sacrotuberous and sacrospinous ligaments as well as the pyriformis and coccygeus

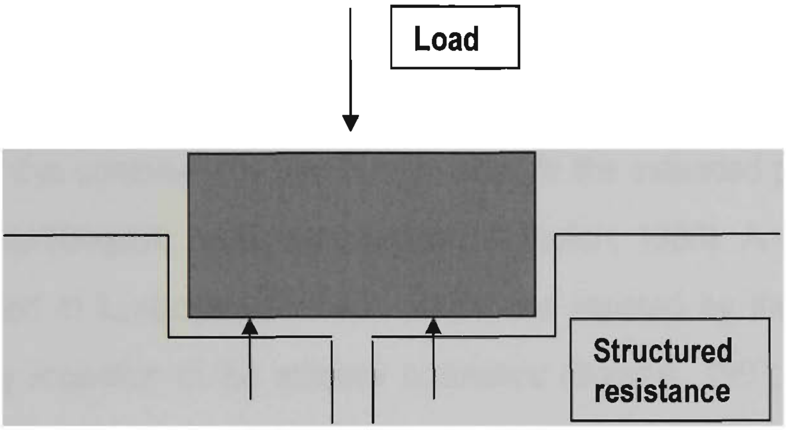
muscles, all contributing to force closure by compressing the joint surfaces (Snijders et al., 1997). Muscles considered to stabilise the articulation have been divided theoretically into the inner unit and outer unit (Lee, 1999, Ch 5). The inner unit consists of the levator ani and pelvic floor muscles, the transversus abdominis, the multifidis and the diaphragm. Transversus abdominus contraction has been found to generate tension in the thoracodorsal fascia which may create tension in the dorsal sacroiliac ligaments, and early activation of this muscle is lost in chronic low back pain (Hodges & Richardson, 1996). The diaphragm and pelvic floor muscles are linked together synergistically with the transversus abdominus in the control of intra-abdominal pressure (Hodges & Richardson, 1996; Lee, 1997). Multifidis contraction causes sacral nutation, which tenses the interosseus, sacrotuberous and sacrospinous ligaments (Vleeming et al., 1997).

The outer unit consists of the latissimus dorsi, gluteus maximus and the thoracodorsal fascia making up the posterior oblique system; the erector spinae, the deep lamina of the thoracodorsal fascia, the sacrotuberous ligament and the biceps femoris making up the deep longitudinal system; the oblique abdominals, the contralateral adductors of the thigh and the anterior abdominal fascia making up the anterior oblique system; and finally the gluteus medius and minimus and the contalateral thigh adductors making up the lateral system. The relationship between these muscle systems has been found during anatomical studies, where tension is applied through fibres of a particular tissue and displacement noted in related tissues (Vleeming et al., 1997).

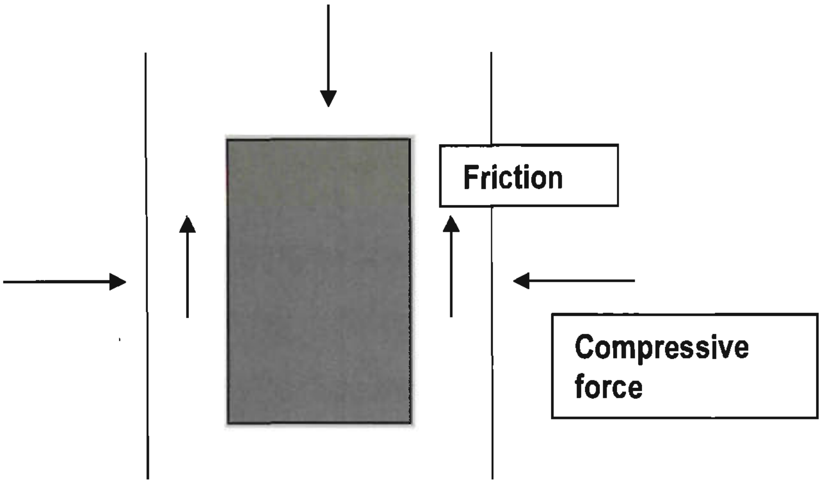
When the latissimus dorsi contracts with the contralateral gluteus maximus, compression of the SIJ results. This function of the posterior oblique system is reported as important in rotational activities like walking and running (Gracovetsky, 1997; Greenman, 1997; Lee, 1999; Mooney et al., 1997; Vleeming et al., 1997). The deep lamina of the thoracodorsal fascia is tensed by the gluteus maximus and latissimus dorsi, thereby compressing the SIJ. The sacrotuberous ligament and biceps femoris tendon exert tension on one another to resist sacral nutation (Vleeming et al., 1997). Despite the gluteus medius and minimus muscles not being involved in direct force closure of the SIJ, their role in stabilising the pelvis is important in walking and erect postures, and they are reported to be reflexely inhibited when the SIJ is unstable (Lee, 1999, Ch 5).

The model proposed by Vleeming, Snijders et al (1997) (see Figure 9) demonstrated that the sacroiliac joints are stabilised by a combination of form and force closure methods. The failure of any of the components of these methods through ligament laxity or muscle weakness is considered to result in instability and decompensation of movement patterns in the lower back, hip and knee (Vleeming et al., 1997; Lee, 1999, Ch 5).

This is supported by Panjabi (1992), who stated that stability in the spine is an interplay between three subsystems - passive bony elements, active muscle elements and the neural control system; any change in one subsystem will increase the need for enhanced neural activity in compensation.



A. Form closure



B. Force closure

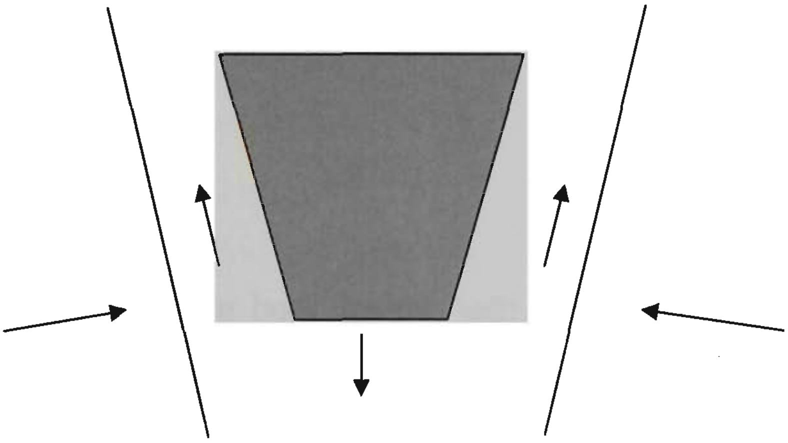


**Figure 9** Combining form and force closure (Adapted from Vleeming et al., 1997)

### 2.3.2.2 *Lumbosacral spine*

The lumbosacral spine absorbs compressive loads through both the vertebral body/intervertebral disc complex and, particularly when in the extended position, the zygapophyseal joints (Bogduk, 1997; Gracovetsky & Farfan, 1986). Anterior shear forces are generated in lumbosacral flexion, which are resisted by the iliolumbar ligaments and bony impaction of the articular processes (Bogduk, 1997; Lee, 1999, Ch 5). The myofascial structures of the thoracodorsal fascia, operating with contraction of the multifidus and transversus abdominus, assist in maintaining dynamic stability (Hodges & Richardson, 1996).

### 2.3.2.3 *Symphysis pubis*

The symphysis pubis absorbs shearing forces during gait (see Section 4) (Norkin & Levangie, 1992), and although some authors state that this function is of minor importance (Hoek van Dijke et al. 1999; Snijders et al., 1997), experienced clinicians believe the presence of a dysfunctional motion in this articulation is an important factor in chronic pain syndromes of the lower back (DonTigny, 1990; Greenman, 1989; Mitchell et al., 1979; Reynolds, 1980).

### 2.3.2.4 *Coxofemoral joint*

The hip joint helps distribute body weight, with a complex system of trabeculae mostly passing through the acetabula, demonstrating the continuity of weight bearing function between the pelvis and femur. The labrum deepens the articular cavity and therefore provides stability. The extra-articular ligaments are all taut in hip extension, the position of most stability. In bilateral stance, there is a gravitational extension moment, and each hip takes 33% of the total superincumbent body weight. In one legged stance, the single hip must take 83% of the body weight, complicated by an adduction torque which results in a large demand on the ipsilateral abductor muscles to maintain erect posture (Norkin & Levangie, 1992).

## *3 Sacroiliac Joint Dysfunction*

A key element of this study was the clinical entity known as Sacroiliac Joint Dysfunction. The aetiology and diagnosis of this condition is not clear across all disciplines, nor has the condition been validated by experimental research. It remains a controversial observation by clinicians that guides treatment, and so it is essential to clarify the diagnosis and terminology utilised in the literature.

### *3.1 Definitions and Aetiology*

The controversy in the literature regarding the diagnosis of sacroliac joint dysfunction (SIJD) is, at least in part, a result of researchers using different definitions for the label. The definitions hinge on whether the joint is tender to the patient, whether it is positive to pain provocation tests, and whether it is relatively hyper- or hypo- mobile. Researchers attempting to validate the diagnosis of SIJD by intra-articular injected pain provocation (Dreyfuss et al., 1996; Fortin, 1993; Fortin et al., 1994; Fortin et al., 1997; Schwarzer et al., 1995) tend to define SIJD by whether the joint is producing pain or not. Researchers assessing the reliability of manual tests for pain provocation (Avillar et al., 1997; Dreyfuss et al., 1996; Laslett & Williams, 1994; Laslett, 1997; Potter & Rothstein, 1985) have used the painful response as a diagnostic feature of SIJD, at least in part. Other researchers focus on mobility tests, generally utilising hypomobility as an essential diagnostic criteria (Bachrach, 1997; Boline et al., 1988; Carmichael, 1987; Cibulka et al., 1988; DonTigny, 1997; Dreyfuss et al., 1994; Gajdosik et al., 1985; Herzog et al., 1989; Hesch, 1997; Macintyre & Lloyd-Smith, 1993; Osterbauer et al., 1993; Paydar et al., 1994; Pope et al., 1979; Potter & Rothstein, 1985; Van Deursen et al., 1990; Wiles, 1980; Wilson, 1989).

The probability of disagreement and conflict arises when multiple definitions and diagnostic criteria are in use. In general, medical and physical therapy researchers have searched for the structure(s) generating the pain, and analysed whether manual tests are able to reliably localise that structure (Schwarzer et al., 1995; Laslett & Williams, 1994); whereas chiropractic researchers define SIJD as joint "fixation" (Herzog et al, 1987, p 296) and osteopaths use the term "somatic dysfunction" of the SIJ – combining altered motion tests with asymmetrical structural landmarks and tenderness and altered tone of associated soft tissues (Beal, 1982, p 1027; Kuchera, 1997, p478).

Various definitions for SIJD have thus emerged, including:

- a painful sacroiliac joint with no "demonstrable lesion, but .... some type of biomechanical disorder" (Dreyfuss et al, 1996, p2594);
- reduced movement and "malalignment between the left and right innominate bones" (Cibulka et al, 1988, p1359)
- "a state of relative hypomobility within a portion of the joint's range of motion with subsequent altered structural (positional) relationships between the sacrum and ilium" (Dreyfuss et al, 1994, p1138);
- "impaired SIJ mobility" (Carmichael, 1987, p164);

- "synonymous with SIJ mechanical pain and SIJ syndrome" (Cole and Dreyfuss, 1996, p128);
- "mechanical dysfunction, also known as osteopathic lesion, hypomobility, malalignment, fixation, malrotation, joint binding or subluxation" (Dreyfuss et al, 1994, p1138);
- "SI blockage" (Van Deursen et al, 1990, p96); and
- "upslip, downslip, anterior or posterior fixed innominate" (Walker, 1992, p906).

Using a more interdisciplinary approach, Lee (1999, Ch 5) has defined this entity as mechanical dysfunction of the SIJ, with subdivisions of hypomobile with or without pain, hypermobile with or without pain, and normal mobility with pain. This includes all definitions, and enables the testing procedures to be specific for the stated dysfunction. That author and others (Dreyfuss et al., 1994) make the point that abnormal function of a joint may be painless, whilst a mechanically normal joint might have a painful sensation.

The causes of SIJD have been described in the literature as being either primary or secondary (Beal, 1982; Gitelman, 1979). Primary causes are direct injuries such as falling, strains, childbirth and disease; secondary causes are maladaptions of the pelvis to extrinsic phenomena like dysfunctional gait and/or posture, repetitive occupational activities, short lower extremity, injuries to lower extremity or spine, abnormal spine curvature, diseases of the musculoskeletal system, and viscerosomatic reflexes from organ disease (Heinking et al., 1997; Kuchera, 1997; Lee, 1999). Also reported is trauma from awkward lifting (Avillar et al., 1997), rear end motor vehicle accidents (with ipsilateral foot on the brake) and repetitive lumbar spine rotation in sport and performance (Bernard & Cassidy, 1991; Fortin, 1993).

Women are predisposed to SIJD during pregnancy and menstruation because of hormonal changes (Alderink, 1991; Gitelman, 1979).

### *3.2 Prevalence*

The sacroiliac joint is a significant source of low back and pelvic pain. It was reported to be the primary source of pain in 22.5% of 1,293 low back pain patients, as well as the primary source of presenting pain in 30% of patients with L5/S1 spondylolisthesis. This was on the basis of case history, clinical testing and exclusion (Bernard & Kirkaldy-Willis, 1987). Bernard & Cassidy (1991) analysed another 250 patients with clinically diagnosed SIJD, and found 38 had concurrent posterior facet pain, 31 had lateral recess spinal stenosis, 15 had herniated nucleus pulposus, 20 had lumbar disc syndrome and 5 had arachnoiditis. These investigators place SIJD as the most common of the pathological conditions of the SIJ, followed by trauma, infection, inflammation, degeneration and tumors.

Greenman (1992), in a longitudinal study of 183 back pain patients who were not responding to treatment, found a high incidence of SIJD and pubic dysfunction using osteopathic clinical tests and radiographs; 96.2% had innominate rotations of which 55.2% were anterior rotations, 52.5% had sacral torsions and 75.4% had pubic symphysis dysfunction.

Of 1000 consecutive patients presenting to a back care centre with low back pain, 98% were reported to have mechanical dysfunction of the SIJ, the commonest finding being anterior rotation of the innominate. Treatment of these dysfunctions led to relief of symptoms in “almost all” cases, and 2 patients required lumbar disc surgery (Shaw, 1992). This high figure was reported in a conference proceedings without further detail, and must be considered critically with reference to other reports of incidence.

Injection of the SIJ with contrast and local anaesthetic has been used as a reliable method of diagnosis by pain provocation and/or treatment by local anaesthetic blockade. In one study, a reported 25-30% of patients had symptomatic SIJs related to their concurrent pathologies, and 5-10% had primary SIJ pain (April, 1992). In another injection study of 100 low back pain patients, 13-30% were diagnosed as having the SIJ as the primary source of pain, depending on the criteria employed. This incidence was described as a minimum, as the study only took subjects with pain below L5/S1, which excludes some possible subjects who might have atypical pain from the SIJ. This study noted that 18 symptomatic patients had ventral capsular tears in the SIJ, 9 of whom gained relief from injection of local anaesthetic. These authors warned that simple provocation of pain by injection may have a negative predictive value, and should not be a diagnostic criterion in SIJD (Schwarzer et al., 1995).

Laslett (1997) reported on a study of 202 chronic low back pain patients (mean duration of symptoms 85.3 weeks), and found 60% had at least one SIJ pain provocation test positive. The author warned that these tests stress other structures apart from the SIJ, and when applying lumbar spine and hip joint exclusion tests, 17.3% of the subjects had at least one test positive.

SIJD appears to be a significant primary cause of low back pain, as well as being a concurrent feature of other low back pathologies. Mechanical and somatic dysfunctions of the SIJ seem to be present in the clinical picture of low back pain.

### *3.3 Role in lower back and pelvic pain*

Attempts to clarify the specific role that the SIJ plays in low back pain have proven to be both difficult and controversial, possibly because of the difficulty examining the joint owing to its anatomical location (Cole et al., 1996). Also, the SIJ region is a common site for pain referral from other structures, including the posterior facet joints, lumbar discs and nerve roots (Bernard & Cassidy, 1991).

Up until Mixter and Barr's seminal paper of 1934, the SIJ was considered to be the most important factor in low back pain. The reporting by these authors of the herniated nucleus pulposus of the intervertebral disc caused interest in the role of the SIJ in low back pain to decrease (Cole et al., 1996). There is a paucity of literature concerning the role of the SIJ in pain, though clinical theories have been proposed.

Because of the wide ennervation of the SIJ and the asymmetry of its distribution, the pain of SIJD can be widely referred and in varied patterns. The capsule and ligaments both can be a source of pain, as well as the various muscles listed in Section 2.1.4, owing to the arthrokinetic reflex from articular mechanoreceptors which control regional muscle tone (Cole et al., 1996; Fortin et al., 1994; Hershey, 1943).

The pain of patients with SIJD can be sharp, aching or dull. It can refer to the buttocks, groin, posterior thigh and knee (Bernard & Cassidy, 1991), and be pseudo-radicular and mimic sciatica (Cole et al., 1996). Pain was found to refer to below the knee into the foot during one provocation by injection study, although the researchers found that groin pain was the only reliable discriminating symptom for

SIJD (Schwarzer et al., 1995). The most common referral zone in another injection study was found to be a 3 X 10 cm area inferior and lateral to the ipsilateral PSIS (Fortin et al., 1994, Fortin et al., 1997).

As mentioned, instability of the lumbo-pelvic-hip complex may be a result of failure of the form or force closure mechanisms of the SIJ (Vleeming et al., 1997). Hypermobility from ligament laxity associated with muscular weakness is proposed to affect stability in this biomechanical model, and pain may be generated by the postural myofascial reactions to this instability (Beal, 1982; DonTigny, 1997; Hesch, 1997; Irvin, 1997). Lee (1999) put forward the view that when there is stiffness in a joint, stress during movement is transferred to normal joints above and below, which may become symptomatic.

This idea is central to the discussion of the role of SIJD in painful conditions, particularly of the lower back and pelvis, and especially if the SIJ in question does not test painful or is not the primary source of pain; further exploration of the literature that supports this follows.

DonTigny (1990) claimed that SIJD is the primary cause of idiopathic low back pain syndrome, calling it a non ligamentous reversible painful lesion resulting from joint dysfunction that is a subtle variation from normal. He has proposed that the fixated anterior innominate is the main variant of SIJD, and stated that it results from anterior gravity strains. This theory also attempts to explain the effect that SIJD has on the lumbar spine and intervertebral discs, in that forces from heel strike during gait are normally dissipated by the SIJ, but when dysfunctional may allow translational forces into the lumbar spine articulations and discs and exacerbate spondylolisthesis or cause an unstable lumbar segment.

This type of theory has been discussed in a physical therapy text by White and Sahrmann (1994), who named their approach the "movement system balance" (MSB) theory. This was described as an ideal mode of movement system function, where any deviation from that ideal is less efficient and more stressful to the components of that system. The authors claim that many painful syndromes are a result of cumulative repetitive micro trauma, and this occurs when an articulation's instantaneous axis of rotation (IAR) is altered, even within normal ranges, and stress and adaptation occur. Any change to the articular surface or the surrounding muscle lengths and neural control can alter the IAR, and assessment is based on observing, palpating and moving the patient to discover these patterns of motion dysfunction. The authors particularly state that therapists should mobilise asymptomatic hypomobile joints that are contributing to symptomatic hypermobile structures. This is similar to the idea termed the "Motion Cascade" (Cole et al., 1996), in which it was proposed that each component of a functional chain depends on every other component. The pelvis was considered to contribute greatly to remote parts of the kinetic chain, and the term lumbo-pelvic-hip complex dysfunction was thought to reflect the high mechanical interdependency of this region.

The principle of treating dysfunctions of a functioning whole, in order to optimise biomechanical efficiency for the treatment and prevention of a wide range of conditions, is exemplified in the writings of osteopathic authors like Greenman (1990), Kuchera and Kuchera (1994), Bachrach (1997) and Irvin (1997).

The broad variability of symptoms, some of which mimic other low back and pelvic pathologies, creates difficulty in the specific diagnosis of SIJD. The overlap of pain sensitive structures in the region results in the possibility of co-existing conditions in low back pain syndromes. Diagnostic procedures that have high specificity and sensitivity become desirable to the clinician in order to plan appropriate treatment.

## 3.4 Diagnosis

There are a number of different diagnostic models in use, and many tests have been proposed to lead to a diagnosis of SIJD. Following is a summary of the literature on these issues, with particular focus on the tests that have been used.

### 3.4.1 Theoretical models

The method of diagnosis of SIJD depends on what definition is in use. Combining all of the diagnostic models appearing in the literature, a classification list is necessary. The following list includes all the various models of diagnosis:

A SIJ as primary source of pain, resulting from (Bernard & Cassidy, 1991):
    A1 SIJ syndrome
    A2 Trauma
    A3 Infection
    A4 Inflammation
    A5 Metabolic disease
    A6 Tumor
    A7 Iatrogenic causes
    A8 Referred

B SIJ Hypomobility (Fixation, Subluxation, Block) (Lee, 1999, Ch 6):
    B1 With pain

B2 Without pain

C SIJ Hypermobility (Lee, 1999, Ch 6):

- C1 With pain
- C2 Without pain (Jacob & Kissling, 1995)

D SIJ Somatic Dysfunction (Greenman, 1989):

- D1 Anteriorly rotated innominate
- D2 Posteriorly rotated innominate
- D3 Superior (upslipped) innominate
- D4 Inferior (downslipped) innominate
- D5 Inflared (internally rotated) innominate
- D6 Outflared (externally rotated) innominate
- D7 a Flexed sacrum (unilateral)
  - b Flexed sacrum (bilateral)
- D8 a Extended sacrum (unilateral)
  - b Extended sacrum (bilateral)
- D9 a Forward sacral torsion (left on left)
  - b Forward sacral torsion (right on right)
- D10 a Backward sacral torsion (left on right)
  - b Backward sacral torsion (right on left)

Somatic Dysfunction is defined as impaired or altered function of related components of the somatic system: skeletal, arthrodial, and myofascial structures; and related vascular lymphatic and neural elements. It is diagnosed by the presence of three criteria - asymmetry of paired bony landmarks, range of motion alteration (hypo- or hyper- mobility), and tissue texture abnormalities (Beal, 1982; Kuchera, 1997).

There is overlap in these diagnostic models, in that A1 (SIJ syndrome) may include B1 and C1 (painful hypo- and hyper-mobilities). Also D (somatic dysfunction) may be the same as B2 and C2 (painless alterations in range of motion).
The diagnostic category A1 is the painful SIJ demonstrated by joint blockade and/or pain provocation tests that has been proven negative for, or excluded from, the categories A2 to A8.

In the categories A2 to A8, the conditions are defined by causative factors and uncovered by single investigations or combinations of them; for example, serological testing for Erythrocyte Sedimentation Rate and Rheumatoid Factor, combined with plain radiographs and nucleotide bone scans in the category A4 (inflammation). This procedure of differential diagnosis in category A is well established in the medical community (Cole et al., 1996; Shwarzer et al., 1995).

Categories B, C and D are diagnosed by patient history and clinical examination. To diagnose B1 (hypomobility with pain), a combination of static landmark asymmetries, restricted motion and positive pain provocation tests would be necessary (Fortin, 1993). Diagnosis B2 (hypomobile without pain) requires the same criteria to be met as B1, but without positive pain provocation tests (Lee, 1999, Ch 6). C1 (hypermobile with pain) and C2 (hypermobile without pain) are diagnosed by manual tests that stress the SIJ and demonstrate increased motion, and for diagnosis C1 would be painful from this provocation.

Some authors believe that the B diagnosis of subluxation, fixation or hypomobility can be a consequence of what is primarily a C diagnosis of a hypermobile joint (Grieve, 1981; Hesch, 1997; Lee, 1999, Ch 6; Macintyre &Lloyd-Smith, 1993). The theory is supported by the amount of joint surface separation found to be necessary in order to produce significant joint motion (Bernard & Cassidy, 1991; Wilder et al., 1980). This category C (hypermobile) could then have a more severe or "totally blocked" form of B1 (hypomobile with pain) on motion testing and positional asymmetries (Grieve, 1981; Lee, 1999, Ch 6).

The issue of whether the SIJ must test positive for pain on provocation in category D (somatic dysfunction) is unclear; though some authors have added tenderness on palpation, not specifically from provocation testing, as a fourth criteria for somatic dysfunction (Greenman, 1989; Kuchera & Kuchera, 1994).

The fixations and positional asymmetries of the B, C and D categories have not been demonstrated by plain radiography (Bernard & Cassidy, 1991; Cole et al., 1996). Sacral base unlevelling is implicated in SIJD (Irvin, 1997; Kuchera, 1997), and as a reflection of short lower extremity is reliably demonstrated using plain erect radiographs (Ravin, 1997). Dorman (1997) and Ravin (1997) have both used the term "asymlocation" as a structural definition of asymmetry of the skeleton, and demonstrated that the rotated position of the sacrum is readily visible on CT and MRI scans. However, there is neither analysis of this diagnostic approach in the literature, nor tests of its sensitivity and specificity for SIJD. Unless the diagnosis of SIJD includes an inflammatory process in the joint, then uptake studies will not demonstrate the dysfunction (Cole et al., 1996).

In the osteopathic literature, these theoretical diagnostic labels are a combination of descriptors that come from historical developments and from clinical findings emerging in the 1960s from the development of the muscle energy technique theories of Fred Mitchell Sr (Mitchell, 1967; Mitchell et al., 1979). These diagnoses define the altered mobility component of somatic dysfunction (previously called "osteopathic lesion") as being at extreme ends of the normal range of the joint. The older labeling models (Strachan et al., 1938) used positional descriptors of the sacrum in relation to the ilium or the ilium to sacrum. These historical diagnoses were often "anterior" or "posterior" sacrums or iliums, which defined both the positional relationship as well as the specific motion limitation, which on testing was restricted to return to the opposite direction; for example the sacrum is restricted to move anteriorly in the case of the posterior sacrum. The observation of sacral rotation and sidebending coupling in normal cadaver function (Strachan et al., 1938) and normal gait in vivo (Mitchell, 1967) led to the oblique axis theory, as mentioned in Section 2.3.1, and these diagnoses continue to be applied (Greenman, 1989; Heinking et al., 1997). The hypothesis of an oblique axis is not totally accepted within the osteopathic profession (Beal, 1982), nor has it been experimentally proven.

Diagnosis D1, the right anteriorly rotated innominate and D9b, the left on left anterior sacral torsion, are both considered to be the most common of SIJD (somatic dysfunctions) (Greenman, 1989; Kuchera, 1997; Macintyre & Lloyd-Smith, 1993; Mitchell, 1967; Mitchell et al., 1979), based on clinical observation. The patterns of SIJ mobility dominance to one side has been discussed by Pitkin and Pheasant in 1936, where they noticed eye and hand side dominance tended to be associated with decreased iliac inclination (anterior rotation) ipsilaterally. These authors also noticed that the innominate rotated anteriorly when the leg was experimentally shortened (by a lift under the opposite leg). A "biomechanical musculoskeletal stress pattern" was identified in 1964 by Dunnington. The proposed pattern is a result of normal mechanical stresses, and includes a right anteriorly rotated innominate and metatarsal dysfunctions that would affect gait; the author suggested that pain might develop in any of the stressed areas of the body from this whole body pattern.

The anterior innominate dysfunction is considered to be the most common and important SIJD by DonTigny (1990), who described a gravitational aetiology for its prevalence, in that an increased lordosis of the lumbar spine shifts the line of gravity forward of the acetabula, causing a sagittal rotational moment in the innominate. The author believed this dysfunction affects gait by reducing the dynamic elasticity of the SIJ ligaments, and therefore results in shear forces to the lumbar intervertebral discs. Kuchera (1997) believed that both of these dysfunctions are part of the same compensatory pattern, which is due to gravitational strains in normal life. Bachrach (1997) has put forward the clinical theory that an anterior innominate dysfunction is often present in low back pain patients, as a secondary result of chronic asymmetric psoas major shortening.

The examination procedures to reveal these dysfunctions are a combination of static structural measurements by palpation and observation, both screening and joint specific mobility tests and palpatory findings of texture change and tenderness of related soft tissues (Beal, 1982; Greenman, 1989; Heinking et al., 1997; Kuchera, 1997; Lee, 1999, Ch 6).

Lumbosacral congenital abnormalities may play a role in the development of low back pain, and are well visualised by plain radiographs (Ravin, 1997). There is a widely accepted radiographic procedure for symphysis pubis hypermobility, used for many decades, based on Chamberlain's work in the 1930's (Greenman, 1992).
The validity of the SIJD diagnosis in each of the categories A1, B, C and D, is dependent on the consistency of the symptoms and signs. As discussed above, symptoms vary widely and overlap with other conditions, and controversy surrounds the validity and reliability of the physical examination signs.

### **3.4.2 *Manual tests*** (Greenman, 1989; Mitchell et al., 1979)

Table 2 summarises the commonly reported manual testing procedures for diagnosing SIJD. Following that, they are described in detail before continuing with a discussion of their validity and reliability.

| **Category code** | **Category name** | **Manual tests** |
|---|---|---|
| A1 | SIJ Syndrome | Spring tests<br>Thigh thrust test<br>Patrick's test |
| B1 | Hypomobility with pain | Static landmark asymmetries<br>Spring tests<br>Gillet test<br>Standing flexion test<br>Seated flexion test<br>Thigh thrust test<br>Patrick's test |
| B2 | Hypomobility without pain | Static landmark asymmetries<br>Spring tests<br>Stork test<br>Standing flexion test<br>Seated flexion test |
| C1 | Hypermobility with pain | Spring tests<br>Thigh thrust test<br>Patrick's test |
| C2 | Hypermobility without pain | Spring tests |
| D | Somatic Dysfunction (specific criteria for categories in this study are listed in section 6.4) | Static landmark asymmetries<br>Standing flexion test<br>Seated flexion test<br>Spring tests |

**Table 2**

**Manual tests utilised in the diagnosis of SIJD**

#### ***3.4.2.1 Standing Flexion test***

Subject stands with bare feet shoulder width apart (Figure 10), knees locked in extension. Examiner lightly contacts the inferior slope of the PSIS with their thumbs bilaterally, and asks the subject to bend forward slowly towards touching their toes without bending the knees. Examiner monitors the movement of the PSIS bilaterally and compares their relative palpatory and visual excursion. Normal movement is thought to be a small supero-posterior shift of the PSIS relative to the surrounding structures on trunk and hip flexion, occuring symmetrically. A positive test is when one PSIS moves more supero-anteriorly than the contralateral pair.

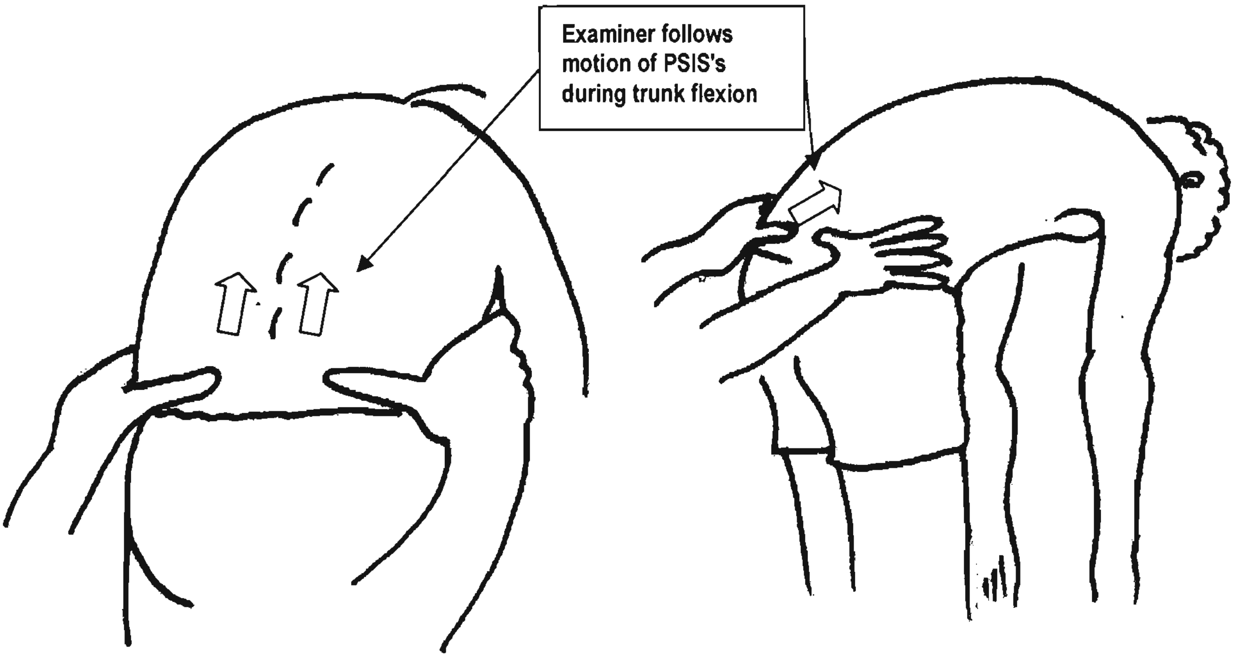
False positive tests may occur from:

- shortened hamstring musculature on the contralateral side, which may restrict the innominate range of motion, and hold the PSIS inferiorly;
- fused lumbar or sacral articulations on the positive side (Orrock, unpublished observation).

Subjects may be screened for these by (as done in the current study):

- assessing the passive range of hip flexion with the knee extended, and applying a passive hamstring muscle stretch to the subjects with significant restriction on the side contralateral to the side of the positive test; and
- springing the lumbar and sacral articulations.

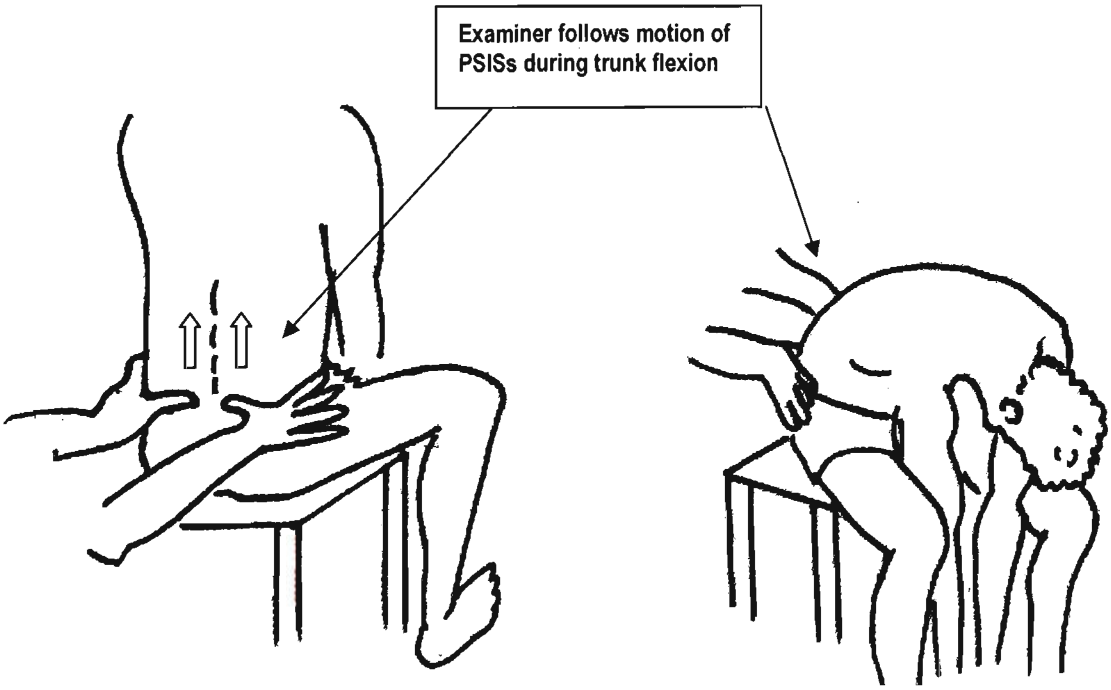
A false negative test may occur if both sides are equally positive, as the motion is relative to the contralateral side.



Examiner follows motion of PSIS's during trunk flexion

Figure 10

Standing flexion test



Examiner follows motion of PSISs during trunk flexion

Figure 11

Seated flexion test

#### *3.4.2.2 Seated Flexion test*

The subject is seated on a flat bench with both feet stable on the floor (Figure 11), and with the hips and knees at ninety degrees of flexion. The subject's hands are loose between the knees, which are shoulder width apart. The examiner gently places thumbs on the inferior slope of each PSIS, and asks the subject to bend forward in order to touch the floor with both their hands.

The examiner monotiors the motion of the PSIS and compares their relative visual and palpatory excurion. Normal movement is thought to be a small supero-posterior shift of the PSIS relative to the surrounding structures on trunk and hip flexion, occuring symmetrically. A positive test is when one PSIS moves more supero-anteriorly than the contralateral pair.

False positive tests may occur from:

- unilateral shortened paravertebral and/or quadratus lumborum musculature, which may pull the innominate superior during flexion, resulting in a superior PSIS
- fusion of the lumbar and/or sacral articulations (Orrock, unpublished observation).

Subjects may be screened for these by (as done in the current study):

- passive stretching of the musculature by trunk flexion and sidebending;
- passive springing test of the lumbar and sacral articulations to reveal severe motion restrictions.

There is a reported carry over effect in between the standing and seated flexion tests, where both may be positive. Greenman (1989) reported that the most positive test in terms of asymmetry should be considered as the primary positive test. Also, predominance for right sided positive seated flexion tests ($x^2 = 4.5$) was found in an asymptomatic group of subjects (Dreyfuss et al., 1994).

A false negative test may occur if both sides are equally positive, as the motion is relative to the contralateral side.

### *3.4.2.3 Iliac Spring test*

With the subject supine on a bench (Figure 12), the examiner gently puts low amplitude, low velocity posteriorly directed pressure through the palm of the hands into one and then the other ASIS on the subject. Relative unilateral resistance is considered a positive test.

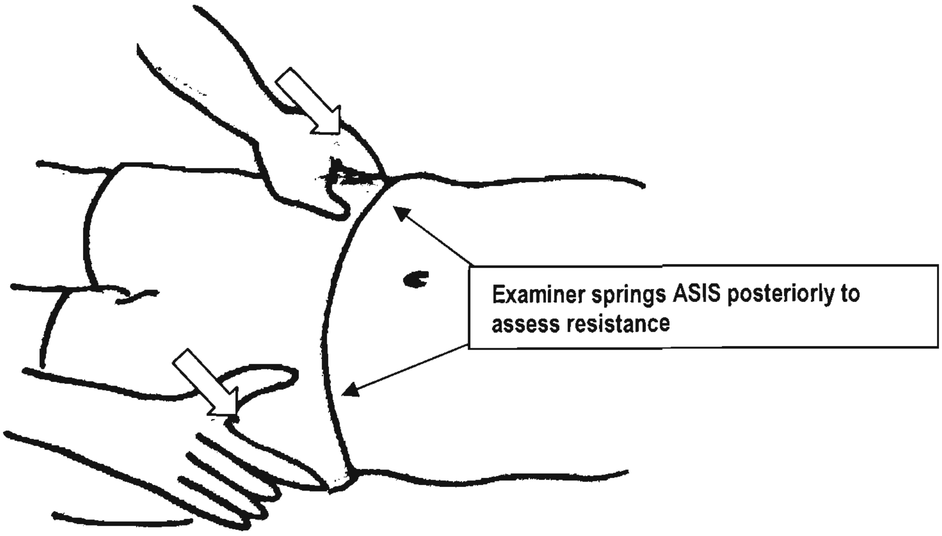
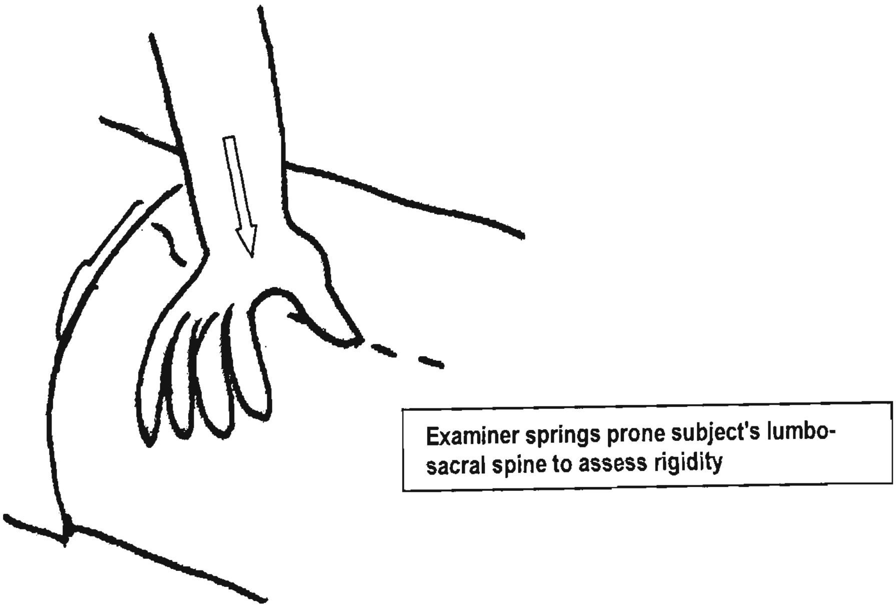


**Figure 12**

**Iliac spring test**

### *3.4.2.4 Lumbo-sacral Spring test*

With the subject prone on a bench (Figure 13), the examiner gently puts low amplitude, low velocity anteriorly directed pressure through their hand into the interspinous space of the L5/S1lumbar vertebra. Solid resistance is considered positive. The same pressure is applied to all the lumbar vertebrae and the PSIS bilaterally when screening for articular fusion.



Examiner springs prone subject's lumbo-sacral spine to assess rigidity

**Figure 13**

**Lumbo-sacral spring test**

### *3.4.2.5 Sacral Inferolateral Angle Spring test*

With the subject prone on a bench, the examiner gently puts low amplitude, low velocity anteriorly directed pressure through their hand onto the unilateral infero-lateral angle of the sacrum, similar to the lumbo-sacral spring test (Figure 13).

Relative resistance is considered positive. This procedure has developed from the researchers experience, and is a rational method to confirm the motion restriction proposed to exist from the sacral torsion dysfunction.

### *3.4.2.6 Gillet test*

With the patient standing (see Figure 14), one thumb palpates the ipsilateral PSIS whilst the other thumb palpates the sacral base parallel to it. The patient is instructed to flex the ipsilateral thigh towards their chest and ipsilateral displacement of the PSIS relative to the sarum is noted. A positive test is when the PSIS does not move relative to the sacrum. This is considered a test of SIJ mobility, although tests just one direction in the sagittal plane (posterior innominate rotation) (Lee, 1999, Ch 5).

### *3.4.2.7 Thigh thrust test*

The examiner (see Figure 15) applies a posterior shearing force through the flexed thigh into the SIJ whilst palpating the posterior SIJ ligament structure. A positive test is familiar pain being reproduced in the SIJ region.

### *3.4.2.8 Patrick's test*

The patient's whole lower limb is placed in a position of flexion (see Figure 16), external rotation and abduction, with their ipsilateral foot resting over the contralteral knee region. The examiner applies a gentile posterior pressure to the ipsilateral knee. A positive test is pain reproduced in the sacroiliac region, although this test is known for its stressing of the hip ligaments as well, so is not specific (Greenman, 1989).

Figure 14 Gillet test

Figure 15 Thigh thrust test

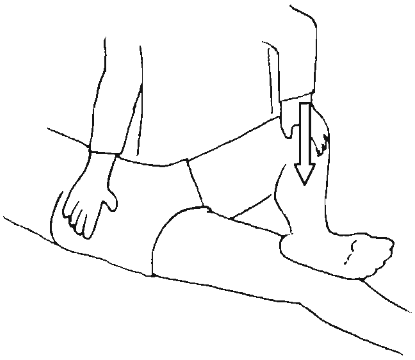


Figure 16 Patrick's Test

### *3.4.3 Validity of manual tests*

The ability of a diagnostic test or combination of tests to make a specific diagnosis is termed validity. Specificity is the probability of a true negative finding, whilst sensitivity is the probability of a true positive finding.

Testing for the presence of the criteria discussed in the preceding chapter, which should be present in order to make a diagnosis of SIJD, will depend upon which criteria are used. Fluoroscopically-guided, contrast-enhanced sacroiliac joint inta-articular anaesthetic block injection appears to be a gold standard procedure to define the painful SIJ (Aprill, 1992; Cole et al., 1996; Fortin, 1993; Fortin et al., 1994; Fortin et al., 1997; Shwarzer et al., 1995). Schwartzer et al (1995) concluded that none of the conventional historical features or active provocation tests for aggravation of pain could demonstrate the presence of the painful SIJD as defined by 75% relief from anaesthetic block. The features examined in this study were: the subjects' pain was worse or better for sitting, standing, walking and/or worse for flexion, extension, rotation and combined extension and rotation of the trunk. There were no passive provocation or tests for range of motion utilised.

The claim that a painful SIJD is related to hypomobility has not been validated experimentally. Sturesson et al (1989) found no difference of motion between the right and left SIJs of subjects who were diagnosed positive for unilateral SIJD by an orthopaedic surgeon, a chiropractor and two physiotherapists. The examiners considered the diagnosis proven if the subjects were positive in one of the standing flexion and standing hip flexion tests, and two of the flexion-adduction, hyperextension or sacral springing tests. It is not stated if these tests were all used to provoke pain or measure motion or both, as the procedure is cited in an untraceable German manual medicine text. To examine symptomatic subjects, the examiners should have been deciding if the joints were positive to provoked pain (diagnosis A1); and to validate the manual diagnostic procedure, pain relief by anaesthetic would be the standard criterion against which it would be measured. In the year of publication of this study the injection procedures were not clearly used for that role. If the examiners were testing for motion of the SIJs, then the criterion used in this study was appropriate. The problem was that subjective symptoms have been mixed with tests for hypomobility (or asymmetrical motion).

The study by Dreyfuss et al (1996) compared the validity of a diagnosis of SIJD by a physician and a chiropractor using 12 tests for SIJD that were chosen by an expert multidisciplinary panel, compared with 90% or more pain relief by intra-articular local anaesthetic. SIJD was defined as "pain from a sacroiliac joint that exhibits no demonstrable lesion, but which is presumed to have some type of biomechanical disorder that causes the pain" (Dreyfuss et al., 1996, p2594). 85 symptomatic joints of subjects were assessed, and the conclusions were that there was no historical factor that was sensitive or specific to the SIJ, and that none of the manual tests for SIJD were proven to be diagnostically sound, whether performed by the physician or the chiropractor. Sensitivity and specificity did not improve by increasing the number of tests. The tests which were utilised for revealing SIJD, were:

1 Pain drawing depicting pain over the SIJ
2 Pain drawing depicting pain into the buttock
3 Pain drawing depicting pain into the groin
4 Pointing to within 2 inches of the PSIS to indicate site of maximal pain
5 Sitting with partial elevation from the chair of affected buttock

6 Gillet test
7 Thigh thrust
8 Patrick's test
9 Gaenslen's test (performing Patricks test on the contralateral side)
10 Midline sacral thrust
11 Sacral sulcus tenderness
12 Joint play

These last seven are manual tests that are meant to be able to locate the dysfunctional SIJ, but again the methodology has utilised a procedure that mixes both motion tests (6 and 12) and pain provocation tests (7-11). Whilst there is no evidence that a hypomobile SIJ can be a painful SIJ, and clinical authors accept that hypomobility can exist without pain (Beal, 1982; Greenman, 1989; Kissling & Jacob, 1997; Lee, 1999, Ch 6), then there is flaw in the logic of a method that compares a manual examination procedure for both pain and hypomobility against simple pain relief by injection. The spring tests used in this study can be used for testing hypermobility during physical examination and can elicit pain (Lee, 1999); whether in this case this was the sign of a positive test, as opposed to hypomobility, is not clear.

The tests with the highest sensitivity were the sacral sulcus tenderness (0.95), pain over the SIJ (0.85), buttock pain (0.80) and patient pointing to the PSIS (0.76); these demonstrated that the local pain at the joint was the primary dysfunction. Combining these tests did not increase the sensitivity or specificity significantly against the physical examination.

In both of these studies, symptomatic relief by SIJ injection was the standard criterion against which the clinical examination was compared. The paradoxical results from the pain provocation tests in the Schwarzer study, with negative correlation of positive tests to SIJ block, demonstrate a possible weakness in the use of this procedure as a criterion standard.

To be valid, a diagnostic test needs to demonstrate specificity to the dysfunction it purports to reveal. Dreyfuss and co-workers (1994) analysed a collection of manual tests on a sample of 101 asymptomatic volunteers, and found 20% had false positive results in one or more of these tests. The single examiner was a physical therapist who was blinded, as there was some symptomatic subjects who were not used in the analysis. The subjects had no low back pain for 6 months nor pain that had lasted more than 2 weeks in the 6 months previous; they had no demonstrable leg length inequality; there was no history of lower extremity or low back trauma or surgery, they were not pregnant and had no condition causing a limp or altered gait. The definition of SIJD was different to that used in the 1996 study: this study operated under the definition "relative hypomobility ... with subsequent altered relationship between the sacrum and ilium". The authors stated that SIJ pain is most commonly due to SIJD, though they accept that SIJD can be asymptomatic. The tests utilised were the standing and seated flexion tests and the Gillet test; all tests designed to reveal hypomobility and asymmetry of motion, not pain. These subjects may have had any of the following categories of SIJD by the broader definitions mentioned earlier:

- A1, as they did not include groin pain in the exclusion list, which was considered the only defining feature of SIJD in one study (Schwarzer et al., 1995);
- B2, hypomobility without pain;
- C2, hypermobility (asymmetrical) without pain, and
- D, somatic dysfunction.

This again demonstrates the definitional confusion, which is continued when the authors of this study refer in their discussion to these false positives leading to "implicating the SIJ as the source of pain"; plainly, these tests are not designed to reveal the source of pain generation.

SIJ hypomobility and hypermobility are proposed to be part of the diagnosis of SIJD in categories B, C and D. The relationship of symptoms to these diagnoses requires validation. Hypermobility has been researched and proposed as a pain generator at the pubic symphysis during pregnancy (Walheim et al., 1984), and in the SIJ (Grieve, 1981; Kissling & Jacob, 1997; Lee, 1995). SIJ stiffness was measured on 14 healthy women utilising a vibrational color doppler imaging system, sometimes called mechanical palpation (Buyruk et al., 1997) (measurements were taken 3 times on each subject, in order to establish reliability, which returned a reliability coefficient of 0.94 - 0.97). The authors concluded that this method is able to discriminate inter-individual differences. The results showed a wide range of SIJ stiffness in normal subjects. The researchers then measured stiffness in a normal group of women (n=45) compared to a group (n=56) of women with peripartum pelvic pain. The results showed no significant differences in mean mobility between groups, and no difference in hypo- or hyper-mobility. A significant result was found in the comparison of the differences of the patients' SIJ stiffness between sides compared to the control group, and the authors concluded that this asymmetry of stiffness between one individual's left and right SIJs had a positive association with pain in the pelvis and low back, whereas stiffness of one particular SIJ did not.

The validity of palpation of motion and symmetry of landmarks in the diagnosis of SIJD has been brought into further question more recently. Freberger and Riddel (2001), in a review of 19 articles that deal with the validity of these tests, conclude that the results were poor, and that they do not believe that movements of such small magnitude can be palpated. The same authors stated that some pain provocation tests appear to be valid, as well as patient descriptions of pain location over the PSIS. Again, these tests are only useful if the diagnostic criteria of SIJD include a painful joint.

Van der Wurff et al (2000b) performed a systematic methodological review of 11 selected articles and found that in terms of validity, the methodological quality was poor, with only one study showing an acceptable score. A major problem encountered in the selected studies was that there is no gold standard diagnostic criteria for mobility against which to compare the tests.

Both of these review articles appeared after the current study was completed.

### *3.4.4 Reliability of manual tests*

Reliability is the extent to which an instrument can be relied upon to produce consistent results. With regards to manual testing, reliability is high when the measurement produces the same result with the same investigator over multiple tests (intra-examiner or test-retest), and with different investigators (inter-examiner or inter-rater) (DePoy & Gitlin, 1994).

The statistical analysis as applied to reliability studies needs to be appropriate. The most commonly used measures in reliability testing are the kappa statistic, the Pearson coefficient, percentage agreement and the Z value. The kappa statistic is a measure of chance corrected concordance, but may become unstable when the variation in the population for the test is limited, which can put the percentage of expected agreement up to 85% (Haas, 1991; Paydar et al., 1994). Also, when a large number of statistical tests are conducted, the risk of type 1 error becomes higher (Boline et al., 1988; Maclure and Willet, 1987). The Pearson *r* is a correlation coefficient for two variables, and falls between –1 to +1. It has been stated that inferential statistics like this should be included as well as descriptive statistics, in order to achieve valid results (Boline et al., 1988).

Percentage agreement does not include a calculation for chance agreement, and this may be as high as 50% if the result of a test is a simple positive/negative. Therefore the chi-square goodness-of-fit test applied in the Potter and Rothstein (1985) study at 70% may be misleading (Laslett & Williams, 1994; Laslett, 1997; Potter & Rothstein, 1985). The Z value is calculated using the kappa score divided by its standard error; a value of 1.96 or greater indicates $p<0.05$ for a statistically significant result (Paydar et al., 1994).

Provocation tests for pain have demonstrated the best reliability. In one study, 17 subjects with unilateral buttock pain were examined by eight therapists with 13 different SIJD tests (Potter & Rothstein, 1985). Two tests were found to be have high percentage agreement. The "supine iliac gapping test", which tests for the patient's familiar pain when the innominates are laterally and posteriorly distracted with manual force to provoke familiar buttock or crural pain, was found to have a 94% agreement between therapists. The "side lying iliac compression test", using medial manual force to reproduce the patient's familiar pain, had a 76% agreement.

The thigh thrust or "posterior pelvic pain provocation test", used clinically to reproduce familiar gluteal pain, was tested by 2 blinded physiotherapists in a cross-over study on 72 pregnant women. Positive predictive values were 70% and negative predictive values 88%, whilst sensitivity was reported as 81% and specificity 80% (Ostgaard et al., 1992).

Laslett and Williams (1994) assessed the interexaminer reliability between 2 examiners (one blinded) of 7 pain provocation tests on 51 subjects with symptoms of unilateral low back or buttock pain. These included the thigh thrust, supine gapping and compression tests analysed in the above two studies, and returned similar percentage agreements of 78-94% for the seven tests. The kappa coefficient was also reported in this study, as this discounts the proportion of agreement that would be expected by chance. Using kappa results, one test (sacral thrust) had moderate reliability, 5 tests (distraction, compression, pelvic torsion right and left, and cranial shear) had substantial reliability, and one test (thigh thrust) had almost perfect reliability.

Palpation of anatomical structures related to the SIJ to elicit tenderness has been put forward as a diagnostic criteria for SIJD by many authors Fortin, 1993; Kuchera & Kuchera, 1994; Lee, 1999; Paydar et al., 1994; Vleeming et al., 1996), although studies analysing the reliability of this practice are few. The structures include the posterior SIJ ligaments, the long dorsal ligament, the sacrotuberous ligament, the piriformis muscle and the gluteus maximus muscle. The reliability of palpating tenderness at the PSIS was analysed by Paydar et al. (1994), and found to have significant inter-examiner (90% agreement; kappa = 0.732; Z value = .818) and intra-examiner (96.8% agreement; kappa = 0.911; Z value = 3.81) reliability.

Manual tests for mobility of the SIJs have been analysed in a number of studies, and found to have poor reliability using a number of measures. Lee (1999, Ch 7) has made the point that many of these tests have been designed to evaluate function, and not the presence of pain; when they are tested against a criterion standard of pain blockade, there exists a major flaw in the logic of the method, and confusing results will occur.

The standing flexion test (or “overtake (Vorlauf) phenomenon”), described in section 3.4.2, is well established in the osteopathic (Beal, 1982; Greenman, 1989; Kuchera & Kuchera, 1994; Mitchell et al., 1979) and other manual medicine literature (Avillar et al., 1997). In a study by Van Deursen et al. (1990), three physicians used this test and five other SIJ mobility tests to examine 45 low back pain patients; their kappa coefficient statistic demonstrated agreement scores from fair to ones even less than by coincidence. It is noticeable that the authors did not mention any specific screening for false positives or negatives; shortened myofascial structures in the posterior thigh and lumbar spine (Greenman, 1989; Mitchell et al., 1979), fixed or hypomobile articulations in the lumbar spine and hip (Lee, 1992), as well as a short lower extremity with a related lumbar scoliosis (Bernard & Cassidy, 1991) are known to create false positives. False negatives can be created by bilateral positive tests (Greenman, 1989). Also the explanation of the positive test (as used in this study) included the possibility of contralateral hypermobility. This hypothesis is not consistent in the literature and may be confounding to the examiner, as in the theory of this test the PSIS on the hypomobile side moves more than the normal side, as it is thought to become locked and is carried forward (Greenman, 1989; Mitchell et al., 1979).

Potter and Rothstein (1985) also used the standing flexion test in their study of three movement tests and 7 palpated landmarks, and despite including the screening for hamstring “tightness”, found a very low agreement of 43%. Cibulka and colleagues (1988) used these same tests for a limited definition of SIJD (anterior/posterior tilting or rotation), and found that by allowing the 2 examiners to combine 4 of these tests (standing flexion, prone knee flexion, supine long sitting and palpation of PSIS heights) to decide on the diagnosis, the kappa score was excellent, at 0.88.

Other authors have discussed how a gross motion test like the standing flexion test is influenced by trunk and lower extremity muscles and articulations, so is best used alongside the testing of those other regions in order to decide if the primary cause of the motion asymmetry is the SIJ hypo- or hyper-mobility (Hesch et al., 1992; Lee, 1999).

The seated flexion test has also been examined for reliability by Potter and Rothstein (1985) and Paydar et al. (1994). In the former study, the percentage agreement was 50%. In the latter study, 32 asymptomatic subjects were examined by 2 chiropractic students who were trained together in the use of the tests, and found a poor inter-examiner agreement of 34.4% (kappa = .089). The intra-examiner result was also poor at 58.1% (kappa = 0.286). These studies did not include screening for myofascial or articular restrictions in the lumbar spine that may create false positive results in this test (Greenman, 1989; Mitchell et al., 1979), and may return improved results with these conditions excluded. This test also features in the literature as a test for SIJD (Avillar et al., 1997; Beal, 1982; Greenman, 1989; Kuchera & Kuchera, 1994; Mitchell et al., 1979).

The Gillet test (also known as the stork test or spine test) is thought to be a test for SIJ mobility. The subject stands erect and flexes one hip to bring the knee off the ground (modified to keeping the foot on the floor in the spine test for elderly subjects) whilst the examiner palpates the sacrum and ilium to feel normal posterior motion of the ipsilateral innominate. Clinical authors have supported its use in the diagnosis of

SIJD (Avillar et al., 1997; Gitelman, 1979; Greenman, 1989; Kirkaldy-Willis & Hill, 1979).

In an early single blind study of the reliability of this test (Wiles, 1980), 6 pairs of chiropractors examined 46 healthy young male subjects and graded the six types of Gillet test (inferior, superior and bilateral for the left and right sides) numerically as normal (1), moderate restriction (2) or severe restriction (3). The results were correlated using the Pearson product-moment correlation coefficient. Three of the six tests, the inferior left and right and bilateral right, were found to have significant agreement and correlation, and the whole set of tests had significant correlation of $r$=0.18 ($p<.01$). The authors found that expertise enhanced agreement, and that these three tests had high specificity, but low sensitivity.

Potter and Rothstein (1985) also analysed the Gillet test and found only a 46.67% agreement between their 8 therapists. Another study (Carmichael, 1987) gave a more specific operational definition of the tests, and trained 10 students in the use of these procedures, but still found kappa scores of only “fair” concordance (0.18) for intraexaminer reliability and “slight” concordance (0.314) for interexaminer reliability, despite finding percentage agreements of 89% for each, demonstrating the importance of including chance agreements. The authors found the Gillet reliable when used by a single examiner on the same patient repetitively, and that the superior or upper pole part of the test had moderate kappa scores. Also, they disagreed with the Wiles (1980) results, and found that the test had moderate sensitivity to detect abnormality.

The same test was analysed using 10 chiropractors trained in two parts of the Gillet test, with 11 subjects reported as having SIJ “problems” (Herzog et al, 1989). The examiners saw each subject twice, and intra and interexaminer scores were calculated on the positive (graded) and negative findings. Intra-examiner reliablity was significant based on 68-79% agreement, and inter-examiner reliability was significant overall, although inconsistent between sessions, with 54-78% agreement. The investigators found that expertise correlated negatively with percentage intra-examiner agreement. The statistical test used in this study (chi-square) has been criticized, as the sample size was small (Paydar et al., 1994). The Gillet test appears to induce motion in a posterior rotation around the transverse x axis, and therefore does not include other directions of possible hypomobility. This test may not be valid for all the diagnoses listed in 3.4.1.

Palpation for static landmark symmetry is a feature in a majority of diagnostic procedures for categories B, C and D. Potter and Rothstein (1980) again examined the interexaminer reliability of palpation of the iliac crest heights, the ASIS and the PSIS levels in the standing and sitting positions. The results ranged from 35-43% agreement, which is poor. Cibulka et al (1988) also assessed the interexaminer reliability of palpating the PSIS heights as part of a combination of four tests, and found an excellent kappa of 0.88. Paydar et al (1994) found the inter- and intra-examiner agreement of palpation of iliac crest heights was poor at 53% and 32% respectively (kappa = 0.239 and –0.8; Z = 1.729 and –0.58), and palpation of PSIS heights was also poor at 46% and 51% respectively (kappa = 0.15 and 0.248; Z = 1.096 and 1.851).

Measurement of static erect pelvic tilt by one examiner with a caliper and trigonometry method on 20 healthy males, was analysed for intra-examiner reliability using the Pearson product-moment correlation coefficient (Gajdosik et al., 1985). Measuring the standing, anterior and posterior pelvic tilt angle were all found to be reliable (0.86-0.92) as was the total range between posterior and anterior pelvic tilt (0.87).

A popular static palpation test is the "long sitting test", where the symmetry of the subject's medial malleoli levels are observed to change when going from a supine to a seated posture (Cibulka et al., 1988; Potter & Rothstein, 1985). Potter and Rothstein (1985) found poor results with 40% agreement, and Cibulka and fellow investigators found a significant kappa of 0.88 for the combination of four tests, so it is difficult to ascertain the reliability of this test alone. These same researchers had similar findings with the prone knee flexion test, where the change in malleoli relationship is theorised to demonstrate the side and type of SIJD - a low agreement for the test on its own (23%) (Potter & Rothstein, 1985), and high kappa score when combined with other tests (Cibulka et al., 1988).

Other tests that Van Deursen et al. (1990) found to have poor reliability were the palpated motion with translation (kappa score = 0) and the flexion adduction test for hip muscle shortening (kappa score = .03).

These studies reflect the position regarding palpation in the musculoskeletal system; that subjective pain provocation has some reliability, whilst palpation tests for structure, mobility and texture have poor results at the present time (Boline et al., 1988).

Examiner training and experience is an issue in comparing techniques, particularly with regards to the aim of the test, the procedural consistency and the explanation of the findings. The tests for SIJD are known to be widely varying in procedure and description in the literature, and this creates a high possibility for inter-examiner error

(Biline et al., 1988; Cibulka et al., 1988; Laslett, 1997; Paydar et al., 1994; Potter & Rothstein, 1985; Wiles, 1980). The Patrick's test (or Fabere) is a good example of an ill-defined test that, depending on how an examiner has learnt it, could be a test for pain provocation of the hip and possibly the SIJ (Bernard & Cassidy, 1991), but also a mobility test for the hip and/or the SIJ (Van Deursen et al., 1990).

In summary, the Potter and Rothstein (1985) study used eight therapists, from 6 different schools, with varied levels of experience from 2 to 18 years, and who had attended courses on the SIJ; it was not mentioned if they had attended the same course. The examiners followed written guidelines that they had reviewed and agreed upon. Laslett and Williams (1994) used two therapists who had "several" training sessions in order to maximise the reliability in achieving their high level of agreement. Van Deursen et al (1980) used three experienced educator/physicians, and it was not stated whether they learnt the tests at the same course of study, or compared procedures before the study. Paydar et al (1994) used two chiropractic students who had trained together.

Clinical authors have stated that they practice utilising a battery of tests to diagnose these dysfunctions, and that decisions are never made on one test alone (Beal, 1982; Cibulka et al., 1998; Gitelman, 1979; Greenman, 1989; Lee, 1995); therefore studying the reliability of one test alone may not reflect true practice. Others state that an unreliable test is not made reliable by putting it with other unreliable tests (Bogduk, 1997). All testing has a probability of having false positives and false negatives, and a clinician has to assess that probability across a number of tests. It is known that using multiple tests that have less than perfect specificity and sensitivity (eg 80%) is a reliable practice, as long as each test supports each other as positive or negative; when the test results disagree the diagnostic decision is obviously not assisted by using multiple tests (Griner et al., 1981).

This is also a position taken in two more recent review articles, van der Wurff (2000a) and Freburger and Riddle (2001). These authors agree that multitest regimes and scores should be developed in order to test clinical practice more closely, following Haas' (1991) suggestions.

Van der Wurff (2000a), as mentioned in section 3.4.3, performed a two part systematic methodological review on 11 papers dealing with clinical tests of the SIJ; part one was concerning reliability. Nine of these papers had acceptable scores for methodology quality, and the authors concluded that because of this quality, the poor reliability reported for the tests examined was confirmed. Two exceptions were made - the Gaenslen and thigh thrust provocation tests appeared reliable.

The reliability of manual testing for any of the diagnostic criteria has been studied, and often criticised, in the manual medicine literature. It is important that the individual manual tests and combinations of them are clearly used for the purpose for which they were designed. In the case of SIJD, that is to examine either for pain on provocation, hypomobility, hypermobility or simple asymmetry of structure and/or motion. In some cases a manual test may be used to reveal a combination of these positive findings. The challenge is to find a series of tests that are relevant to the diagnostic criteria, and prove reliable on testing. The series of tests utilised in this study has not been tested for reliability, but the specific combination of tests and their relationship to the diagnoses have been published in textbooks and utilised by osteopathic and other clinicians for over 20 years (Beal, 1982; Greenman, 1989; Kuchera & Kuchera, 1994; Mitchell et al, 1979).

# 4 Gait

## 4.1 Introduction

The characteristics of gait need to be fully explained, as the results of this study will be explained with reference to the specific characteristics of gait that are significantly different between groups.

The word gait is from the Old Norse *geta,* meaning 'a way'; it is the way the animals on the planet get from one place to another, also known as ambulation or locomotion. In the context of this thesis it is the specific way a human individual walks.

Walking is a complex whole body phenomena, as evidenced by the fact that the trunk and pelvis have autonomous reciprocal rotations which appear to dampen forces and smooth the gait (Stokes et al., 1989). Biomechanically, the kinematic chain comprising the pelvis and the two lower limbs alternately opens and closes during initial contact and pre-swing, when the main bursts of muscle activity take place (Huson, 1997). The kinematics of one chain affects the kinematics of all other chains related to it, again showing the interdependence of the structures in the lumbo-pelvic-hip region.

The three main tasks for walking gait are: firstly, the maintenance of support for the head, arms and trunk (HAT) against gravity; secondly, maintenance of upright posture and balance; and thirdly, control of foot trajectory to achieve safe ground clearance and a gentle heel contact (Winter, 1989). The pelvis is integral to each of these functions. It has been termed “a gravitational force transducer” (Dorman, 1997; Snijders et al., 1993) relaying the ground reaction forces from the lower limbs into the trunk. The pelvis acts as a postural control mechanism (Gracovetsky et al., 1989; Panjabi, 1992; White & Sahrmann, 1994), and as the proprioceptive centre in the placement of the foot, it acts as a critical component of balance (Redfern & Schumann, 1994). Placement of the foot also determines the stride length, the walking base and the toe out. The stride length is the distance between two successive placements of the same foot, consisting of two step lengths for each foot (Perry, 1992; Whittle, 1991).

The walking base is the distance between the line of the two feet side to side, demonstrating the width required to stabilise the gait, and the angle between the direction of progression and a line through the sole of the foot is called the toe-out (Murray et al., 1964). This toe-out is related to external rotation of the limb, and this external rotation is one of the factors biomechanically influencing sub-talar pronation (Perry, 1992; Valmassy, 1996).

Minor dysfunctions of gait are thought to be a factor in painful conditions of the lower back and pelvis (Dananberg, 1993a; Dananberg, 1993b; Greenman, 1989; Lee, 1995). This is supported by the fact that an estimate of weight bearing time per day was 80 minutes, which resulted in 2500 stance/swing cycles per limb, which would be 1 million steps per limb per year; by the age of 30 this approaches 30 million (Dananberg, 1993b).

Figure 17

Degree of toe-out

The normal for free speed walking in males is 7 degrees (Murray et al., 1964)

Figure 18

Stride length

The distance from one reference limb heelstrike to the next (Perry, 1992; Valmassy, 1996)

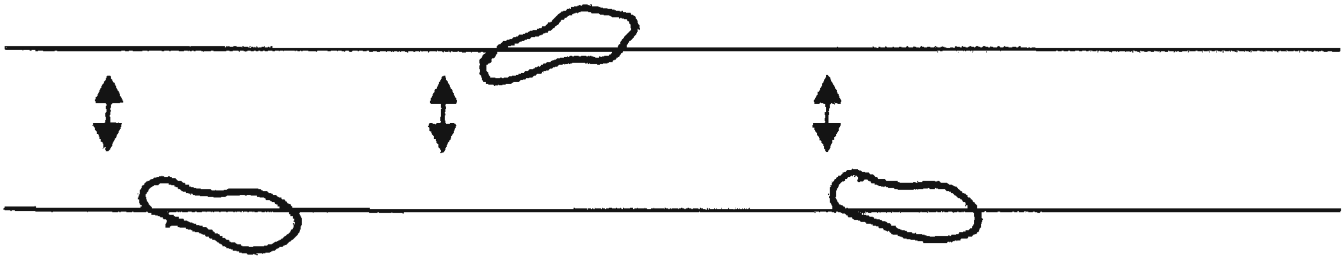


Figure 19

Width of the base of support

The distance between the left and right heel midpoints (Perry, 1992; Valmassy, 1996)

## *4.2 Theories of gait production*

Theories about how gait is initiated are divided between the traditional lower limb theory, and the more recent trunk muscular theory, or “spinal engine” (Gracovetsky & Farfan, 1986). Inman et al. (1981) described the power generation for initiating walking as concentric muscular contraction, which creates force moments across joints, creating motion. Subsequent studies demonstrated that the muscle action of the weightbearing leg was actually “turned off” during push off, which appears to disprove the concentric muscular action theory (Valmassy, 1996). Dananberg (1993b) has put forward a theory based on the primary pulling action of the non-weightbearing limb, and the momentum of the centre of mass acting in an elastic structure; the pendular limbs in effect store energy. Perry (1992) believed this to be a second pulling force, acting after the weightbearing limb pulls the centre of mass forward. In Dananberg’s theory, the forward momentum depends on the leverage to pull the weight forward over the calcaneus and the first metatarsophalangeal joint, which can be a primary cause of gait dysfunction if an individual is not able to have a full range of painless motion (Dananberg, 1993b). This author and others (DonTigny, 1990) have called gait a “controlled fall”, due to the interaction between the forward leaning trunk weight and the lower limbs striding to arrest the fall.

## *4.3 Variability of normal gait*

Normal human gait has some individual variation. High intra-subject variability was found in the kinetic measures of joint moments in the knee and hip of one female subject, with coefficients of variation (CV) 67% and 72% respectively; although the ankle (CV=22%) and net support moment for the whole limb (CV=25%) were much less variable (Winter, 1984). Winter (1984) also found that over 9 trials on that subject, vertical ground reaction forces had a low CV of 7% whilst anterior-posterior forces had a slightly higher CV of 20%. In the same study, the kinematic results measured on a 16mm cine camera had low within subject variability of 19% for the joint angles in the hip, 10% for the knee and 9% for the ankle.

In another study with 62 normal subjects, ground reaction forces as expressed in 34 parameters, were found to have varying symmetry (Herzog et al., 1989; Robinson et al., 1987). A symmetry index (see Section 4.6.2) was utilised and found that the vertical force, stance time and anterior-posterior force were all within 4% of symmetry between legs. The highly variable parameters were ones where the magnitude of the measures were very small, and so small differences between legs results in large symmetry indices. These included the impulse averages for the antero-posterior and mediolateral parameters, and the time measures of the maximum slope; both of these are close to zero in normal human gait. The medial-lateral scores were asymmetrical, possibly owing to the small measures for this direction in general (Herzog et al., 1989).

Acceptable levels of symmetry, defined as a coefficient of variation (CV) below 10% for vertical and anterior-posterior time domains, were found with 10 normal males performing 10 trials on each leg (Giakas & Baltzopoulos, 1997). Medial-lateral readings were highly variable (CV>10%). A frequency domain analysis, which quantifies the oscillation pattern of the force-time curves, was also completed, and CVs of 6.9% in the vertical, 9.8% in the anterior-posterior and 6.6% in the medial-lateral were reported on the variation in GRFs between legs. The authors concluded that normal gait is symmetrical, except in the medial-lateral time parameters.

In contrast, Sadeghi and co-authors (2000) stated in a review of the gait literature that despite the fact that symmetry of gait has been historically assumed, there is evidence of a natural functional asymmetry in normal gait. The Herzog et al (1989) and Giakas & Baltzopoulos (1997) studies discussed above were cited as the evidence for this in studies of ground reaction forces.

Speed has been found to alter parameters of gait. Knee and hip flexion and extension moment peaks are positively related to speed of gait, and may be increased by up to three times the walking measures with increased speed (Winter, 1984). Cadence and step length appear to vary linearly with increasing speed, whereas time of support and swing are inversely proportional to speed (Andriacchi et al., 1977). Some investigators believe a natural speed must be allowed to ensure valid results for that individual (Giakas & Baltzopoulos, 1997; Osterbauer et al., 1993). Others have controlled the speed to reduce variability, most often to 1.5m/s ± 10%, which conforms to the literature of normal speed (Section 4.5) (Herzog et al., 1988; Herzog et al, 1989; Herzog et al., 1991; Herzog et al., 1994; Osterbauer et al., 1993; Robinson et al., 1987). Another system for minimising the variability was developed by Stokes et al (1989), where the subject established their normal free speed (F), and this as well as four other speeds were analysed; F-20%, F+20%, F+40% and F+60%. Andriacchi and co-workers (1977) demonstrated that stride length varied from 0.55m at a walking velocity of 0.8m/s, to 0.74m at 1.5m/s. This was a positive linear relationship, whereas an inversely proportional relationship existed between velocity and time of support – at 0.8m/s time of swing was 600ms and at 1.5m/s this time was reduced to 450ms. Nottrodt et al (1982) found that transverse pelvic rotations increased with higher walking velocities, proposed to be an adaptive change to lengthen stride. Stride and step length, and therefore cadence, has been found to vary with leg length, height, age and sex (Murray et al., 1964; Whittle, 1997; Whittle & Levine, 1999).

## *4.4 Determinants of gait*

These are traditionally described kinematic features of gait that represent adjustments made by the body to keep the excursions of the body's centre of gravity (COG) to a minimum. These are considered to be energy saving mechanisms. The first three determinants minimise the elevation of the COG, the fourth minimises the depression of the COG, and the fifth minimises the side-to-side motion of the COG (Norkin & Levangie, 1992; Rose & Gamble, 1994; Saunders et al., 1953).

### *4.4.1 Lateral pelvic tilt*

As the COG moves over the stance limb, it undergoes both an ipsilateral lateral movement and a rise in a sinusoidal wave pattern. To minimise the upward motion there is a rotation of the pelvis as a whole around an anteroposterior axis to the contralateral side, sometimes called pelvic list. This drops the COG towards the contact surface, and is resisted by the ipsilateral abductor muscles. The effect of this pelvic list on vertical trunk displacement has been challenged by Gard and Childress (1997), who found pelvic list was at neutral when the trunk was at its peak vertical displacement (based on video tracking of reflective markers attached to the pelvis on 3 normal subjects).

### *4.4.2 Knee flexion*

As the COG moves to its high point in midstance, the knee flexes by a few degrees to decrease the height over which the body has to climb.

### *4.4.3 Knee, ankle and foot interactions*

As the COG moves from its low point at initial contact towards its high point at midstance, the knee flexes, the ankle plantarflexes and the foot pronates; these relatively shorten the extremity and minimise the rise in the COG. When the COG begins to fall after midstance, the knee extends, the ankle plantarflexes, and the foot supinates to cause a relative lengthening of the extremity to minimise the fall in the COG.

### *4.4.4 Forward and backward rotation of the pelvis*

Rotations of the pelvis around the vertical axis in the transverse plane also relatively lengthen each extremity in order to minimise the rise and fall of the COG. In terminal swing as the COG reaches its first low point, the pelvis is at its most anterior, causing limb lengthening; similarly in preswing the pelvis is at its most posterior position when the COG is dropping to its second low point, lengthening the limb.

### *4.4.5 Physiological valgus at the knee*

The physiological valgus moves the feet closer together in the base of support; this decreases the lateral motion of the COG necessary to shift from one extremity to the other.

### *4.5 Kinetics of Gait*

In order to describe the phases of gait, an understanding is also necessary of the kinetics that are observed by instrumentation. In accordance with Newton's third law, where the force exerted by one mass on another produces and equal and opposite reaction force in the second object, the forces exerted by the walking surface against the feet in gait are called ground reaction forces (GRF) (Hamill & Knutzen, 1995; Rose & Gamble, 1994).

#### *4.5.1 Ground Reaction Forces*

Ground reactions are responses to the weight of the body and its muscular actions transmitted through the feet, and are measured through force plates. The measurements are separated into vertical force (directed upward), two horizontal shear forces (forward and backward, lateral left and right), the normal moment and the centre of pressure (COP). In the current study, the normal moment and the centre of pressure were not used in evaluation of gait.

#### *4.5.1.1 Fz Vertical*

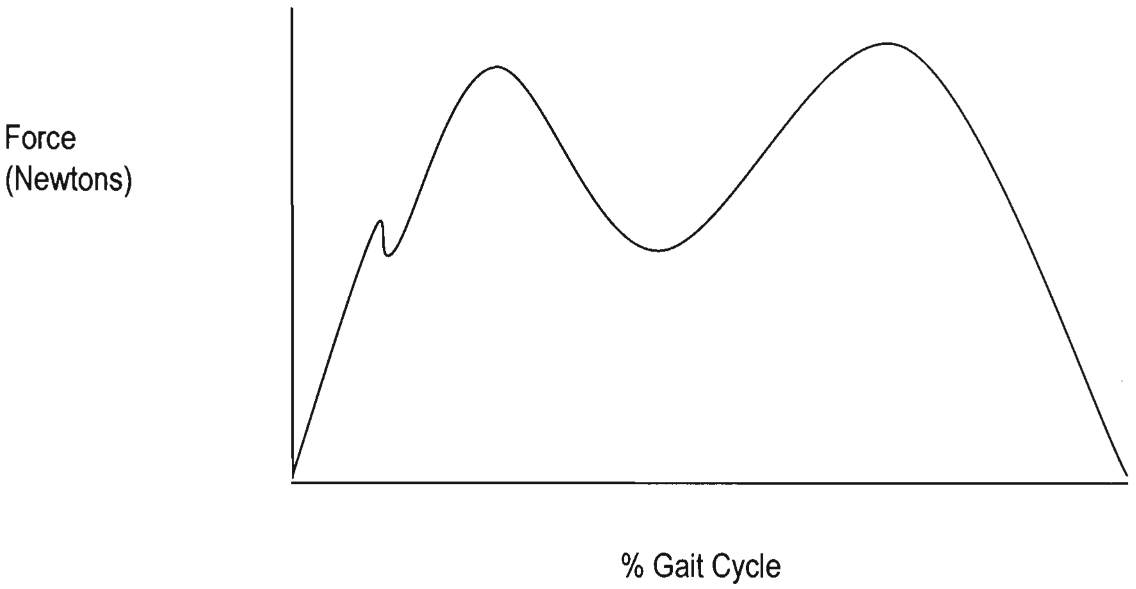


**Figure 20**

**The vertical GRF** (adapted from Perry, 1992)

The vertical stance phase pattern for normal gait has two peaks separated by a valley. The peaks are usually 110 – 125% of body weight, whereas the valley is about 80%. The first of the biphasic peaks represents an upward acceleration of the COG during initial loading in early stance. The valley represents a reduction in downward force as the body moves over the leg in midstance and the swinging contralateral limb unloads the force plate. The second of the biphasic peaks is due to the deceleration and lowering of the COG over the forefoot rocker, as the downward motion is checked in late stance (Perry, 1992; Valmassy, 1996).

There is usually a "heelstrike transient" early in loading response that may last 10-20ms, and is only seen when the instrument is responding at high speed and the sensitivity is set to collect this feature; there appears to be no certain biomechanical explanation for this event (Whittle, 1991).

#### *4.5.1.2 Fy Anteroposterior*

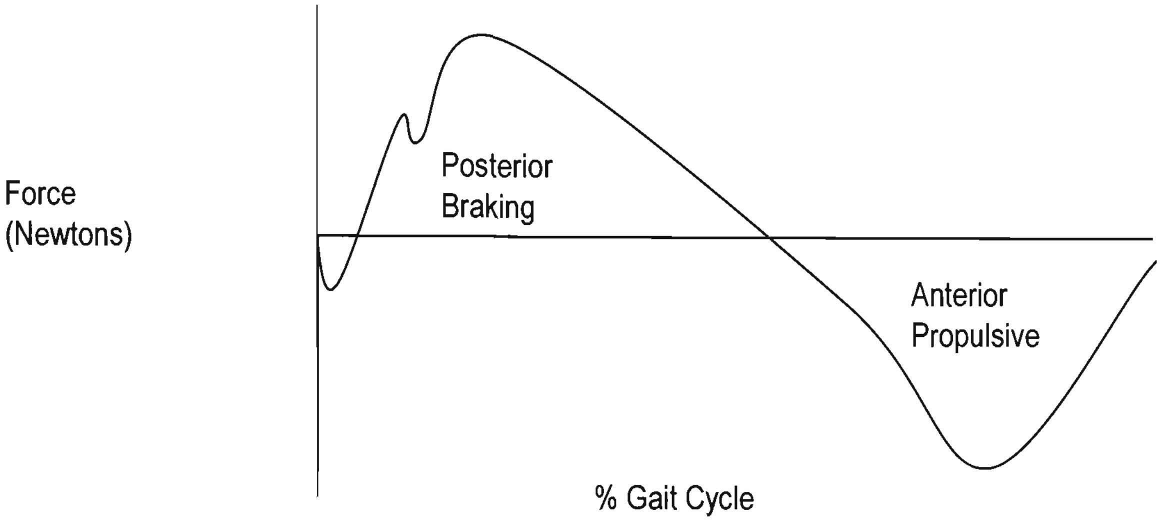


**Figure 21**

**The anteroposterior GRF** **(adapted from Perry, 1992)**

The profile of the fore-aft force is divided between the positive posterior braking force, and the negative anterior propulsive force. There is a minor posteriorly directed heelstrike transient that is believed to assure early weight bearing stability (Perry, 1992; Whittle, 1991).

#### *4.5.1.3 Fx Mediolateral*

The mediolateral forces are very small and variable. The profile shows the small medially directed peak early in stance, and the lateral peak in terminal stance approaching toe-off (Perry, 1992; Whittle, 1991).

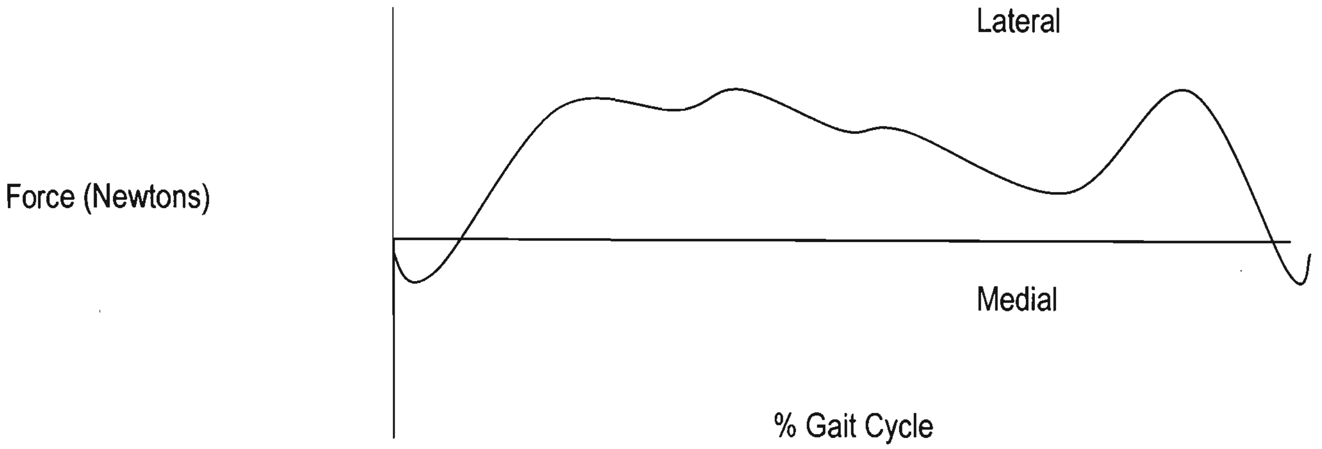


**Figure 22**

**The mediolateral GRF** (adapted from Perry, 1992)

### *4.6 Phases of the gait cycle*

The phases of the gait cycle describe the activities of the so-called reference extremity from firstly touching the ground to touching it again. The reference extremity passes through two phases, a single stance phase and a single swing phase. Stance phase begins when the foot initially touches the ground at initial contact or heel strike, and finishes when it lifts off the ground at pre-swing or toe-off; it is 60% of the total cycle. As soon as the toe leaves the ground it begins its swing cycle, and ceases just prior to initial contact or heel strike, accounting for the 40% of the cycle remaining. Two periods of double support occur in a total cycle, when the stance phase of one lower limb is beginning, and the stance phase of the other is near completion; this accounts for 22% of the total cycle. These figures represent walking at a normal speed, which has been defined as between 1.25-1.5 m/s (Perry, 1992; Rodman & McHenry, 1980).

In the descriptions of the subdivisions of the phases, the modern terminology is used. As much of the clinical literature is written utilising the traditional terminology, clarification and comparison of the two systems is explained in Table 3.

| **Traditional** | **Modern** |
|---|---|
| Heel strike | Initial contact |
| Heel strike to foot flat | Loading response |
| Foot flat to midstance | Midstance |
| Midstance to heel off | Terminal stance |
| Toe off | Preswing |
| Toe off to acceleration | Initial swing |
| Acceleration to midswing | Midswing |
| Midswing to deceleration | Terminal swing |

**Table 3**

**Comparison of Gait Terminology** **(Norkin and Levangie, 1992)**

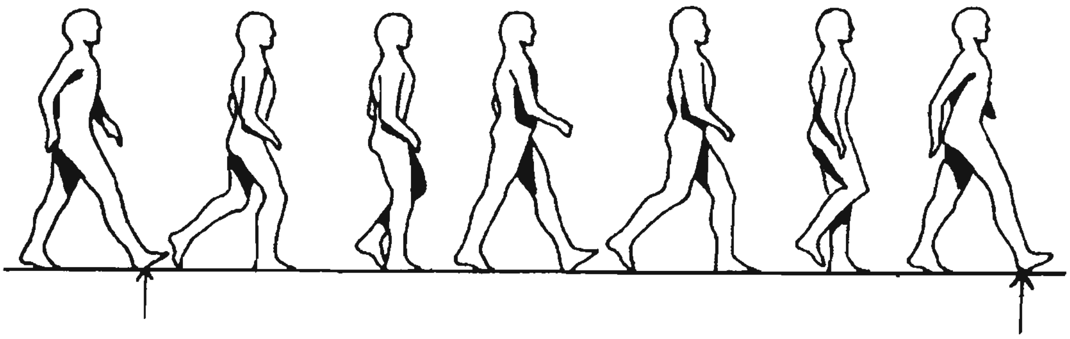
The stance phase is subdivided into:

- initial contact, which is the instant the leading foot strikes the ground,
- loading response, which is immediately following this until the end of double support when the contralateral limb lifts off the ground,
- midstance, which is from when the contralateral limb is lifted off the ground until the body has progressed over the support limb,
- terminal stance, which is the period from the end of midstance to just prior to initial contact of the contralateral limb, and

- preswing which encompasses the period just following heel off to toe off.

The swing phase is subdivided into:

- initial swing, which is when the foot leaves the ground and continues until maximum knee flexion of the reference limb,
- midswing encompassing the period following knee flexion until the leg is vertical,
- terminal swing which is from after the lower leg is in the vertical position until just before heel strike.



Initial Contact ⇒ Loading response ⇒ Midstance ⇒ Terminal Stance ⇒ Preswing ⇒ Initial to Mid-Swing ⇒ Terminal Swing

**Figure 23**

**Summary of the phases of gait** (adapted from Norkin and Levangie, 1992)

Each of these 8 subdivisions will now be explained with reference to time and distance parameters as well as the kinetics and kinematics of the lower limbs, pelvis, trunk and upper limbs. The temporal variables include stance time, single limb and double support time, swing time, stride and step time, cadence and speed. Distance variables include stride length, step length, width of walking base and degree of toe out. These parameters may be affected by age, sex, height, joint mobility, muscle strength, type of clothing and footwear and psychological status (Murray et al., 1964; Norkin & Levangie, 1992; Rose & Gamble, 1994).

### 4.6.1 *Initial contact*

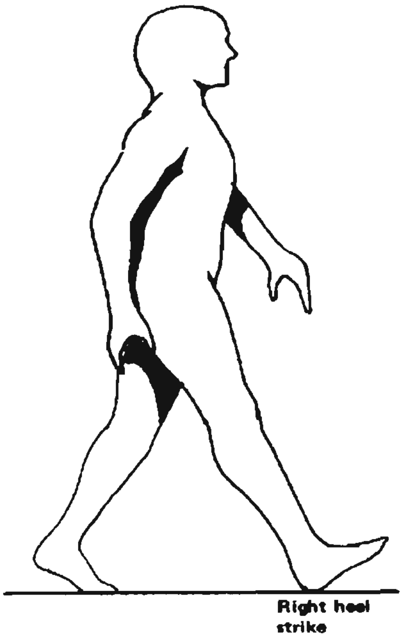


**Figure 24**

**Initial Contact** (adapted from Norkin and Levangie, 1992)

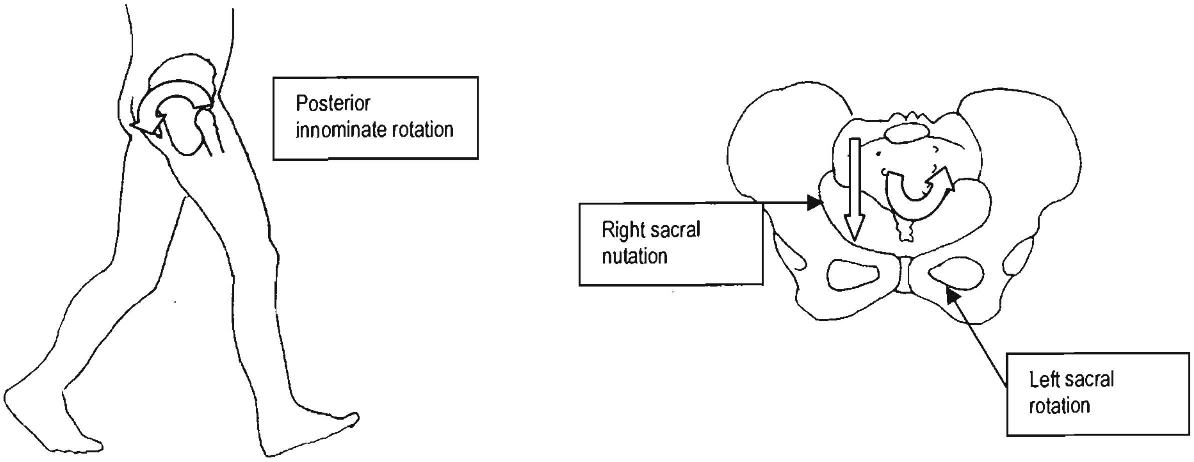


**Figure 25**

**Proposed pelvic rotations at initial contact** (Greenman, 1990; Lee, 1995)

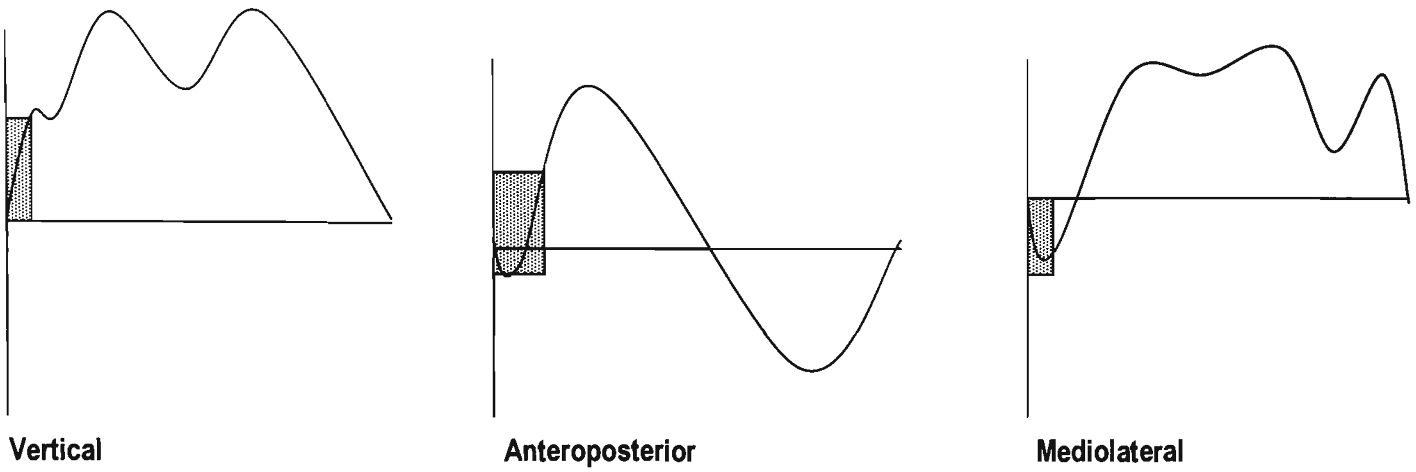


**Figure 26**

**Ground Reaction Forces at initial contact** (Valmassy, 1996).

For initial contact of the right leg, the right hip joint is at 30 degrees flexion (see Figure 25) and experiencing a flexion torque, which is resisted by the gluteus maximus and adductor magnus (Valmassy, 1996). The right limb also medially rotates on the pelvis. The right knee is extended and flexion is strongly resisted by the quadriceps. There is a valgus thrust to the knee joint and medial rotation of the tibia. The right ankle begins at neutral, but is rapidly plantarflexed to the floor. This results in a considerable passive subtalar pronation, which subsequently adducts the foot. The soleus and gastocnemius are active to limit internal rotation and forward movement of the tibia. The centre of pressure (COP) pathway through the plantar surface of the foot has a characteristic pattern and begins at the posterolateral edge of the heel (Rose & Gamble, 1994; Skinner at al., 1985; Valmassy, 1996).

The right innominate is thought to rotate posteriorly on the sacrum in the sagittal plane following the hip flexion (Alderink, 1991; DonTigny, 1997; Greenman, 1990;

Lee, 1995; Mitchell et al., 1979). Near maximal tension on the hamstring muscles (Rose & Gamble, 1994) results in tension through to the sacrotuberous ligament, and is thought to stabilise the right SIJ for initial contact in force closure (Vleeming, 1995). This innominate rotation is reported to be anterior at initial contact in two studies. The first one found the maximal anterior rotation occurred at initial contact, with a total sagittal rotation of 3.6 ±1.2 degrees (Kawate et al., 1992), and the second found that the maximal anterior rotation was just preceding initial contact, whereas maximal posterior rotation (3 degrees total) occurred just after initial contact (Murray et al., 1964)(refer to Figure 25). These studies both related this anterior rotation to the trunk and femur by utilising reflective targets and not the sacrum, which is difficult to attach a relective target to utilising this system. This may explain the discrepancy between these studies. Dananberg (1997), like Murray et al. (1964), states that the maximum anterior sagittal rotation occurs just before initial contact, as well as the sacral nutation with the innominate; it is unclear if the author is defining this sacral motion in terms of its relationship to the adjacent innominate (osteokinematic motion) or its articular (arthrokinematic) motion. Other authors are of the opinion that the sacrum rotates to the left around a vertical axis (Greenman, 1989; Lee, 1995), and this motion added to the posterior innominate rotation results in right sacral nutation in arthrokinematic terms. Lee in 1999 (Ch 5) had changed view to stating that the sacrum rotates right around the vertical axis, but still nutates; this does not seem logical in arthrokinematic terms, as the right sacral base would have to move posteriorly on the right to rotate right, but anterior to nutate. DonTigny (1990) also stated that the sacrum rotates right around the vertical axis at right initial contact, in response to the anterior transverse pelvic rotation; there is no experimental evidence to support this.

Maximum transverse pelvic rotation occurs similarly to the left, allowing the right pelvis to rotate anteriorly around a vertical axis (Thurston & Harris, 1983; Rowe & White, 1996; Valmassy, 1996). Thurston and Harris (1983) measured this at a mean of 10.1 degrees. The degree of transverse rotation increases significantly as walking speed increases (Nottrodt et al., 1982), and has a direct positive relationship with stride length (Thurston & Harris, 1983; Valmassy, 1996).

The lumbar spine appears to rotate to the left after the pelvis (Thurston & Harris, 1983) around an oblique vertical axis, with coupled contralateral rotation around the anterior-posterior axis (right sidebending) and rotation around the medial-lateral axis (flexion). There is uncertainty regarding the coupling motion of the lower segments of L4 and L5, with some specimens sidebending to the same side as rotation (Bogduk, 1997; Gracovetsky & Farfan, 1986; Lee, 1999, Ch 5). Recently, Whittle and Levine (1999) found that the lumbar spine rotated transversely to the opposite of the pelvis, although this result was from reflective markers placed at the thoracolumbar junction, and so may not be valid for mid and lower lumbar segment motion. The erector spinae contract actively at initial contact, possibly to resist the flexion moment at the hip (Norkin & Levangie, 1992). The quadratus lumborum and the rectus abdominus also contract, possibly as part of the coupled lumbar sidebending (Lee, 1999, Ch 5).

The thorax has been shown to follow the pelvis in vertical axis rotation at initial contact, in contrast to the rest of the gait cycle when it rotates to the opposite of the pelvis (Stokes et al., 1989).

The centre of gravity (COG) follows a figure of eight pattern in both the sagittal and transverse planes (Gard et al., 1996); at initial contact it has moved to the right by 10mm, and is close to its most inferior position at -12mm (Whittle, 1997).

The ground reaction forces (GRF) at initial contact (see Figure 27) demonstrate the rapid rise of vertical force to 110-125% of body weight (Valmassy, 1996). The anterior-posterior force has a momentary posterior direction as the heel decelerates when it strikes the floor, which interrupts the forward motion (Valmassy, 1996), although Perry (1992) believes that this is dynamic limb retraction to assure early weightbearing stability. This reaches a peak of 10-15% of body weight at the end of the loading response phase. Mediolateral shear begins a rise toward the medial at initial contact (Perry, 1992).

### *4.6.2 Loading response*

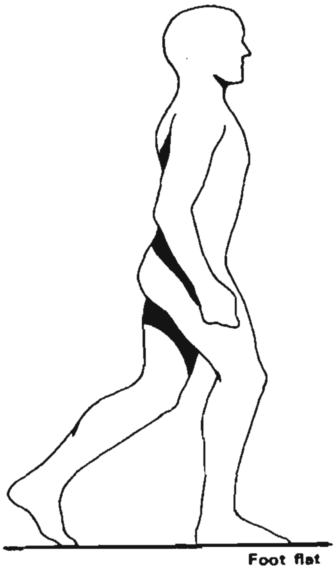


**Figure 27**

**Loading response** **(adapted from Norkin and Levangie, 1992)**

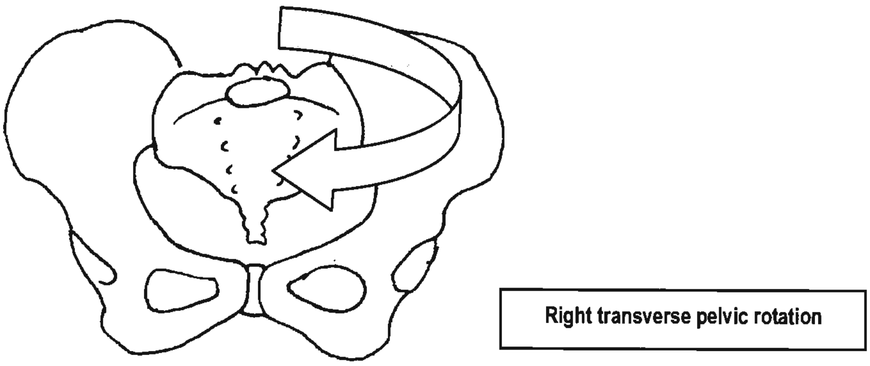


**Figure 28**

**Pelvic rotations in loading response** (Rose & Gamble, 1994)

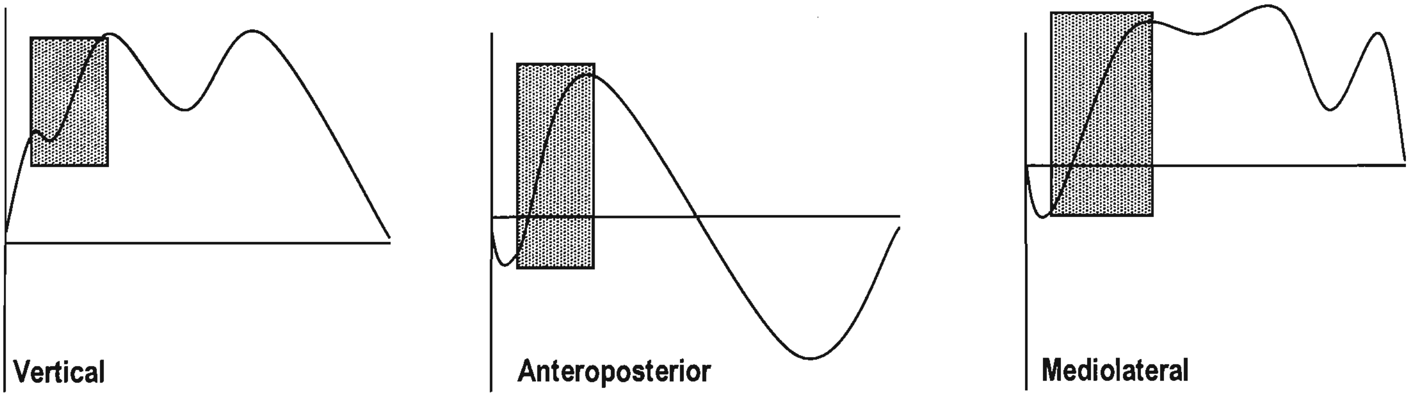


**Figure 29**

**Ground Reaction Forces in loading response** (Valmassy, 1996)

This subdivision occurs during 0-10% of the total time of the cycle (Valmassy, 1996), and finishes at the end of double support. The right hip remains flexed, but now the right knee also flexes to 15 degrees from the gastrocnemius contraction (Sutherland et al., 1980), and the right ankle plantarflexes 15 degrees to the floor. The subtalar pronation reaches its maximum. The COP moves to the lateral plantar surface, at the midtarsal joint (Norkin & Levangie, 1992; Rose & Gamble, 1994; Skinner at al., 1985; Valmassy, 1996).

The left side of the pelvis begins to move forward, as the transverse rotation reverses to the left (Rose & Gamble, 1994). The trunk as a whole falls to its lowest point during this double support phase, with a total of 46mm from there to the peak rise (Perry, 1992). Also the forward speed of gait reaches its highest velocity in this phase (Stokes et al., 1989; Whittle, 1997).

The COG is accelerating forward, moving medially toward the midline and begins its rise toward the midpoint (Whittle, 1997).

The vertical GRF continues its rise (see Figure 30), whilst a steady increase in the braking posterior force takes place towards its peak to 11-15% of body weight at the end of loading. The medial force reaches its peak here at appoximately 5% of body weight (Perry, 1992; Valmassy, 1996).

### 4.6.3 *Midstance*

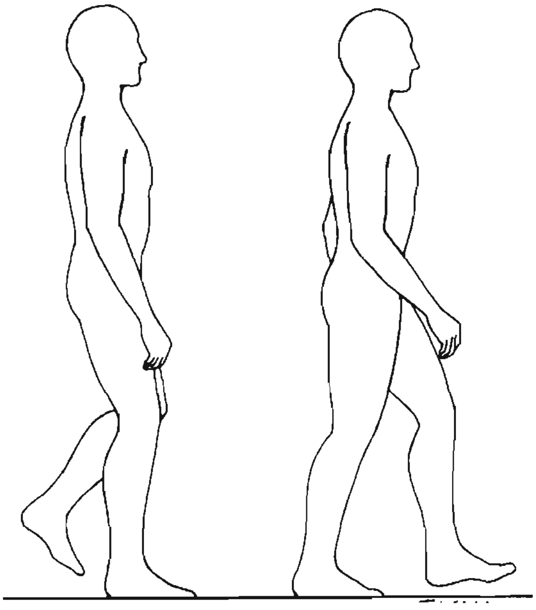


**Figure 30**

**Midstance** (adapted from Norkin and Levangie, 1992)

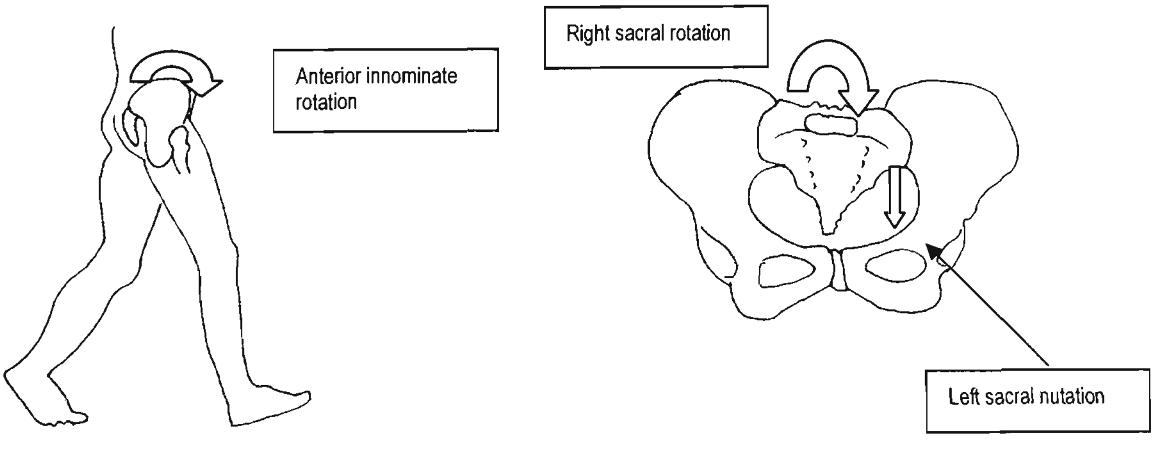


**Figure 31**

**Pelvic rotations in midstance** (Greenman, 1990; Mitchell et al, 1979)

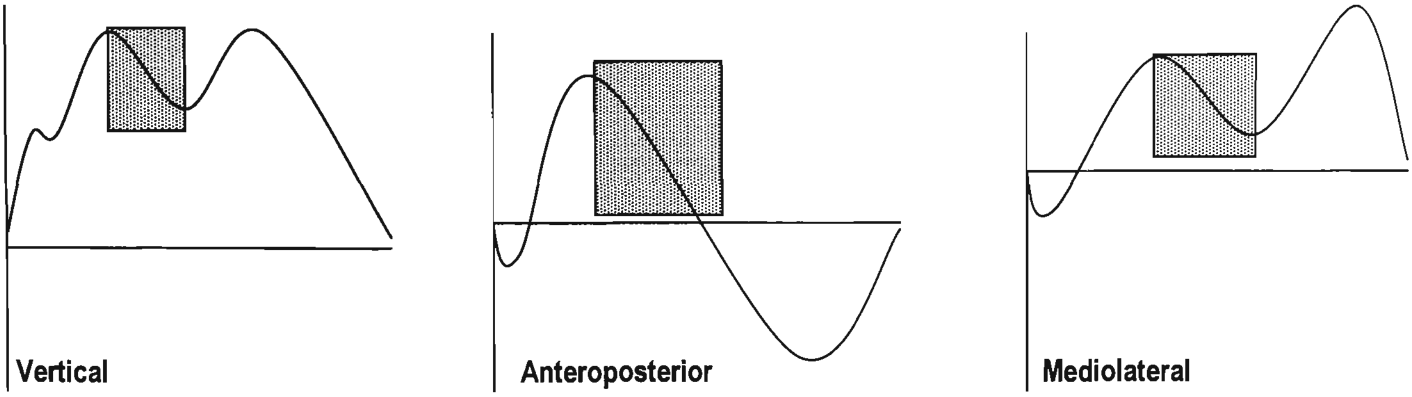


**Figure 32**

**Ground Reaction Forces in midstance** (Valmassy, 1996)

This subdivision, the first half of the single support interval, takes up 10-30% of the gait cycle, and begins as the contralateral foot is lifted and continues until the body weight is over the ipsilateral forefoot (Perry, 1992).

The hip moves to extension of up to 25 degrees from the gluteus maximus contraction, with an adduction moment and decreased medial rotation to neutral from the swing momentum of the contralateral limb (Skinner et al., 1985). The knee begins to extend from quadriceps contraction, the ankle dorsiflexes as the body weight moves over the support limb and the relative external limb rotation creates supination in the subtarsal joint. These motions are supported by gastocnemius and soleus contraction (Valmassy, 1996).

The ipsilateral innominate is believed to now rotate anteriorly, and the contralateral one posteriorly. As the maximal load develops on the ipsilateral hip and SIJ, the sacrum develops a right rotation around the vertical axis and a left rotation around an AP axis (sidebending); this causes left sacral nutation (Greenman, 1990). This coupled motion of the sacrum is thought to occur on an oblique axis based on piriformis contraction, or in DonTigny's (1997) opinion the short dorsal SI ligament. In right midstance it is called a right (rotation) on right (oblique axis) anterior sacral torsion (Greenman, 1990; Mitchell et al., 1979). Lee (1999 Ch 5) contradicted these findings, stating that the sacrum rotates left during this phase, despite agreeing with Greenman's findings earlier.

Coronal plane rotation of the pelvis (pelvic list) occurs (mean = 7 degrees) to the contralateral side, producing a Trendelenberg phenomenon (Kawate, et al., 1992; Stokes et al., 1989; Thurston & Harris, 1983). This is stabilised by the ipsilateral gluteus medius and minimus, and the tensor fascia latae.
The COG translates laterally to its maximum along the mediolateral axis by a range of 26.6 - 75.4mm over the stance limb (Thurston & Harris, 1983). The trunk rises to its maximal height in the middle of single support (Perry, 1992, Stokes et al., 1989). The COP begins its medial movement across the plantar surface of the foot to be midline in this phase (Norkin & Levangie, 1992).

As the body weight translates anteriorly over the stance limb, the trunk begins to oppose the right rotation of the pelvis by rotating to the left; the right arm swings forward as an autonomous part of this counterbalancing (Whittle & Levine, 1999). The lumbar spine remains rotated right around the anterior-posterior axis, and rotated left around the vertical axis (Greenman, 1990).

The vertical GRF reaches its first peak at the onset of midstance (110-125% body weight), and drops to the valley (80% body weight) by the end of the subdivision as the body weight decelerates over the stance foot. The posterior peak is dropping back from its braking maximum as the body rises over the stationary foot and speed decreases. There is a lateral drift of the mediolateral GRF back to neutral (Perry, 1992; Valmassy, 1996).

### 4.6.4 Terminal stance

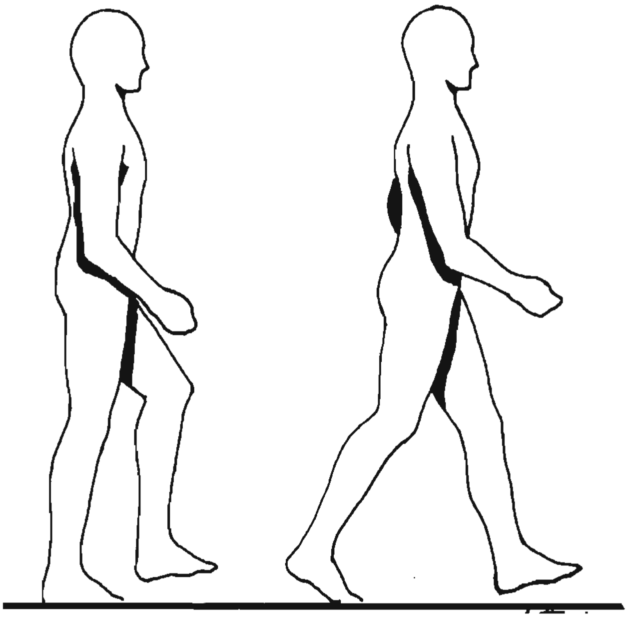


**Figure 33**

**Terminal stance** (adapted from Norkin and Levangie, 1992)

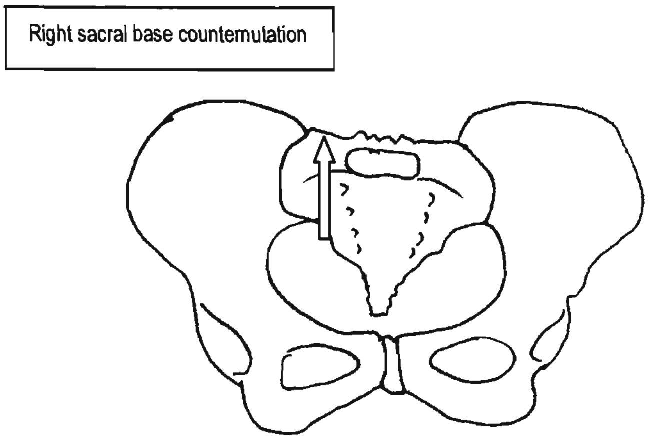


**Figure 34**

**Pelvic rotations in terminal stance** (Greenman, 1990; Lee, 1995)

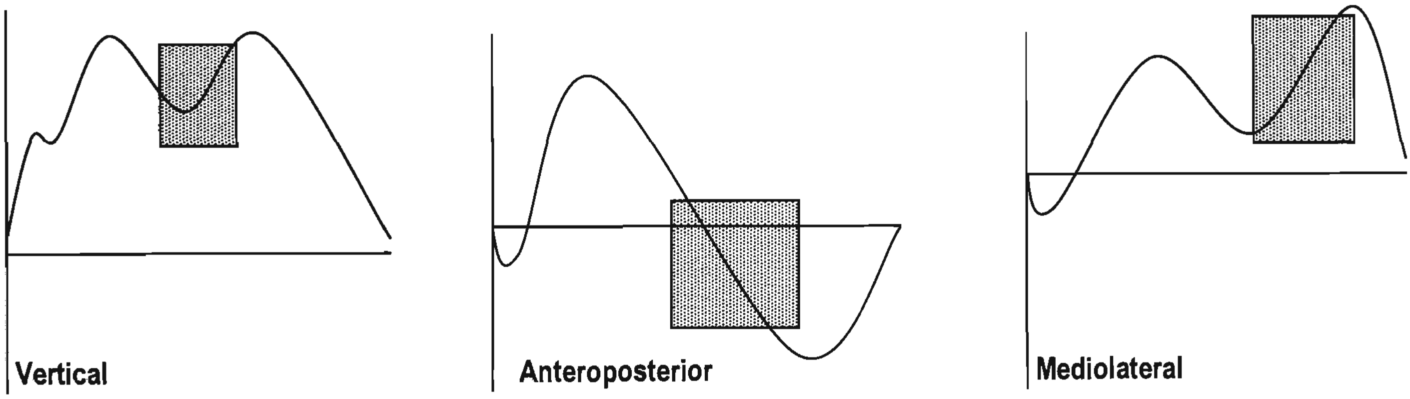


**Figure 35**

**Ground Reaction Forces in terminal stance** (Valmassy, 1996)

This subdivision of the stance phase takes up the next 30-50% of the gait cycle, and begins with heel rise continuing until the contralateral foot strikes the ground (Perry, 1992). The hip continues into extension up to 20 degrees, with lateral rotation and adduction of the femur. The knee goes back into relative extension (3 degrees flexion) and the tibia laterally rotates; this increases stride length (Valmassy, 1996). The ankle undergoes a dorsiflexion moment, resisted by the gastrocnemius and soleus, and the subtalar joint continues supination (Skinner, 1985).

The right pelvis externally rotates on the hip, and rotates to the right around the transverse axis to move posteriorly (Norkin & Levangie, 1992; Valmassy, 1996). Sagittal plane motion is thought to involve the innominate moving to maximal anterior rotation, whilst the right sacral base is counternutating around the dynamic transverse axis relative to it (Greenman, 1990; Lee, 1995). This posterior motion of the right sacral base is resisted by the long dorsal SIJ ligament (Vleeming et al., 1996). The trunk is at maximal counter rotation to the left just before contralateral initial contact (Stokes et al., 1989). Concurrent with firing of the contralateral latissimus dorsi (Gracovetsky, 1997; Vleeming et al., 1997), the gluteus maximus contracts to extend the hip (Rose & Gamble, 1994); these muscles tense the thoracodorsal fascia and facilitate force closure through the sacroiliac joint in preparation for left initial contact (Lee, 1999, Ch 5).

The COG slows to its minimal anterior velocity, moves to the extreme of its lateral excursion (14mm), and drops from the vertical peak (16mm) towards its peak inferior position (Whittle, 1997). During this stage, the vertical GRF is in a valley, the anterior-posterior force is at zero and moving to the anterior under the influence of the swing limb acceleration, and the lateral force begins to rise towards a peak (Perry, 1992; Valmassy, 1996).

### *4.6.5 Preswing*

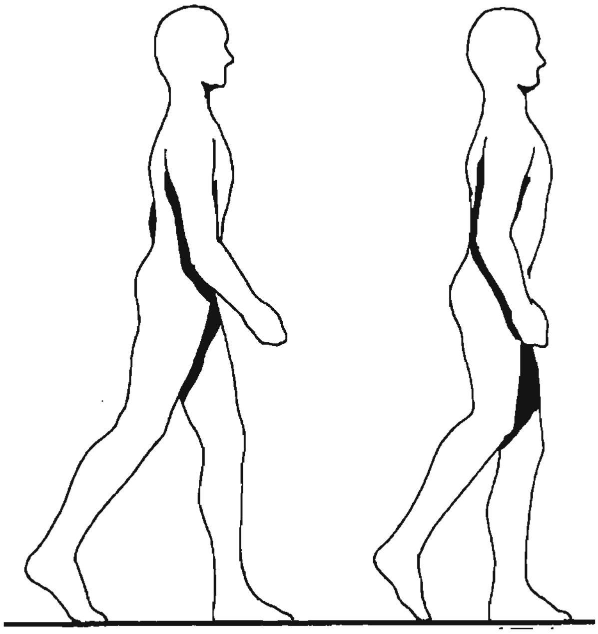


**Figure 36**

**Preswing** **(adapted from Norkin and Levangie, 1992)**

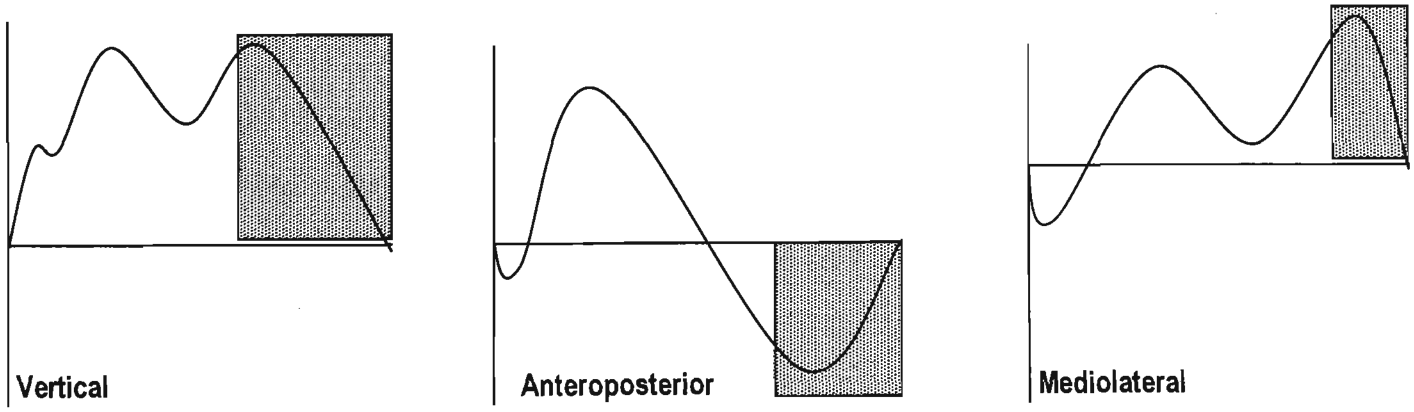


**Figure 37**

**Ground Reaction Forces in preswing** **(Valmassy, 1996)**

The last subdivision of stance is at the 50-60% stage of the total gait cycle, and is the second (terminal) double stance interval as it begins with initial contact of the contralateral limb, and ends with ipsilateral pre-swing or toe-off (Perry, 1992).

The hip reaches its maximal extension and external rotation, abducts, and the lateral pelvic tilting ceases as the contralateral limb begins stance phase. There follows a rapid flexion from iliopsoas contraction. The knee passively moves from 3 to 40 degrees of flexion, the tibia is laterally rotated and the ankle dorsiflexes as the COP moves anterior to the metatarsal heads. The metatarsophalangeal joints hyperextend to 60 degrees and the COP continues its medial direction towards the first metatarsal. At pre-swing or toe-off just the first toe is in contact with the ground (Norkin & Levangie, 1992; Rose & Gamble, 1994; Skinner at al., 1985; Valmassy, 1996).

The lumbar spine is shown to be at maximal lordosis in this phase, though this is reported as asynchronous and variable (Thurston & Harris, 1983).

The COG begins the steep anterior climb as acceleration occurs, moves over neutral towards lateral and begins the rise upwards over the contralateral limb (Whittle, 1997). The vertical GRF reaches its second, usually largest, peak at 110-125% body weight as the forefoot takes the load. As the leg moves forward of the ankle, a posterior shear peaks up to appoximately 20-25% of bodyweight as toe off occurs. Lateral shear also reaches a peak at this stage up to approximately 7% of bodyweight (Perry, 1992; Valmassy, 1996).

### *4.6.6 Initial swing*

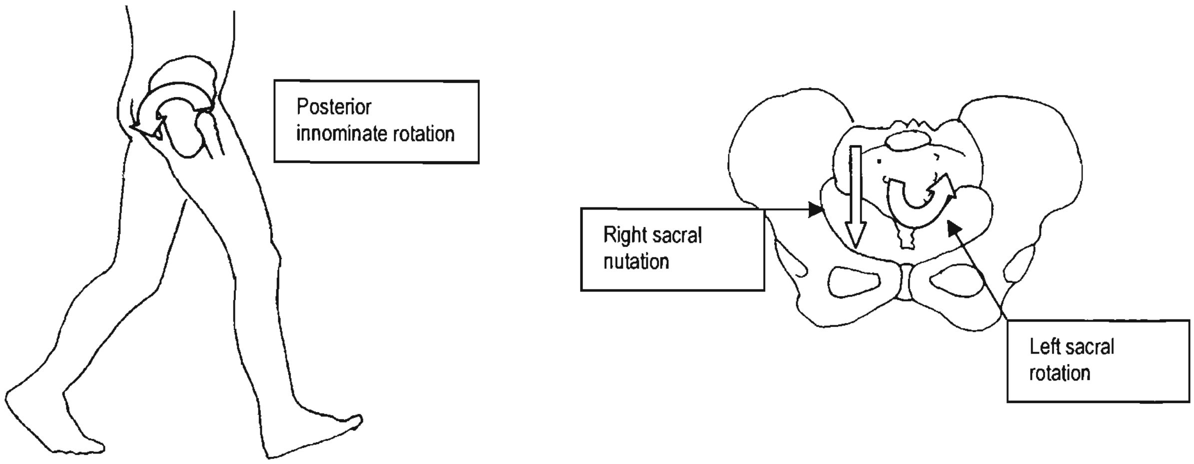


**Figure 38**

**Pelvic rotations in initial swing** (Greenman, 1990; Lee, 1995)

This first subdivision of the swing phase has an interval of 60-73% of the total gait cycle, and begins with the lift of the limb from the floor and ends when the swinging foot is opposite the stance foot (Perry, 1992). The hip continues its flexion to 30 degrees, as rotation reverses to medial. The knee flexes to 60 degrees, and the tibia also medially rotates and the ankle dorsiflexes back to neutral. The pelvis tilts downwards (AP axis ipsilateral rotation) and rotates to the left around the transverse axis, bringing the right pelvis forward (see Figure 39)(Norkin & Levangie, 1992). The stride length is affected by the degree of this motion (Thurston & Harris, 1983; Valmassy, 1996), reported as a direct positive relationship with stride length (Nottrodt et al., 1982).

The innominate appears to gradually rotate posteriorly around the medial-lateral axis in the sagittal plane during swing, causing a relative sacral nutation; the sacrum rotates right around an AP axis (sidebends) (see Figure 39) as it rotates left around the vertical axis (Greenman, 1990; Lee, 1995).

The thorax and shoulder move posteriorly on the right, in opposition to the transverse pelvic rotation (Murray et al., 1964).

The COG reaches its peak 16mm rise over the contralateral limb, moves towards the peak lateral movement over that same limb and attains peak anterior speed at 14mm displacement (Whittle, 1997).

### *4.6.7 Midswing*

At an interval of 73-87% of the total gait cycle, this subdivision begins with the ipsilateral limb opposite the stance limb, and ends with the ipsilateral leg forward and tibia vertical (Perry, 1992). The hip, knee and ankle are all in flexion to clear the ground (Valmassy, 1996), and the pelvis continues to rotate anteriorly around the vertical axis in the transverse plane (Rose & Gamble, 1994), and rotate posteriorly around the medial-lateral axis in the sagittal plane (Greenman, 1990).

The COG slows again towards neutral, reaches its peak left excursion over the contralateral limb at 14mm and begins to drop inferiorly towards neutral height {Whittle 1997 104 /id}.

### 4.6.8 Terminal swing

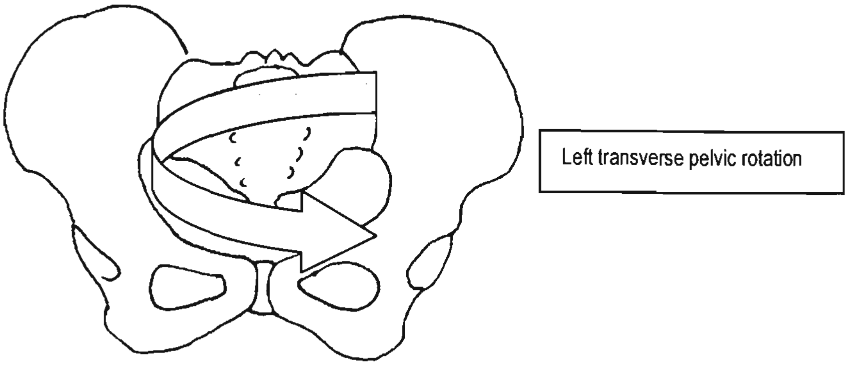


**Figure 39**

**Pelvic rotations in terminal swing** ((Rose & Gamble, 1994)

The final subdivision of the gait cycle takes up the interval between 87-100% of total time, beginning as the tibia is vertical and ending just before the foot strikes the floor (Perry, 1992). The hip is at 30 degrees flexion and medial rotation, and the ankle remains in neutral. The tibia appears to be carried forward by momentum, and then the knee is actively extended by the quadriceps, which is resisted by an eccentric contraction of the hamstrings (Skinner et al., 1985). This contraction may assist in force closure of the SIJ by tensing the sacrotuberous ligament (Vleeming et al., 1997).

The pelvis reaches its maximum left rotation around the vertical axis in the transverse plane (see Figure 40) (Rose & Gamble, 1994) bringing the ipisilateral pelvis anterior, and also the maximal posterior rotation around the medial-lateral axis in the sagittal plane (Greenman, 1990). The lumbar spine has controversial findings; it is thought to either rotate left around an oblique vertical axis coupled with right rotation around the AP axis (side bending) (Greenman, 1990), or rotate and sidebend left in the lower segments (Lee, 1999, Ch 5), or rotate right around the vertical axis (Whittle & Levine, 1999). The biomechanical findings are complex, and are most likely due to the difference between the upper segments coupling in opposite directions, and the L4/L5 and L5/S1 segments behaving in a variable way with regards to coupling (Greenman, 1997; Lee, 1999; Mitchell et al., 1979).

The COG begins to anteriorise again as acceleration begins, and drifts towards the right as ipsilateral initial contact approaches. The bodyweight drops towards the floor, taking the COG towards its inferior peak (Whittle, 1997).

## *4.7 Gait dysfunction*

### *4.7.1 General*

The reported components of pathological and dysfunctional gait need an introduction at this point in order to compare these to the specific dysfunctions tested in this thesis. Also pelvic, hip and lower limb abnormalities might be a component of a larger lumbo-pelvic-hip kinematic chain dysfunction (refer to Section 2.3), which may include SIJD. A brief consideration of these follows, preceding a closer examination of the SIJD in gait.

Gait changes throughout the life cycle. Compared to normal adults, toddlers walk with a wider base of support, a shorter step time, a slower velocity and a higher cadence (Rose-Jacobs, 1983). Gait appears to stabilise to an adult pattern at 8-10 years of age, although velocities and accelerations have been found to be larger in adolescents than in prepubescents (Donatelli, 1990).

The elderly appear to demonstrate a decrease in natural walking speed, shorter stride and step lengths (Murray, 1964), longer duration of double support and a smaller swing phase. This may be related to fitness level, as it appears that the differences between the elderly and young adults are less if the elderly are more fit and active (Winter, et al., 1990).

Studies of pathological gait are numerous in the literature, but do not relate to this study. The sacroiliac dysfunctions described in Section 3.1 are non-pathological in nature, in that they are not identifiable disease states, but rather changes in function.

Perry (1992) described a number of gait errors, classified under the three planes of motion. In the sagittal plane, an anterior pelvic tilt could be caused by weak hip extensors or flexor spasticity, and result in altered ground reaction forces at midstance and loading response. A posterior pelvic tilt is rare and effects limb advancement. In the coronal plane, pelvic hike (or upward tilt) could be caused by excessive ankle plantar flexion, and may result in altered swing phase gait. Contralateral pelvic drop may be caused by weak hip abductor muscles, contracted hip adductor muscles or contracted contralateral hip abductor muscles, and result in a trunk lean (or a lateral translation) over the stance limb. Ipsilateral pelvic drop could be caused by contralateral hip abductor weakness, a short ipsilateral limb, calf muscle weakness or scoliosis, and result in deviation of the COG away from the stance limb. In the transverse plane, excessive forward rotation may occur in order to attain normal stride length in the presence of ineffective hip flexors, and excessive backward rotation may be caused calf muscle weakness and result in a compensated relative long leg.

Abnormal hip rotations can occur because of hip muscular deficiencies, abnormal foot contact or as a compensatory event for another problem. This will result in abnormal toe-out or toe-in patterns, which influence foot biomechanics (Whittle, 1991).

### *4.7.2 Sacroiliac joint dysfunction and gait*

The effect of SIJD on gait has rarely been studied. The theoretical and clinically observed theories of Mitchell et al (1979), DonTigny (1985), Greenman (1990) & (1997) and Lee (1999) about the SIJ and its dysfunction in gait have not been demonstrated with scientific experiment. The information presented thus far has described what is known of the kinematics of the SIJ and pelvis, and the measured kinematics of the pelvis as a whole during gait. It is plausible to suggest that the SIJ has motion that is integral to normal gait, both kinematically and kinetically, but this has not been measured experimentally.

The concept of instability of a SIJ, or hypermobility with or without pain affecting gait is discussed in the clinical literature. Greenman (1990 & 1997) stated that a loss of ligamentous strength would affect form closure, and a loss of myofascial strength would affect force closure to the detriment of normal walking; the resultant gait dysfunctions were not specified. Lee (1999, Ch 6) has observed that with decreased form or force closure, the COG becomes displaced to the affected side to reduce vertical shear; this appears to result in a compensatory Trendelenberg gait with the ipsilateral femur abducted with respect to the foot. These observations may be related to the findings of Gitelman (1979), who stated that the pelvis on the side of SIJD (diagnosed as painful fixation) showed “less deviation” than normal in gait, and the stride was shortened.

DonTigny (1997) also stated that any SIJD that disturbs the self bracing mechanism during gait would cause loss of the normal rhythmic oscillations of the trunk, pelvis and legs; this could result in increased shear forces on lumbar discs, an increase in spondylolisthesis or cause an unstable segment. The SIJD that this author proposes (anterior innominate rotation) is thought to lengthen the ipsilateral limb (Greenman, 1989; Mitchell et al., 1979), and theoretically may cause the postural compensation of a trunk lean towards the long limb. Simulating a long leg by as little as 1cm was found to produce a postural sway towards the long leg, demonstrating the compensating effect of balance in normal human posture (Mahar et al., 1985); the effect on gait may be similar. The concept that failed stabilisation of the pelvis in general, and the SIJ in particular, may result in lumbar spine disc and facet syndromes is well supported by other authors (Gracovetsky & Farfan, 1986; Vleeming et al., 1997); how this then affects gait is not clear.

Herzog and co-workers made attempts to describe, quantify and test the treatment of SIJD using GRF measured on force platforms; these were reported in the literature from 1987 to 1994. In Robinson et al. (1987), the investigators analysed the GRFs of 9 subjects with "sacroiliac dyskinesia", or unilateral decreased motion of a SIJ, diagnosed by undisclosed palpatory tests. The subjects had at least 6 months of low back pain, though the site of the pain and response to provocation was not included in their report. Each was measured walking at 1.5m/s ± 10% to land on a force platform 3 times with each foot. Every subject was then manipulated by a chiropractor and performed the same number of gait trials. 46 temporal and kinetic gait variables were analysed by a symmetry index. The Symmetry Index used was:

$SI = 2(x_n - x_i)/\ (x_n + x_i)\ X\ 100$

where $x_n$ = the value of a variable obtained from the non affected side, and $x_i$ = the value of the corresponding variable obtained from the affected side.

22 of the original 46 parameters were analysed, as the temporal variables were excluded if the range of their individual variation was greater than 100ms, and the other variables excluded if the absolute value was small compared to its variance. The results showed that there was no significant change after treatment. A second analysis was performed using a sub-group that had asymmetry before treatment, and there was a tendency towards symmetry post treatment ($x^2$ = 13.1). The researchers concluded that gait asymmetry has to be present in people with sacroiliac dyskinesia in order to make the claim that chiropractic treatment improved gait symmetry.

In another study, the same researchers found significant decreases in the force of the vertical and mediolateral GRFs after chiropractic treatment for a painful hypomobile SIJD in a single patient study (Herzog et al., 1987); the anteroposterior forces were not different. They repeated the study using 11 subjects with unilateral hypomobile SIJD who each performed three trials for each leg at a walking speed of 1.5m/s ± 10%, and this time employing the Symmetry Index (Herzog et al., 1988). In contrast to the Robinson et al (1987) study, they found that the subjects became more asymmetrical after treatment for the vertical and anteroposterior forces. The researchers found that the first vertical peak was higher on the involved side for early treatment sessions, but the second vertical peak was higher on the involved side in later treatment. They discussed these peaks as “round” (higher) or “flat” (lower) and hypothesised that this may represent functional reversal between legs as treatment progresses. The authors thought that the same phenomena was responsible for the result that the minimum mediolateral force also decreased significantly as treatment progressed. There was a statistically significant relationship between the patients who had less pain (on the visual analogue scale) and decreased GRF's, although the statistical methods used were not disclosed.

Another study (Herzog et al., 1989) analysed 34 variables of the GRFs of 62 asymptomatic subjects (33 males, 29 females), who performed 5 trials on each leg walking at 1.5m/s ± 10%, and found wide variability and asymmetry between legs. As mentioned in Section 4.3, the vertical, anteroposterior and time parameters were within 4% of perfect symmetry. The authors also analysed whether the subjects had a leg dominance by reversing the direction of walking, and found it "unlikely".

The researchers did not examine the asymptomatic patients for SIJD, which may have been present in some subjects. Also, the subjects wore shoes, which may alter ground friction. Finally, females may have variable mobility of their SIJs owing to hormonal action (Alderink, 1981; Lee, 1999; Pitkin & Pheasnat, 1936). All of these may theoretically affect the gait and the findings in this study.

In a later study (Herzog et al., 1991), the researchers compared outcomes for two treatments - chiropractic spinal manipulative therapy (SMT) and physiotherapy back school, using four measures of outcome: the visual analogue pain scale, the Oswestry functional ability questionnaire, the Gillet motion test, and GRFs in gait analysis. The 37 subjects (25 male, 12 female) performed three trials on each leg walking at 1.5m/s ± 10%, and the same Symmetry Index was utilised to measure the gait outcome. The patients were diagnosed as having a "chronic sacroiliac problem" by two chiropractors, which had to be painful for at least one month, and hypomobile based on the Gillet test. All the patients were significantly asymmetrical before the treatments and more symmetrical only after treatment with SMT ($p \leq 0.05$). This was despite the physiotherapy back school scoring higher on the subjective pain and disability measures; the results show that the relationship between gait symmetry and clinical measures of recovery is unclear.

Further clinical research by another group analysed 10 patients with "sacroiliac syndrome", or painful SIJD, with the mobility status not examined (Osterbauer et al., 1993). The symptomatic patients were screened to exclude other problems (lumbar facet syndrome, sciatica, and organic causes) and to ensure definitive SIJ involvement (three pain provocation tests). Measurements included the visual analogue scale, the Oswestry disability index, postural sway and GRFs on a force platform. A free speed was chosen by each subject, and all completed 5 gait trials. The GRF variables were the same as used by Herzog et al (1988) and were found to have no asymmetry, nor had they changed in a significant way from before to after the SMT treatment, despite decreased pain measured by a visual analogue scale, and improved function measured with the Oswestry disability index . Without diagnosing the relative mobility of the SIJ as a component of its dysfunction, it is difficult to interpret the GRF findings.

Herzog and Conway (1994) responded to this study in a commentary, explaining the differences in the Osterbauer et al (1993) study and the ones in which their group had been involved. They stated that the interventions were different, although both were Spinal Manipulative Therapy (SMT): Osterbauer used activator techniques, not side-lying manipulation. Herzog and Conway wrote that the methods differed: Osterbauer only repeated the 10 trials after the end of the series of treatments, and not repetitively after each treatment; and the walking speed was not controlled, which would increase the variability. Finally, they stated that the interpretation was different, as no Symmetry Index was used. Herzog and Conway concluded that increasing the number of trials, and controlling the speed reduces the variability, although they also stated that gait analysis is not specific or accurate enough to describe the mechanics of SMT.

There have been no studies on the comparison of the GRFs of patients who have low back and pelvic pain combined with a hypomobile SIJD, to those of asymptomatic subjects who have no SIJD. Additionally, there has been no experimental evidence presented in the literature for the existence of the reportedly common forms of hypomobile SIJD – the right anterior innominate and the left on left sacral torsion somatic dysfunctions, nor for the difference between them in their proposed effect on gait.

## *5 Aims*

The main aim of this study was to assess the association between the osteopathic tests and diagnoses of sacroiliac joint dysfunction with GRFs during gait. Specifically, the study aimed to compare the normal walking GRFs of male subjects between 18-55 years of age who were symptomatic of low back and/or pelvic pain and who also tested positive for two types of osteopathically diagnosed somatic dysfunctions of the sacroiliac joint, with an asymptomatic comparable group who tested negative for sacroiliac joint dysfunctions of any category.

Secondarily, the study aimed to test the reliability of both the gait analysis and the diagnostic procedure over time.

# 6 *Methodology*

## *6.1 Sampling*

The sample consisted of convenient male subjects, including staff of campus, clinic outpatients, students aged between 18 and 55 years of age. Females were excluded from this study because of possible hormonal influences on pelvic joint mobility (Alderink, 1991; Greenman, 1989; Pitkin & Pheasant, 1936). Potential subjects were attracted to the study by use of posters on notice boards in public places, and also approached during their visit to the outpatient clinic of Victoria University and the researcher's private clinic. If the subject was involved in treatment, they participated before they had any treatment for their condition, and after participating received the treatment from their normal clinician. There was no payment or incentive for participation in the study. The subjects were free to withdraw from the study at any time. The questionnaire included an informed consent form (Appendix 1), outlining the study and possible risks, and stating that each subject may withdraw from the study at any time.

Table 4 summarises the sample in terms of group number and age. There were 69 subjects in all; 12 of these were re-tested for reliability.

| **Group (see section 6.5)** | **Number** | **Age** | | **Body Mass (kg)** | |
|---|---|---|---|---|---|
| | | **Range** | **Average** | **Range** | **Average ± SD** |
| Norm | 25 | 18-38 | 25.0 | 63-88 | 74.8 ± 7.9 |
| Innominate | 20 | 18-50 | 28.6 | 54-109 | 75.8 ±12.8 |
| Sacral | 24 | 18-53 | 26.1 | 63-89 | 78.3 ± 8.3 |

**Table 4**

**Summary of subject characteristics**

## 6.2 *Questionnaire and informed consent*

Each potential subject completed a questionnaire (Appendix 1), which determined their eligibility for this study. This was to exclude subjects who may have had any condition other than SIJD currently or historically that may alter their gait. Trauma, surgery and painful pathological conditions of the lower limbs may all affect gait. Whilst some of these may co-exist and be associated with SIJD, the gait analysis would be made more complex by the possible influence of multiple patterns of dysfunction and would confound the findings. Exclusion criteria were, therefore, any history of fractures, surgery, or diagnosed arthritis of the lower back and/or lower limbs, visceral disease within the pelvic cavity and/or a diagnosed short lower extremity requiring orthotic support. Further exclusions to refine the diagnostic categories were made at examination (see Section 6.5.4).

## 6.3 *Interview*

If they were not excluded by questionnaire, the potential subjects had a short (10 minute) interview with the examiner. Firstly, this was in order to confirm that they should not be excluded. Secondly, it determined whether they had been symptomatic or asymptomatic of lumbar, pelvic, hip or lower limb pain in the last six months, and the location of their symptoms. Following the literature, low back pain was defined as pain located anatomically above L5, and pelvic pain located below L5. For the subject symptom summary, refer to Table 5.

### *6.4 Examination*

The examination was carried out by the researcher, who had 9 years of experience employing and refining these procedures as a clinician and 3 years teaching and critically reviewing them as a lecturer in higher education institutions.

The test procedures employed were (see Section 3.4.2):

- Standing flexion test
- Seated flexion test
- Iliac spring test
- Lumbosacral spring test
- Sacral inferolateral angle spring test
- Pelvic and limb landmark location

### *6.5 Diagnoses*

Two diagnoses were chosen for the study, based on the fact that they are reported in the literature as the most common forms of somatic dysfunction of the SIJ, and in the researcher's experience appear to affect lower limb function. The first is described as a unilateral dysfunction, an anteriorly rotated innominate. In this study subjects with this diagnosis affecting the right side of the pelvis were selected, and the group was labeled the "innominate" group. The second is thought to be a central dysfunction, in that it affects both SIJs and therefore both sides of the pelvis, and is called a forward sacral torsion. In this study, subjects were selected who had a sub category of left on left torsion, and the group was labeled the "sacral" group.

Because both diagnoses appear to create anterior landmarks in the right side of the pelvis and could be confused with one another, and also because one was thought to be purely unilateral in its potential affect on the lower limb and GRFs, the comparison between the two was thought to be an important feature of the study. There is very little literature regarding the sacral diagnosis, which remains more speculative than the innominate diagnosis.

The diagnostic procedure follows the guidelines in osteopathic texts (Greenman, 1989; Mitchell et al., 1979), with the exception of the consideration of false positives from shortened musculature and fused articulations. Based on the researcher's clinical experience, it is plausible that a false positive test resulting from muscular shortening or joint fusion is possible in any palpatory test that assesses reduced motion for joint dysfunction. Subjects were excluded if there was evidence of either of these conditions on physical examination.

### *6.5.1 Innominate*

This diagnosis was category D - somatic dysfunction, subcategory D1 anteriorly rotated innominate (see 3.4.1).

A subject was considered to have this diagnosis if there were reported symptoms of low back or pelvic pain in the preceding 6 months, and an examination revealed:

1 Positive standing flexion test on the right,
2 Negative seated flexion test,
3 Positive iliac spring test on the right,
4 Right ASIS landmark relatively antero-inferior,

5 Right PSIS landmark relatively antero-superior,
6 Right inferior medial malleolus.

### 6.5.2 Sacral

Diagnosis B was category D - somatic dysfunction, subcategory D9a forward sacral torsion (left on left)(see 3.4.1).

A subject was considered to have a sacral diagnosis if there were reported symptoms of low back or pelvic pain in the preceding 6 months, and an examination revealed:

1 Negative standing flexion test,
2 Positive seated flexion test,
3 Negative lumbo-sacral spring test,
4 Left sacral sulcus shallow,
5 Left inferolateral angle on the sacrum posterior,
6 Left inferolateral angle on the sacrum resistant to spring test.

## 6.6 Groupings

The method of grouping the subjects follows, with reference to Figure 40.

### 6.6.1 Control (norm)

Subjects who were negative on the examination and were asymptomatic were assigned to the group "norm".

### *6.6.2 Innominate*

Subjects who were positive for innominate diagnosis on this examination and were symptomatic of low back or pelvic pain in the last 6 months were assigned to the group “innominate”.

### *6.6.3 Sacral*

Subjects who were positive for sacral diagnosis on this examination and were symptomatic of low back or pelvic pain in the last 6 months were assigned to the group “sacral”.

### ***6.6.4 Exclusions*** (refer to Table 6)

Subjects who were negative on this examination and were symptomatic were excluded, as they may have conditions other than SIJD causing pain, and would confound the study; the number of this group was nine.

Subjects who were positive in this examination and were asymptomatic were excluded; the number of this group was three.

Subjects who were positive on some of this examination and symptomatic of low back or pelvic pain in the last 6 months, but who did not fit the criteria for the two diagnoses included in the study, were excluded from the study as they may confound the findings; the number in this group was twelve.

Subjects with false positives on the testing were excluded; the number of subjects in this group was zero.

| **Group** | **Symptom location** | | | | **Symptom duration** | |
|---|---|---|---|---|---|---|
| **(see 6.5)** | **Lowback** | **Pelvic** | **Both** | **Other** | **< 6 months** | **> 6 months** |
| Norm | nil | | | | nil | |
| Innominate | 11 | 7 | 2 | 3 | 3 | 17 |
| Sacral | 14 | 5 | 5 | 9 | 4 | 20 |

**Table 5**

**Summary of subject symptoms characteristics**

| **Exclusion reason** | **Number** |
|---|---|
| Symptomatic negatives | 9 |
| Asymptomatic positives | 3 |
| Symptomatic positives – other category | 12 |

**Table 6**

**Summary of exclusions**

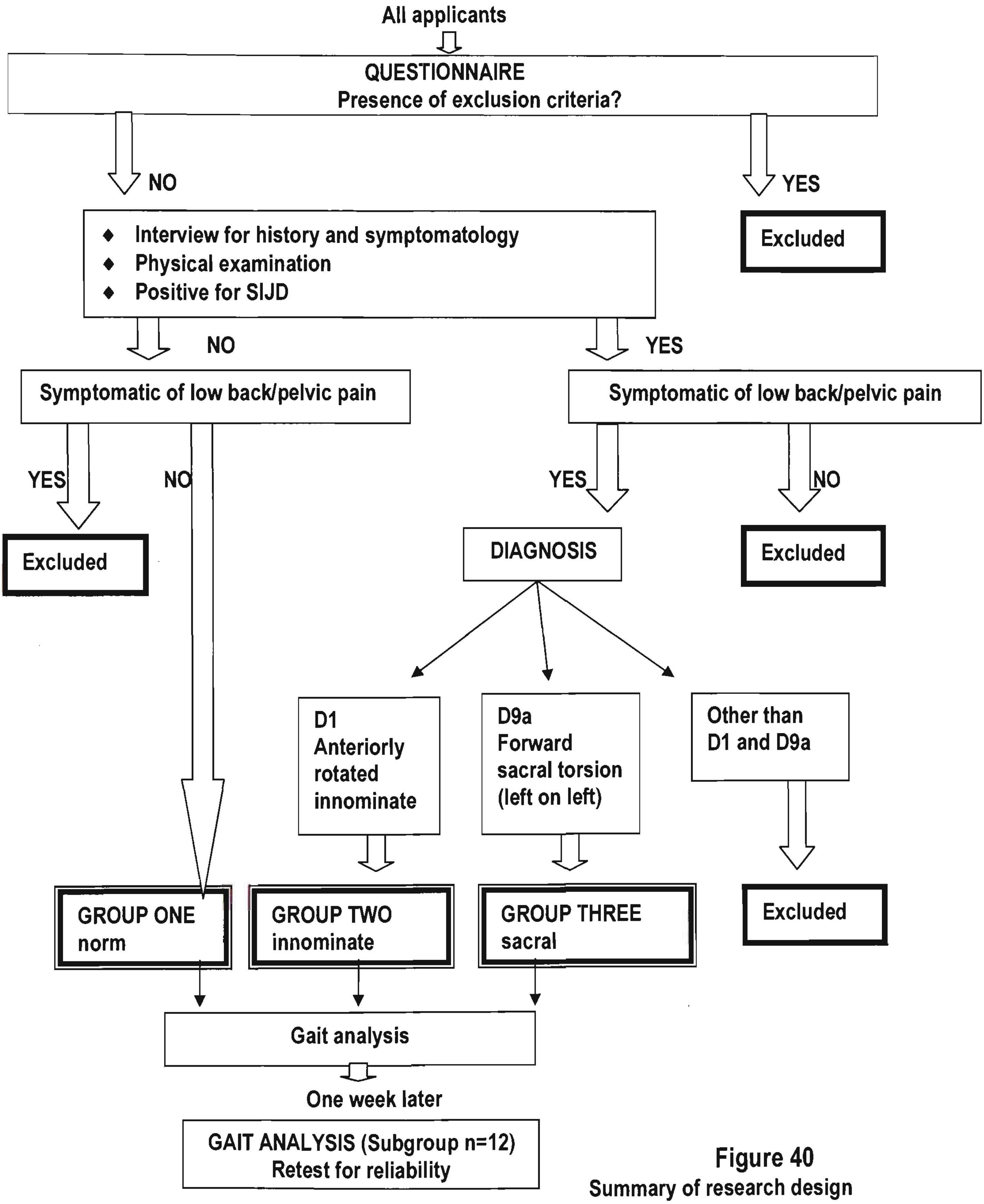


**Figure 40**

Summary of research design

### *6.7 Data Collection*

All subjects were orientated to the 6 metre thin felt tile covered walkway, which was in the centre of a large laboratory with no structural influences to alter their direction. The force platform (AMTI OR6-5) was covered in the same felt and was flush to the floor. Subjects were asked to walk barefoot in one direction until they could reliably contact the platform with one whole foot, looking ahead at a distant object and without targetting or aiming, at a speed of 1.5m/s ± 10%, measured by two photoelectric gates. Subjects varied in reliably landing on the force platform, and took an average of 7.0, 10.0 and 10.7 trials, for the norm, innominate and sacral groups respectively, to attain a natural rhythm and confidence.

Data was collected at a sampling rate of 500 Hz and stored in a 486 computer using BEDAS-2 Biomechanics Data-Acquisition and Analysis Software (Advanced Mechanical Technology Inc., Massachusetts). The program utilised was the Computer Automated Gait Analysis (CAG), which performs an analysis of various gait parameters, listed in Table 7.

Subjects were then asked to walk across the force platform, landing 10 times with their left foot and 10 times with their right foot. Each time they walked at least 5 metres before contacting the force platform. The researcher visually ensured the subject contacted the force platform and also observed the vertical force profile on screen for abnormalities associated with missing the platform. If the subject targetted or missed the platform, this test was discarded until 10 trials were completed for each leg. The order of which leg the subjects first contacted the force platform was randomised with a coin toss.

12 subjects (6 from group norm, 3 each from groups innominate and sacral) were requested to return to the laboratory one week later for repeat examination and gait trials. They received no treatment to the area of the lower back, pelvis or lower limbs in that week. The same examination and gait trials were carried out exactly as before, with another exclusionary criteria employed; that if the diagnosis had changed, it would be recorded, but the gait trials would not proceed.

### *6.8 Measurement parameters*

The parameters measured in this study were the vertical, anteroposterior and mediolateral forces (see section 4.5). These are listed in Table 7.

The normalized figures presented are calculated by dividing the absolute force in Newtons by the body weight in Newtons for the force parameters, and the time in seconds divided by total time for the temporal parameters.

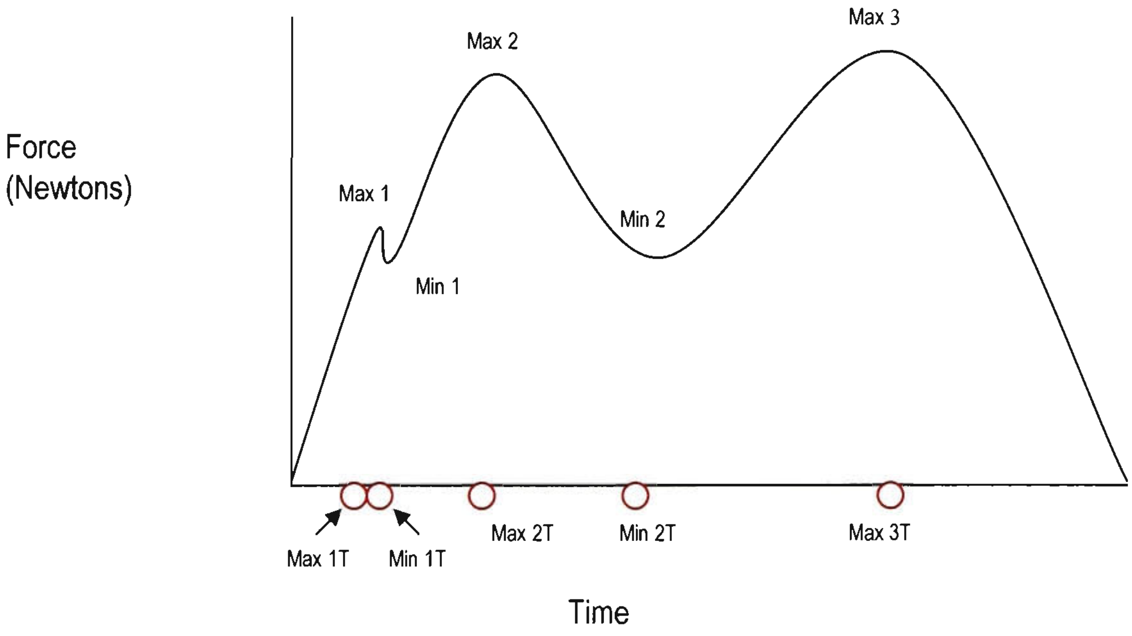
The major features used in calculating the parameters are shown in Figures 41, 42, 43 and 44.

| Component | Parameter | Definition |
|---|---|---|
| **Vertical** | Fz Max1 | First vertical peak (N) |
| | Fz Max1 N | First vertical peak normalised to body weight (N/N) |
| | Fz Max1 I | Impulse up to first vertical peak (N.s) |
| | Fz Max1 mNI | Impulse up to first vertical peak, normalised to body weight and multiplied by 1000 (1000 X N.s/N) |
| | Fz Max1 T | Time of first vertical peak (s) |
| | Fz Max1 TN | Time of first vertical peak, normalised to total time |
| | Fz SI Max1 | Average slope up to the first vertical peak (Fz Max1/Fz Max1T) (N/s) |
| | Fz SI N Max1 | Average slope up to the first vertical peak, normalised to body weight (N/s/N) |
| | Fz Min1 | First vertical trough (N) |
| | Fz Min1 N | First vertical trough normalised to body weight (N/N) |
| | Fz Min1 I | Impulse up to first vertical trough (N.s) |
| | Fz Min1 mNI | Impulse up to first vertical trough, normalised to body weight and multiplied by 1000 (1000 X N.s/N) |
| | Fz Min1 T | Time of first vertical trough (s) |
| | Fz Min1 TN | Time of first vertical trough, normalised to total time |
| | Fz SI Min1 | Average slope up to the first vertical trough (Fz Max1/Fz Max1T) (N/s) |
| | Fz SI N Min1 | Average slope up to the first vertical trough, normalised to body weight (N/s/N) |
| | Fz Max2 | Second vertical peak (N) |
| | Fz Max2 N | Second vertical peak normalised to body weight (N/N) |
| | Fz Max2 I | Impulse up to second vertical peak (N.s) |
| | Fz Max2 mNI | Impulse up to second vertical peak, normalised to body weight and multiplied by 1000 (1000 X N.s/N) |
| | Fz Max2 T | Time of second vertical peak (s) |
| | Fz Max2 TN | Time of second vertical peak, normalised to total time |
| | Fz SI Max2 | Average slope up to the second vertical peak (Fz Max1/Fz Max1T) (N/s) |
| | Fz SI N Max2 | Average slope up to the second vertical peak, normalised to body weight (N/s/N) |
| | Fz Min2 | Second vertical trough (N) |
| | Fz Min2 N | Second vertical trough normalised to body weight (N/N) |
| | Fz Min2 I | Impulse up to second vertical trough (N.s) |
| | Fz Min2 mNI | Impulse up to second vertical trough, normalised to body weight and multiplied by 1000 (1000 X N.s/N) |
| | Fz Min2 T | Time of second vertical trough (s) |
| | Fz Min2 TN | Time of second vertical trough, normalised to total time |
| | Fz SI Min2 | Average slope up to the second vertical trough (Fz Max1/Fz Max1T) (N/s) |
| | Fz SI N Min2 | Average slope up to the second vertical trough, normalised to body weight (N/s/N) |
| | Fz Max3 | Third vertical peak (N) |
| | Fz Max3 N | Third vertical peak normalised to body weight (N/N) |
| | Fz Max3 I | Impulse up to third vertical peak (N.s) |
| | Fz Max3 mNI | Impulse up to third vertical peak, normalised to body weight and multiplied by 1000 (1000 X N.s/N) |
| | Fz Max3 T | Time of third vertical peak (s) |
| | Fz Max3 TN | Time of third vertical peak, normalised to total time |
| | Fz SI Max3 | Average slope up to the third vertical peak (Fz Max1/Fz Max1T) (N/s) |
| | Fz SI N Max3 | Average slope up to the third vertical peak, normalised to body weight (N/s/N) |
| | Fz Imp | Total mpulse of the vertical force (N.s) |
| **Antero-posterior** | Max Prop | Maximum negative Fy force (N) |
| | Max Prop N | Maximum negative Fy force, normalised to body weight (N/N) |
| | MP Time | Time of maximum negative Fy force (s) |
| | MP Time N | Time of maximum negative Fy force, normalised to total time |
| | Avg Prop | Average negative Fy force (N) |
| | Avg Prop N | Average negative Fy force, normalised to body weight (N/N) |
| | Prop Imp | Total negative Fy impulse (N.s) |
| | Prop mNI | Total negative Fy impulse, normalised to body weight and multiplied by 1000 (1000 X N.s/N) |
| | Max Brake | Maximum positive Fy force (N) |
| | Max Brake N | Maximum positive Fy force, normalised to body weight (N/N) |
| | MB Time | Time of maximum positive Fy force (s) |
| | MB Time N | Time of maximum positive Fy force, normalised to total time |
| | Avg Brake | Average positive Fy force (N) |
| | Avg Brake N | Average positive Fy force, normalised to body weight (N/N) |
| | Brake Imp | Total positive Fy impulse (N.s) |
| | Brake mNI | Total positive Fy impulse, normalised to body weight and multiplied by 1000 (1000 X N.s/N) |
| | Fy Avg | Fy average |
| | Fy Avg N | Fy average, normalised to total Fy (N/N) |
| | Fy Imp | Total Fy impulse (N.s) |
| **Mediolateral** | Fx Max | Maximum Fx force (N) |
| | Fx Max N | Maximum Fx force, normalised to body weight (N/N) |
| | Max Time | Time of maximum Fx (s) |
| | Max Time N | Time of maximum Fx, normalised to total time |
| | Fx Min | Minimum Fx force (N) |

| Component | Parameter | Definition |
|---|---|---|
| **Mediolateral (cont)** | Fx Min N | Minimum Fx force (N), normalised to body weight (N/N) |
| | Min Time | Time of minimum Fx (s) |
| | Min Time N | Time of minimum Fx, normalised to total time |
| | Fx Avge | Average Fx force (N) |
| | Fx Avge N | Average Fx force, normalised to body weight (N/N) |
| | Fx Imp | Total Fx impulse (N.s) |
| | Fx Imp mNI | Total Fx impulse, normalised to body weight and multiplied by 1000 (1000 X N.s/N) |
| | X Excur | Total displacement of X centre of pressure |
| | 30% Force | Fx at 30% total time (N) |
| | 30% Force N | Fx at 30% total time, normalised to body weight (N/N) |
| | 30% Exc | Displacement of X centre of pressure at 30% total time |

## Table 7

**Gait parameter definitions** (Advanced Medical Technology, 1993)



## Figure 41

**Vertical parameters** (Advanced Medical Technology, 1993)

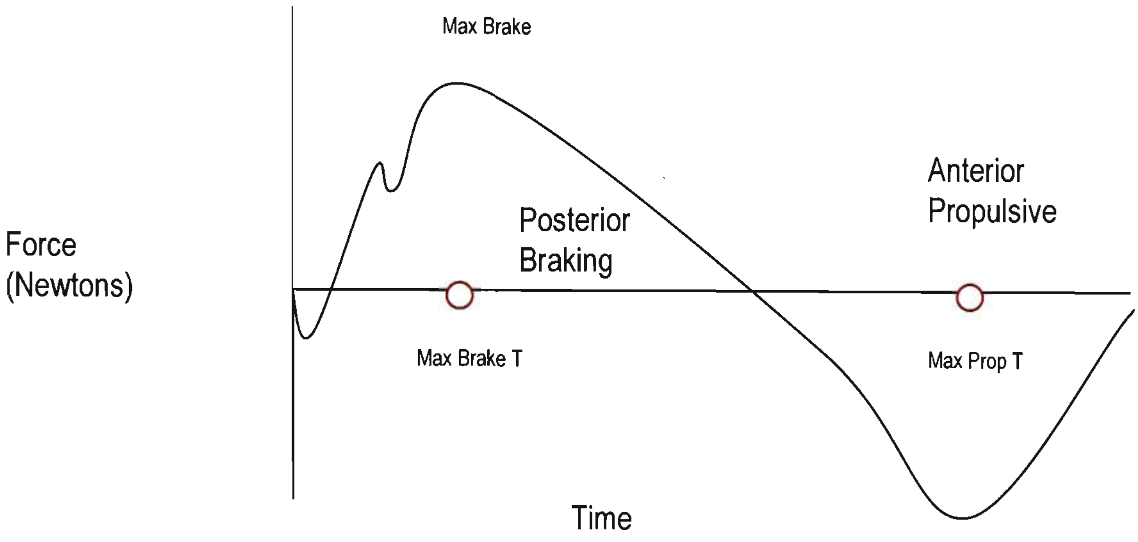


**Figure 42**

**Anterior-Posterior parameters** (Advanced Medical Technology, 1993)

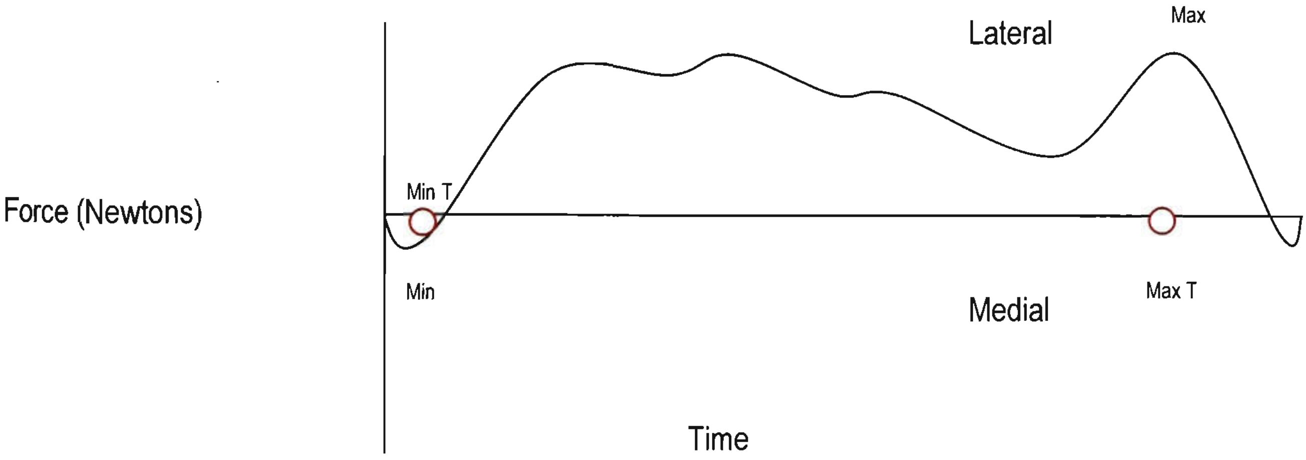


**Figure 43**

**Medial-lateral parameters** (Advanced Medical Technology, 1993)

Every trial was observed for the consistency of measurement and calculation, and certain irregularities were discovered. Some vertical force results showed the relatively small heelstrike transient (see Section 4.5), which was detected by the analysis software. However, for some subjects it was unable to detect this first peak in the force data, despite having a small contour on the graphed profile. Despite adjusting the software sensitivity, it was unable to be adjusted sufficiently to capture this feature for all subjects. So it was decided that these would be excluded. After this process, the average number of trials for each subject was 18.8 (9.4 for each leg) and each subject had a minimum of seven trials for each leg completed.

# *7 Statistical Analysis*

## *7.1 Introduction*

The statistical approach utilised was a multilevel analysis, a form of multiple regression designed for repeated measures data sets. This was chosen because it is considered to be an improvement on traditional methods, as the data is analysed in its hierachical (multilevel) form, and therefore variation among the individuals around the overall mean is recognised and analysed (Winter et al, 2001). Whilst standard analysis of variance procedures accommodate two levels of nesting (subject and within-subject), they do not easily accommodate the three levels of variance nesting in this study (subject, week, trial). In the multilevel approach each of the levels of variance are obtained in the presence of the other levels. Moreover, the design does not have to be balanced in the sense that all subjects do not have to complete the same number of trials (Snidjers and Bosker, 1999). This factor was important in this study, as there was known to be different numbers of trials between individuals.

Multilevel modelling is being used increasingly in sport and exercise science, particularly where the effects of multiple variables have to be teased out and explained (eg Armstrong et al, 1999; De Ste Croix et al, 2001). Models and estimates of this type are described by Hox (1994), Goldstein (1995), and Snijders and Bosker (1999).

For further detail of the statistical models, refer to Appendix 3. The software utilised in this study was MLwiN version 1.10.007, Multilevel Models Project (Institute of Education, University of London, UK).

The dependent variables in this study were the various measurements described in 6.7. The statistical analysis commenced with comparing 12 subjects' data from one week to the next, in order to estimate variability based primarily on change over time. The main analysis compared the differences between legs (asymmetry) between groups, in order to estimate any significant differences between groups on right leg to left leg asymmetry.

### *7.2 Variability over time*

The goal of this first analysis was to estimate week by week variation in the force platform parameters. The rationale for this was to have the weekly variation estimates available in order to contribute to the interpretation of results in the main analysis (see Section 7.3). Previous studies have completed preliminary variability analysis before comparing subjects on the force platform data (Herzog et al., 1988; Robinson et al., 1987).

A total of 225 trials were analysed; an average of 9.4 trials for each leg in 12 subjects for both week one and week two. Estimates were obtained of the absolute value of the week to week variance, the standard error of that variance, and of the total residual variance (as the sum of the estimated variances of trials, weeks and subjects). The week to week variance was considered significant if the estimate was 1.96 or more times its standard error (SE), which is equivalent to $p \leq .05$, and the proportion of total random variance due to weekly variation, obtained by division, was higher than the other variance factors, trials and leg.

### *7.3 Main analysis*

In distinction from the week to week model fitted above, the data for the main analysis were analysed as occuring at two hierarchically organised levels: *trials (within subject)* and *between subject.*

Three models were analysed:

- model one, the variance components at the subject and trial levels;
- model two, comparing group norm with groups innominate and sacral,
- model three, comparing group innominate with groups sacral and norm (the comparison between group norm and innominate having already been analysed in model 2).

The objective was to obtain estimates for the three pairwise group comparisons. A total of 1297 trials were analysed: 9.4 trials for each leg in 69 subjects.

Because of the high number of tests completed, the possibility of a Type 1 error exists, that of finding significance where it does not exist. Because there was not any biomechanical evidence of these diagnostic categories, nor any evidence of how

GRF may be associated with them, there was no a priori theoretical possibilities. In this study, the goal was to explore the data, looking for credible relationships to be confirmed in future research, and to put some restriction on which relationships would be worthy of further study.

## *8 Results*

### *8.1 Variability over time*

The week to week analysis demonstrated that the physical examination procedure with one examiner was consistent, with all subjects returning with the same findings. The variances of the GRFs from week to week are discussed for each parameter in Section 8.2, and are reported in full in Appendix 2.

15 of the 76 variables were found to have significant variation between weeks, and/or to have the weekly variation the highest proportion of the total variance (refer to Table 8). Parameters listed in Table 8 include those where the component of variance and its standard error were calculated as zero, or where the standard error is high, or where the proportion of variance due to weekly variation was higher than trial and leg.

| Parameter | Variance component | Standard Error | Total variance | Proportion (%) due to weekly variance |
|---|---|---|---|---|
| Fz Max 1 I | 0 | 0 | 2.5661 | 11.47 |
| Fz Max 1 T | 0 | 0 | 2.23 | 0 |
| Fz Min 1 mNi | 0.011 | 0.007 | 0.14 | 7.8 |
| Fz Min 1 T | 0.006 | 0.014 | 0.507 | 1 |
| Fz Min 1 TN | 0.046 | 0.046 | 1.31` | 3.4 |
| Fz Min 1 SI | 930276 | 507779 | 20015834 | 4.6 |
| Fz Min1 SIN | 1.608 | 0.883 | 37.1 | 4.3 |
| Fz Max 2 mNi | 0.078 | 0.044 | 0.858 | 9 |
| Fz Max 2 T | 0.117 | 0.059 | 1.61 | 7.2 |
| Fz Max 2 TN | 0.149 | .01 | 0.477 | 3 |
| Fz Max 2 SIN | 17.74 | 3.62 | 18.25 | 97 |
| Fx Avg | 71.26 | 22.90 | 176.19 | 40 |
| Fx Avg N | 0.136 | 0.044 | 0.325 | 41 |
| Fx Imp | 27.57 | 8.86 | 67.44 | 40 |
| Fx mNi | 0.625 | 0.2 | 1.355 | 46 |

**Table 8**

**Parameters with high variability**

As the subject numbers in the week to week analysis were small (ie 6 in the norm group and 3 in each positive group) and the literature is inconclusive regarding variation of gait over time, it was decided to discuss the reliability data in the context of any significant results in each parameter, rather than exclude them from the main analysis.

## *8.2 Main analysis*

The effects of primary interest are the group by leg interaction effects measuring the differences between groups on the difference between legs (asymmetry). It was considered that there would be a level of asymmetry (differences between legs) in the normal population (see section 4.3), and therefore it would be best to measure this asymmetry, and compare it between groups. The asymmetry measure used in the current study was a simple difference between legs, similar to the symmetry ratio used in previous studies (Sadeghi et al., 2000), which simply divided the right leg measure by the left leg measure. This is in contrast to the Symmetry Index described in 4.7.2 (Herzog et al, 1987; Robinson et al., 1987), which measured this difference by dividing it by half the sum of the two legs, and expressed as a percentage. Because this index reports differences against their average value, it has limitations in reporting larger asymmetries and also when the asymmetry is small relative to the measure (Sadeghi et al., 2000).

The following estimates, and their significances were obtained:

- (The difference between legs in group innominate) minus (the difference between legs in group norm),
- (The difference between legs in group sacral) minus (the difference between legs in group norm),
- (The difference between legs in group sacral) minus (the difference between legs in group innominate).

### *8.2.1 Insignificant results*

Table 9 lists the parameters that had insignificant findings.

| Number | Parameter | Difference between asymmetries | | | | | |
|---|---|---|---|---|---|---|---|
| | | Norm Vs Innominate | SE | Norm Vs Sacral | SE | Innominate Vs Sacral | SE |
| | **Vertical** | | | | | | |
| 1 | Fz Max 1 I | -0.06 | 0.32 | 0.08 | 0.30 | 0.14 | 0.32 |
| 2 | Fz Max 1 mNi | -0.0002 | 0.0004 | 0.0001 | 0.0004 | 0.0004 | 0.0004 |
| 3 | Fz Max 1 T | 0.00008 | 0.0006 | -0.0002 | 0.0006 | -0.0003 | 0.0006 |
| 4 | Fz Max 1 TN | 0.0008 | 0.001 | -0.0002 | 0.001 | -0.0009 | 0.001 |
| 5 | Fz Min 1 I | 0.46 | 0.55 | -0.36 | 0.52 | -0.82 | 0.55 |
| 6 | Fz Min 1 mNi | 0.0005 | 0.0007 | -0.0003 | 0.0007 | -0.0009 | 0.0007 |
| 7 | Fz Max 2 I | -0.45 | 0.91 | -0.83 | 0.86 | -0.37 | 0.91 |
| 8 | Fz Max 2 mNi | -0.0003 | 0.001 | -0.001 | 0.001 | -0.0009 | 0.001 |
| 9 | Fz Max 2 T | -0.001 | 0.001 | -0.0024 | 0.0014 | -0.001 | 0.001 |
| 10 | Fz Max 2 TN | -0.001 | 0.001 | -0.0024 | 0.0013 | -0.002 | 0.002 |
| 11 | Fz Min 2 | -2.46 | 3.17 | -1.1 | 2.9 | 1.36 | 3.18 |
| 12 | Fz Min 2 N | -0.001 | 0.004 | -0.001 | 0.004 | -0.00007 | 0.004 |
| 13 | Fz Max 3 I | 0.54 | 1.33 | 1.18 | 1.25 | 0.64 | 1.34 |
| 14 | Fz Max 3 mNi | 0.0007 | 0.001 | 0.0006 | 0.001 | -0.00008 | 0.001 |
| 15 | Fz Max 3 T | -0.0024 | 0.0017 | 0.0001 | 0.001 | 0.0026 | 0.0017 |
| | **Anteroposterior** | | | | | | |
| 16 | Max Brake | 5.47 | 2.45 | 1.65 | 2.30 | -3.8 | 2.4 |
| 17 | Max Brake N | 0.005 | 0.003 | 0.001 | 0.003 | -0.004 | 0.003 |
| 18 | Ave Brake | 1.32 | 0.92 | 0.13 | 0.87 | -1.19 | 0.92 |
| 19 | Ave Brake N | 0.001 | 0.001 | -0.0001 | 0.001 | -0.001 | 0.001 |
| 20 | Ave Brake I | 0.64 | 0.36 | 0.06 | 0.34 | -0.58 | 0.36 |
| 21 | Ave Brake mNi | 0.0007 | 0.0004 | 0.000007 | 0.0004 | -0.0007 | 0.0004 |
| 22 | Max Prop T | -0.001 | 0.001 | 0.001 | 0.001 | 0.002 | 0.0017 |
| 23 | Fy Ave | 0.15 | 0.83 | -0.90 | 0.78 | -1.06 | 0.83 |
| 24 | Fy Ave N | -0.0002 | 0.001 | -0.001 | 0.001 | -0.001 | 0.001 |
| 25 | Fy Imp | 0.13 | 0.50 | -0.58 | 0.47 | -0.72 | 0.51 |
| | **Mediolateral** | | | | | | |
| 26 | Fx Max | 1.86 | 1.21 | 1.99 | 1.18 | 0.13 | 1.26 |
| 27 | Fx Max N | 0.0024 | 0.0016 | 0.0026 | 0.0015 | 0.0001 | 0.001 |
| 28 | Fx Max T | 0.003 | 0.01 | 0.024 | 0.018 | 0.027 | 0.019 |
| 29 | Fx Max TN | -0.01 | 0.03 | 0.03 | 0.02 | 0.04 | 0.03 |
| 30 | Fx Min T | -0.006 | 0.004 | 0.001 | 0.003 | 0.007 | 0.004 |
| 31 | Fx Min TN | -0.01 | 0.007 | 0.002 | 0.006 | 0.013 | 0.007 |
| 32 | Fx Ave | -0.02 | 0.73 | -0.14 | 0.69 | -0.12 | 0.73 |
| 33 | Fx Ave N | 0.00003 | 0.0009 | -0.00008 | 0.0009 | -0.0001 | 0.0009 |
| 34 | Fx Imp | -0.075 | 0.45 | -0.05 | 0.42 | 0.01 | 0.45 |
| 35 | Fx mNi | -0.00001 | 0.0006 | 0.00001 | 0.0005 | 0.00002 | 0.0006 |
| 36 | X Excur | -0.17 | 0.38 | -0.04 | 0.35 | 0.12 | 0.38 |
| 37 | 30 Force | -0.40 | 1.06 | -0.57 | 1.00 | -0.16 | 1.06 |
| 38 | 30 Force N | -0.0003 | 0.001 | -0.0009 | 0.001 | -0.0005 | 0.001 |
| 39 | 30 Excur | -0.01 | 0.14 | 0.03 | 0.13 | 0.05 | 0.14 |

## Table 9

### Insignificant results

### 8.2.2 *Significant results*

These results will be organised into sections:

A first table with;

- Column one with descriptions of the parameters in terms of group and leg,
- Column two is the data for each group and leg, and the 95% confidence interval (CI).

Bar graphs for the variable by group and leg with error bars based on the 95% CI.

A second table reports;

- Estimates of the differences between asymmetries between pairs of groups
- Standard errors
- P values (NA denotes not applicable, as result not significant).

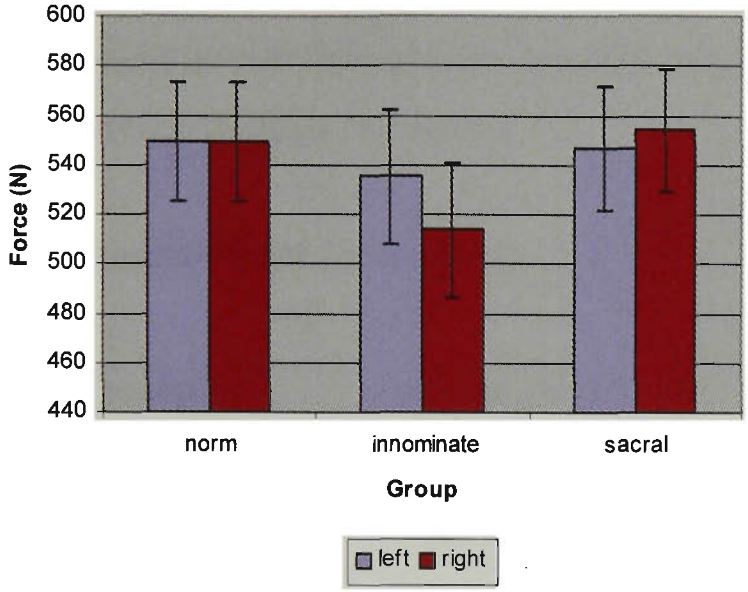
Summary of the variable performance; including

- quantitative descriptions of the differences in asymmetries,
- reliability of the variable as measured by the number of standard errors (xSE), and
- variability over time.

#### *8.2.2.1 Vertical (Fz) parameters*

#### *Fz MAX1- heelstrike transient*

| **Description** | **Measure (95% CI)** |
|---|---|
| Norm left leg | 549.24 (48.49) |
| Innominate left leg | 535.32 (54.29) |
| Sacral left leg | 546.81 (49.49) |
| Norm right leg | 549.41 (48.49) |
| Innominate right leg | 513.77 (54.24) |
| Sacral right leg | 553.99 (49.47) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -21.87 | 7.78 | .002 |
| Norm Vs sacral | 7.01 | 7.32 | NA |
| Innominate Vs sacral | 28.89 | 7.81 | NA |

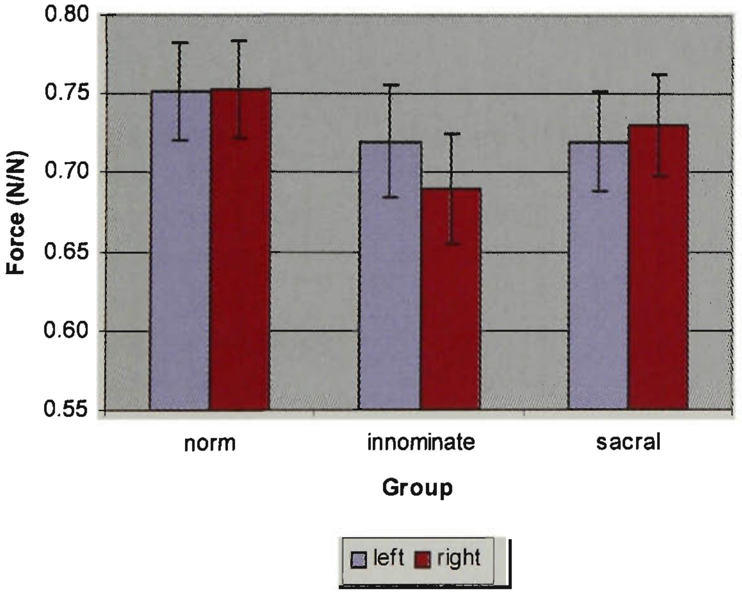
This parameter is the Fz “heelstrike transient” early in loading response that may last 10-20ms. It is expressed in Newtons.

The asymmetry between legs in the innominate group is significantly different from the asymmetry between legs in both norm and sacral groups, which did not differ significantly from each other. This can be seen in the second table where the mean difference between the asymmetries of the norm and innominate groups is greater than 1.96 its SE (column 3), whereas for the norm to sacral groups and the innominate to sacral it is not. This transient vertical peak was lower in the right leg compared to the left in the innominate group (-21.7 N, 3.73 X SE). The right leg is the positive side in the innominate group.

The variation of this parameter over time was low (est≥1.96SE) and was a minor component of total variance (8.2%) (see Appendix 2).

### *Fz MAX1N (N/N) - normalized heelstrike transient*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | .752 (.062) |
| Innominate left leg | .720 (.069) |
| Sacral left leg | .727 (.063) |
| Norm right leg | .753 (.062) |
| Innominate right leg | .690 (.069) |
| Sacral right leg | .735 (.063) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -0.031 | 0.01 | .0009 |
| Norm Vs sacral | 0.007 | 0.009 | NA |
| Innominate Vs sacral | 0.037 | 0.01 | .0001 |

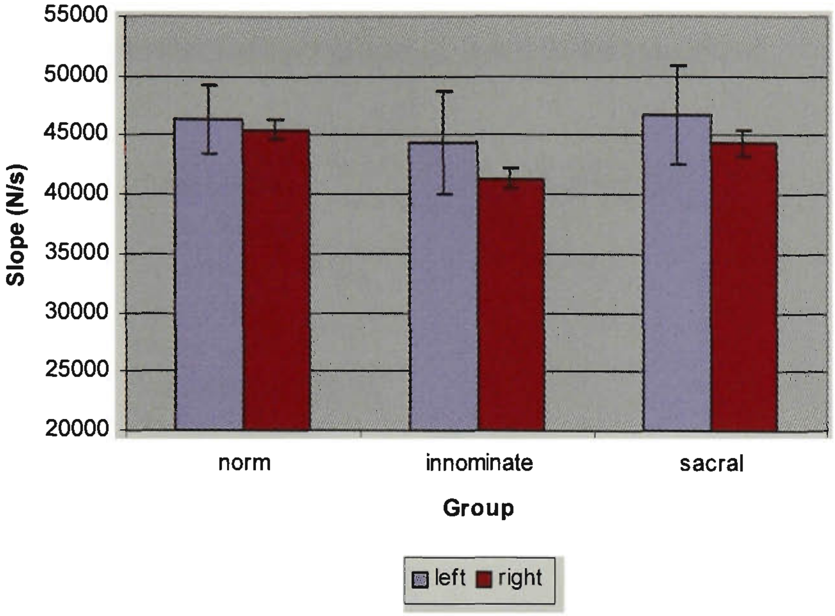
This parameter is the Fz “heelstrike transient” normalized to body weight.

The asymmetry between legs in the innominate group is significantly different from the asymmetry between legs in both norm and sacral groups. This can be seen in the second table where the mean difference between the asymmetries of the norm and innominate groups is greater than 1.96 its SE (column 3), and also for the innominate and sacral groups. This transient vertical peak was lower in the right leg compared to the left (-0.03 N/N, 3.81 X SE), but higher than the sacral group (.037 N/N, 3.7 X SE). The right leg is the positive side in the innominate group.

The variation of this parameter over time was low (est≥1.96SE) and was a minor component of total variance (11.47%) (see appendix 2).

### *Fz SI MAX 1 (N/s) – slope to heelstrike transient*

| ***Description*** | ***Measure (95% CI)*** |
|---|---|
| Norm left leg | 46315 (5787) |
| Innominate left leg | 44350 (8680) |
| Sacral left leg | 46675 (8269) |
| Norm right leg | 45524 (1515) |
| Innominate right leg | 41358 (1716) |
| Sacral right leg | 44342 (2154) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -2201 | 1169 | NA |
| Norm Vs sacral | 782 | 1099 | NA |
| Innominate Vs sacral | 2984 | 1173 | .005 |

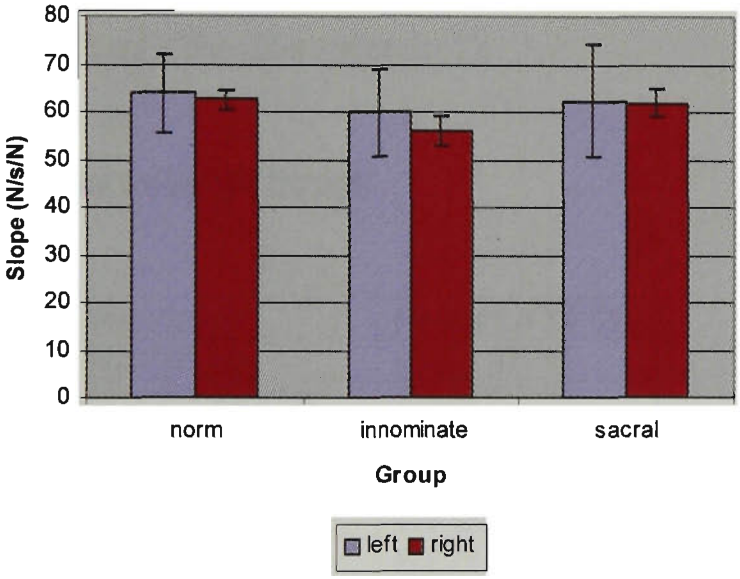
This parameter is the slope to the Fz “heelstrike transient”.

The asymmetry between legs in the innominate group is significantly different from the asymmetry between legs in the sacral group. This can be seen in the second table where the mean difference between the asymmetries of the innominate and sacral groups is greater than 1.96 its SE (column 3). This slope to the transient vertical peak was higher in the right leg compared to the left (2984 N/s, 2.54 X SE). The right leg is the positive side in the innominate group.

The variation of this parameter over time was low (est≥1.96SE) and was a minor component of total variance (9%) (see appendix 2).

## *Fz SI N Max 1 (N/s N)- normalized slope to heelstrike transient*

| ***Description*** | ***Measure (95% CI)*** |
|---|---|
| Norm left leg | 63.79 (8.23) |
| Innominate left leg | 59.87 (12.36) |
| Sacral left leg | 62.27 (11.77) |
| Norm right leg | 62.53 (2.09) |
| Innominate right leg | 56.04 (2.37) |
| Sacral right leg | 59.56 (3.17) |



| **Asymmetry comparison** | **Difference between asymmetries** | **SE** | **P** |
|---|---|---|---|
| Norm Vs innominate | -2.57 | 1.62 | NA |
| Norm Vs sacral | 0.95 | 1.52 | NA |
| Innominate Vs sacral | 3.52 | 1.62 | .015 |

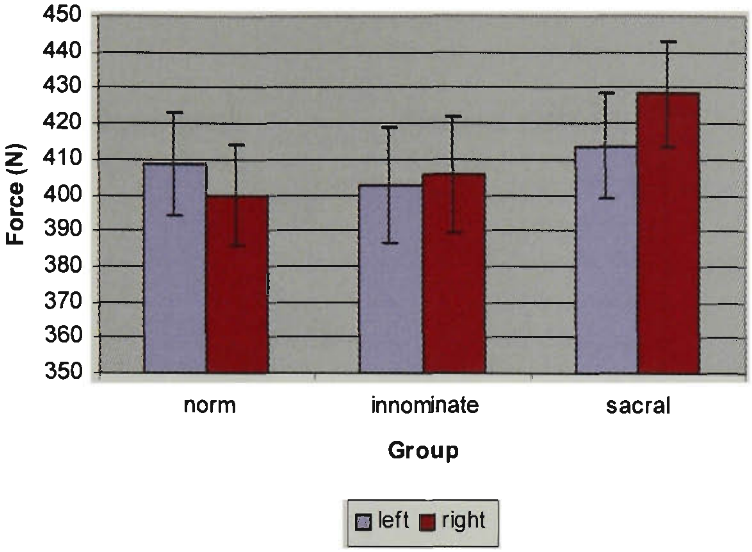
This parameter is the slope to the Fz "heelstrike transient" normalized to body weight.

The asymmetry between legs in the innominate group is significantly different from the asymmetry between legs in the sacral group. This can be seen in the table where the mean difference from the constant for the innominate group right leg (column 2) is greater than 1.96 its SE (column 3), whereas for the norm and sacral groups it is not. This slope to the transient vertical peak was higher in the right leg compared to the left (2984 N/s, 2.54 X SE). The right leg is the positive side in the innominate group.

The variation of this parameter over time was low (est≥1.96SE) and was a minor component of total variance (9%) (see appendix 2).

### *Fz MIN1 (N) - heelstrike transient trough*

| ***Description*** | ***Measure (95% CI)*** |
|---|---|
| Norm left leg | 408.77 (28.79) |
| Innominate left leg | 402.54 (32.19) |
| Sacral left leg | 413.5 (29.38) |
| Norm right leg | 399.98 (28.79) |
| Innominate right leg | 405.886 (32.22) |
| Sacral right leg | 428.29 (29.36) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 12.13 | 5.81 | .018 |
| Norm Vs sacral | 23.58 | 5.46 | 0.000008 |
| Innominate Vs sacral | 11.45 | 5.83 | .024 |

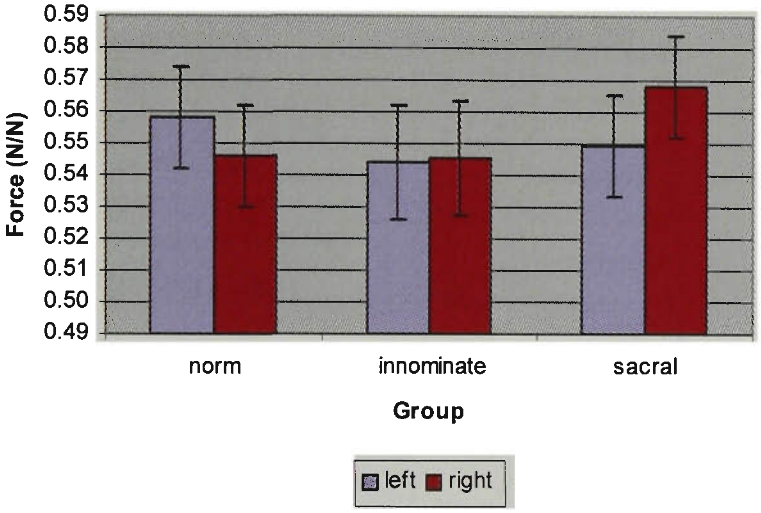
This parameter is the first minimum after the Fz "heelstrike transient" early in loading response (see Figure 42). It is expressed in Newtons.

The asymmetry between legs in the sacral group, with the right leg higher than the left (14.8 N, 3.82 X SE) is significantly different from the asymmetry between legs in the normal group, which was significant but in the opposite direction (-8.8 N, 2.28 X SE). The innominate group had no significant asymmetry.

The variation of this parameter over time was low (est>1.96SE) and was a minor component of total variance (6%).

### *Fz MIN1N (N/N)- normalized heelstrike transient trough*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | .558 (.031) |
| Innominate left leg | .544 (.035) |
| Sacral left leg | .549 (.032) |
| Norm right leg | .546 (.031) |
| Innominate right leg | .545 (.035) |
| Sacral right leg | .568 (.032) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 0.01 | 0.007 | NA |
| Norm Vs sacral | 0.03 | 0.007 | .000009 |
| Innominate Vs sacral | 0.01 | 0.007 | NA |

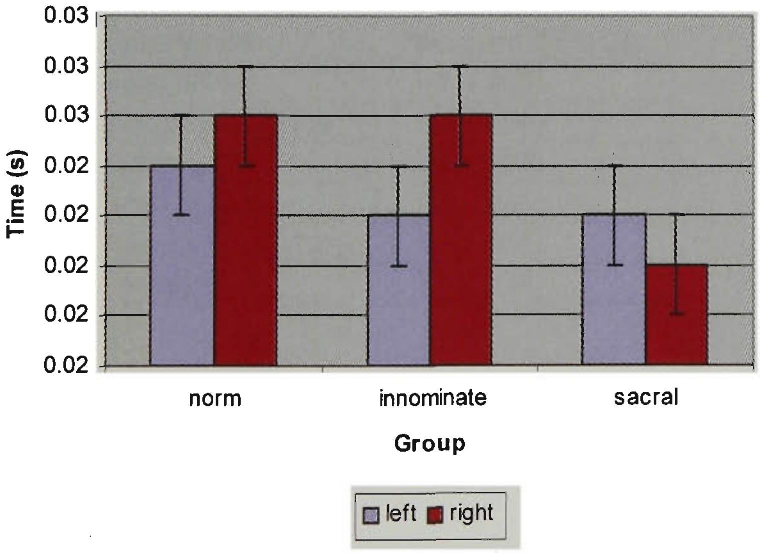
This parameter is the first minimum after the Fz "heelstrike transient" early in loading response (see Figure 29) normalized to body weight.

As shown in the non-normalised results (8.2.3), the asymmetry between legs in the sacral group, with the right leg higher than the left (0.02 NN, 4.0 X SE) is significantly different from the asymmetry between legs in the norm group, which was significant but in the opposite direction (-.012 NN, 2.4 X SE). The innominate group had no significant asymmetry.

The variation of this parameter over time was low (est>1.96SE) and was a minor component of total variance (4.5%).

### *Fz Min 1 T (s)- time to heelstrike transient trough*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | .024 (.001) |
| Innominate left leg | .023 (.001) |
| Sacral left leg | .023 (.001) |
| Norm right leg | .025 (.001) |
| Innominate right leg | .025 (.001) |
| Sacral right leg | .022 (.001) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 0.0012 | 0.001 | NA |
| Norm Vs sacral | - 0.0015 | 0.001 | NA |
| Innominate Vs sacral | - 0.0028 | 0.001 | 0.02 |

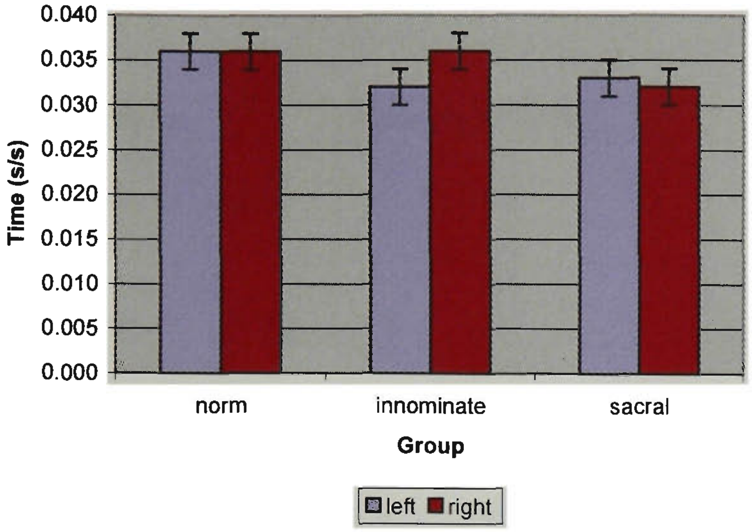
This parameter is the time of the first Fz minimum after the "heelstrike transient" early in loading response normalized to total stance time.

The asymmetry between legs in the innominate group, with the right leg higher than the left (0.0019s, 2.3 X SE) is significantly different from the asymmetry between legs in the sacral group, which was significant with the right leg less than the left (-0.0027, 2.8 X SE). The norm group asymmetry was insignificant.

The variation of this parameter over time was high (est<1.96SE), therefore it must be considered unreliable, although it was a minor component of the total variance (1%).

### *Fz MIN1 TN (s/s)- normalized time to heelstrike transient trough*

| **Description** | **Measure (95% CI)** |
|---|---|
| Norm left leg | .036 (.004) |
| Innominate left leg | .032 (.004) |
| Sacral left leg | .033 (.004) |
| Norm right leg | .036 (.004) |
| Innominate right leg | .036 (.004) |
| Sacral right leg | .032 (.004) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 0.0025 | 0.001 | .006 |
| Norm Vs sacral | -0.002 | 0.0017 | NA |
| Innominate Vs sacral | -0.004 | 0.001 | .00003 |

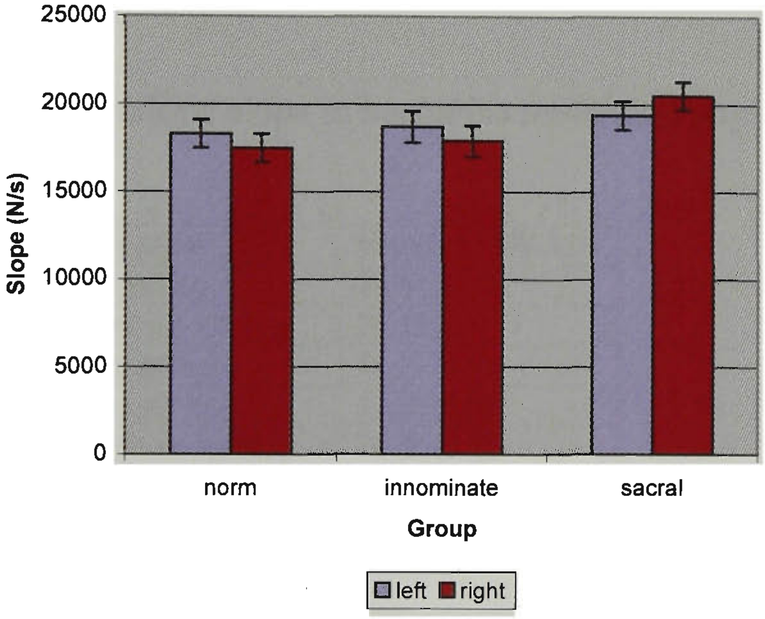
This parameter is the time of the first Fz minimum after the “heelstrike transient” early in loading response normalized to total stance time.

The asymmetry between legs in the innominate group, with the right leg higher than the left (0.0031s/s, 2.38 X SE) is significantly different from the asymmetry between legs in the norm and sacral groups, which were insignificant.

The variation of this parameter over time was high (est<1.96SE), and the inter-trial variability was higher than inter-subject variability; therefore it must be considered unreliable, although it was a minor component of the total variance (3.4%).

### *Fz SI MIN1 (N/s)- slope to heelstrike transient trough*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 18292 (1592) |
| Innominate left leg | 18719 (1780) |
| Sacral left leg | 19386 (1624) |
| Norm right leg | 17489 (1592) |
| Innominate right leg | 17913 (1784) |
| Sacral right leg | 20507 (1622) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -3.29 | 525 | NA |
| Norm Vs sacral | 1923 | 494 | .00005 |
| Innominate Vs sacral | 1927 | 527 | .0001 |

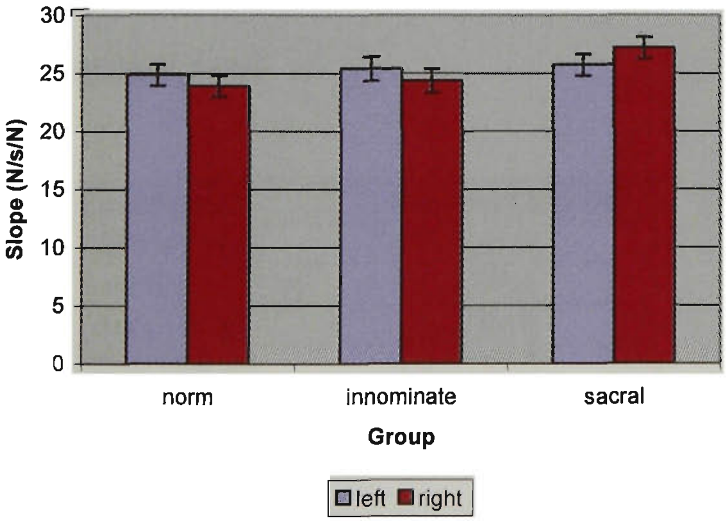
This parameter is the average slope up to the first vertical minimum of the "heelstrike transient" early in loading response expressed in Newtons per second.

The asymmetry between legs in the sacral group, with the right leg higher than the left (1120N/s, 3.19 X SE) is significantly different from the asymmetry between legs in norm group (-803N/s, 2.3 X SE) and innominate group (-806.2N/s, 2 X SE), which were significant but in the opposite direction (-.012 NN, 2.4 X SE).

The variation of this parameter over time was high (est<1.96SE), and therefore has questionable reliability, although it was a minor component of the total variance (4.6%).

### *Fz SI N MIN1 (N/s/N)- normalized slope to heelstrike transient trough*

| **Description** | **Measure (95% CI)** |
|---|---|
| Norm left leg | 24.843 (1.9) |
| Innominate left leg | 25.39 (2.1) |
| Sacral left leg | 25.70 (1.9) |
| Norm right leg | 23.86 (1.9) |
| Innominate right leg | 24.35 (2.1) |
| Sacral right leg | 27.16 (1.9) |



| **Asymmetry comparison** | **Difference between asymmetries** | **SE** | **P** |
|---|---|---|---|
| Norm Vs innominate | -0.06 | 0.74 | NA |
| Norm Vs sacral | 2.47 | 0.69 | .0002 |
| Innominate Vs sacral | 2.52 | 0.74 | .0003 |

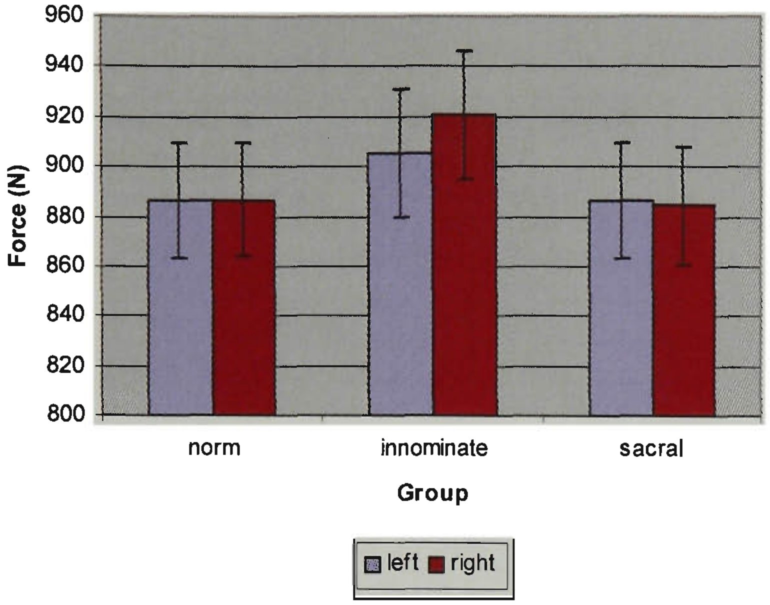
This parameter is the average slope up to the first vertical minimum of the "heelstrike transient" early in loading response normalized to body weight.

The asymmetry between legs in the sacral group, with the right leg higher than the left (1.48N/s, 3 X SE) is significantly different from the asymmetry between legs in the norm group (-0.99N/s, 2 X SE), which was significant but in the opposite direction. The innominate group had insignificant asymmetry.

The variation of this parameter over time was high (est<1.96SE), and the inter-trial variability was higher than the inter-subject variability; therefore it has questionable reliability, although it was a minor component of the total variance (4.3%).

### *Fz MAX2 (N) – first maximal peak*

| **Description** | **Measure (95% CI)** |
|---|---|
| Norm left leg | 886.4 (45.5) |
| Innominate left leg | 905.3 (50.8) |
| Sacral left leg | 886.1 (46.4) |
| Norm right leg | 886.5 (45.4) |
| Innominate right leg | 920.8 (50.9) |
| Sacral right leg | 884.3 (46.4) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 15.48 | 4.97 | .0009 |
| Norm Vs sacral | -1.8 | 4.67 | NA |
| Innominate Vs sacral | -17.27 | 4.99 | .0003 |

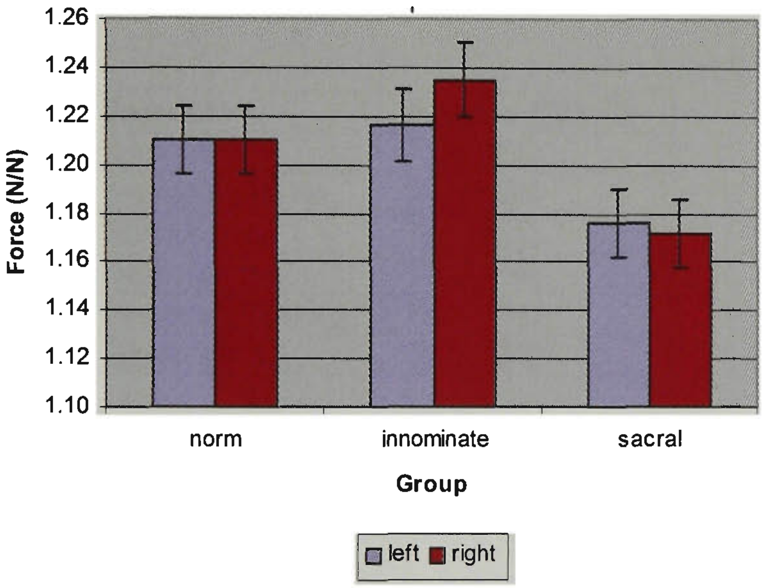
This parameter represents the first peak of the typically biphasic GRF, and is directly related to loading response where the COG moves over the stance limb and is accelerating upwards. It is expressed in Newtons.

The asymmetry between legs in the innominate group, with the right leg higher than the left (15.55N, 4.2 X SE), is significantly different from the asymmetry between legs in the norm and sacral groups, which were insignificant.

The variation of this parameter over time was low (est>1.96SE), and it accounted for a minor component of this total variance (19%).

### *Fz MAX2 N (N/N)- normalized first maximal peak*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 1.21 (.027) |
| Innominate left leg | 1.216 (.030) |
| Sacral left leg | 1.176 (.027) |
| Norm right leg | 1.210 (.027) |
| Innominate right leg | 1.235 (.030) |
| Sacral right leg | 1.172 (.027) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 0.019 | 0.006 | .0009 |
| Norm Vs sacral | -0.005 | 0.006 | NA |
| Innominate Vs sacral | -0.023 | 0.006 | .00006 |

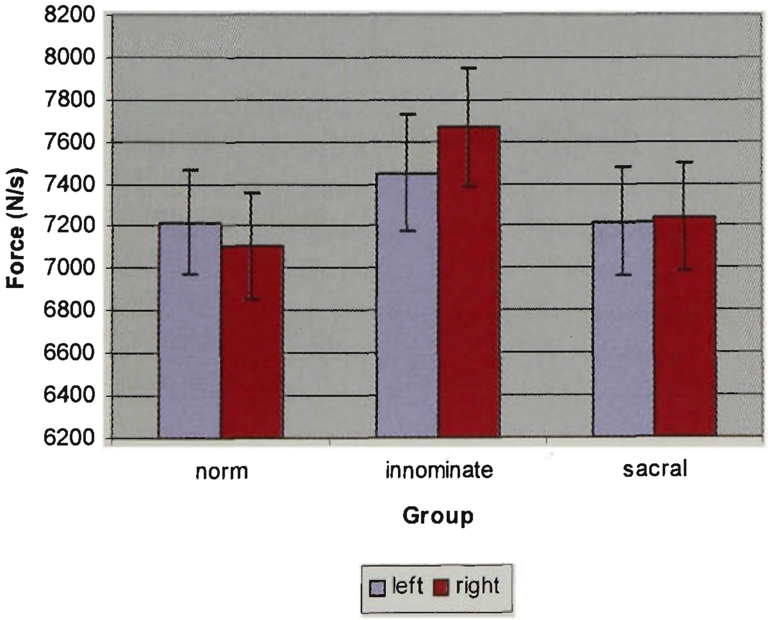
This parameter represents the first peak of the typically biphasic GRF normalised to body weight.

The asymmetry between legs in the innominate group, with the right leg higher than the left (0.012N/N, 3 X SE) is significantly different from the asymmetry between legs in norm and sacral groups, which were insignificant.

The variation of this parameter over time was low (est>1.96SE), and it accounted for a minor component of the total variance (20%).

***Fz SI MAX 2 (N/s)- slope to first maximal peak***

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 7220 (499) |
| Innominate left leg | 7449 (558) |
| Sacral left leg | 7217 (509) |
| Norm right leg | 7102 (499) |
| Innominate right leg | 7668 (558) |
| Sacral right leg | 7237 (509) |



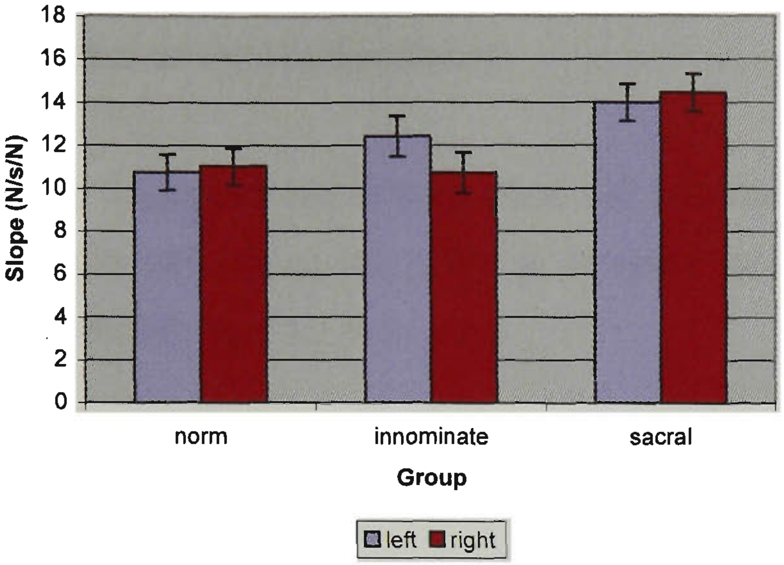
| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 337.4 | 117.6 | .002 |
| Norm Vs sacral | 137.5 | 110.6 | NA |
| Innominate Vs sacral | -199.9 | 118.1 | NA |

This parameter represents the slope up to the first peak of the typically biphasic GRF expressed in Newtons per second.

The asymmetry between legs in the innominate group, with the right leg higher than the left (337 N/s, 2.88 X SE), was significantly different from the asymmetry between legs in the norm and sacral groups, which were insignificant. The variation of this parameter over time was low (est>1.96SE), and it was a minor component of the total variance (9%).

### *Fz SI N MAX2 (N/s/N)- normalized slope to first maximal peak*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 10.75 (1.67) |
| Innominate left leg | 12.42 (1.87) |
| Sacral left leg | 13.99 (1.71) |
| Norm right leg | 11.04 (1.67) |
| Innominate right leg | 10.72 1.88) |
| Sacral right leg | 14.44 (1.71) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -1.99 | 0.48 | .00001 |
| Norm Vs sacral | 0.16 | 0.45 | NA |
| Innominate Vs sacral | 2.15 | 0.48 | .000003 |

This parameter represents the slope up to the first peak of the typically biphasic GRF expressed in Newtons per second, and then normalised to body weight.

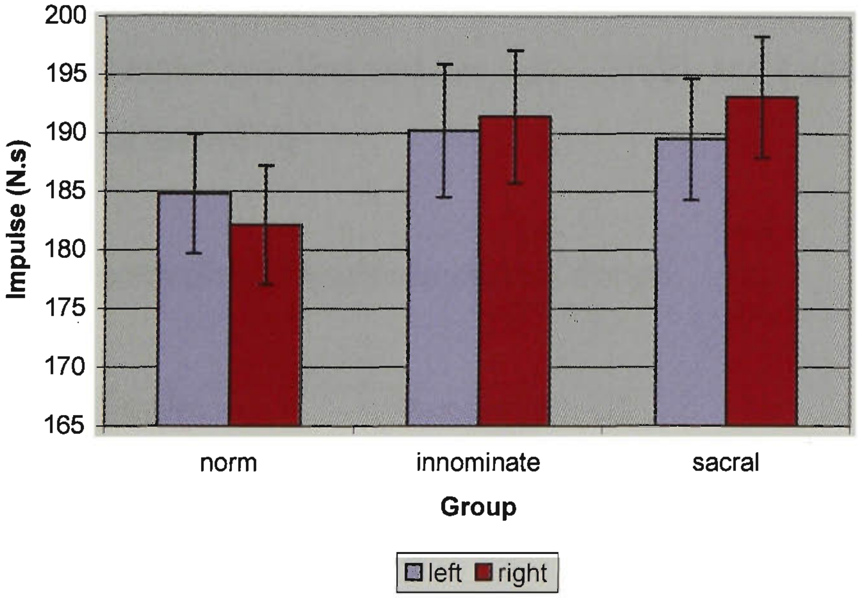
The asymmetry between legs in the innominate group, with the right leg less than the left (-1.7N/s/N, 4.7 X SE), was significantly different from the asymmetry between legs in the norm and sacral groups, which were insignificant. The left leg of the sacral group had a significantly higher slope than the left leg of the norm group (3.25N/s/N, 2.6 X SE).

The variation of this parameter over time was low (est>1.96SE), although it was a major component of the total variance (97%). The findings of a higher right leg in the innominate group in FZ Max 2 SI, in contrast to this normalised figure with a lower left leg, suggest error. This was unable to be resolved from the data, as the average weight of the groups was not significantly different.

The finding on group 3 suggests that although there was no asymmetry between legs, the diagnosis in the sacral group may create an increased vertical slope on the left side compared to the left leg of the norm group.

### *Fz MIN2 I (N.s) – impulse to second trough*

| **Description** | **Measure (95% CI)** |
|---|---|
| Norm left leg | 184.8 (10.2) |
| Innominate left leg | 190.2 (11.4) |
| Sacral left leg | 189.5 (10.4) |
| Norm right leg | 182.1 (10.2) |
| Innominate right leg | 191.4 (11.4) |
| Sacral right leg | 193.1 (10.4) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 3.79 | 1.49 | .005 |
| Norm Vs sacral | 6.22 | 1.40 | .000004 |
| Innominate Vs sacral | 2.43 | 1.49 | NA |

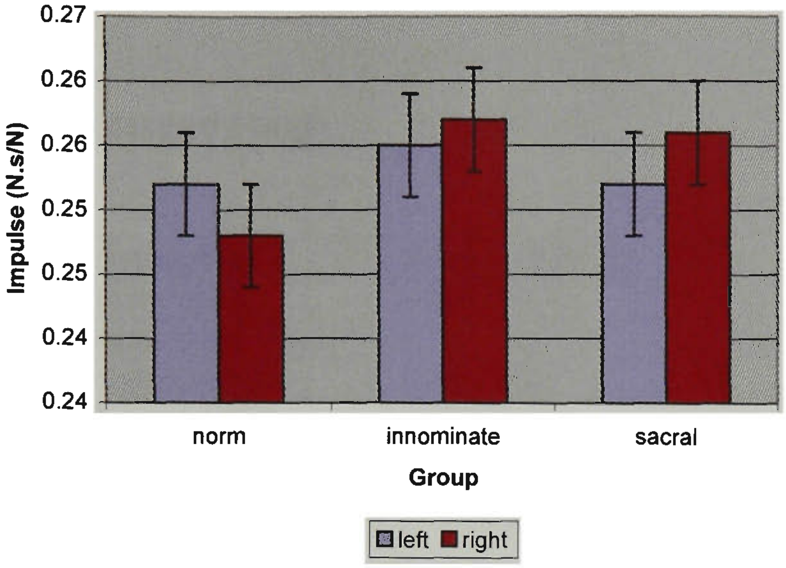
This parameter represents the impulse in Newton seconds up to the trough of the typically biphasic GRF at midstance where the knee extends, the ankle dorsiflexes and the body weight and COG decelerates.

The asymmetry between legs in the sacral group was significantly different from the asymmetry between legs in the norm group. The norm group had the right leg less than the left (-2.59N.s, 2.6 X SE), whilst the sacral group had the right leg greater than the left (3.63N.s, 3.6 X SE). The innominate group also was significantly different from the norm group, with the right leg higher than the left (3.79N.s, 2.54 X SE).

The variation of this parameter over time was low (est$\geq$1.96SE), and it was a minor component of this total variance (9%).

### *Fz MIN2 mNi (N.s/N)- normalized impulse to second trough*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | .252 (.008) |
| Innominate left leg | .255 (.009) |
| Sacral left leg | .252 (.008) |
| Norm right leg | .248 (.008) |
| Innominate right leg | .257 (.009) |
| Sacral right leg | .256 (.009) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 0.0053 | 0.002 | .004 |
| Norm Vs sacral | 0.0079 | 0.002 | .00003 |
| Innominate Vs sacral | -0.001 | 0.001 | NA |

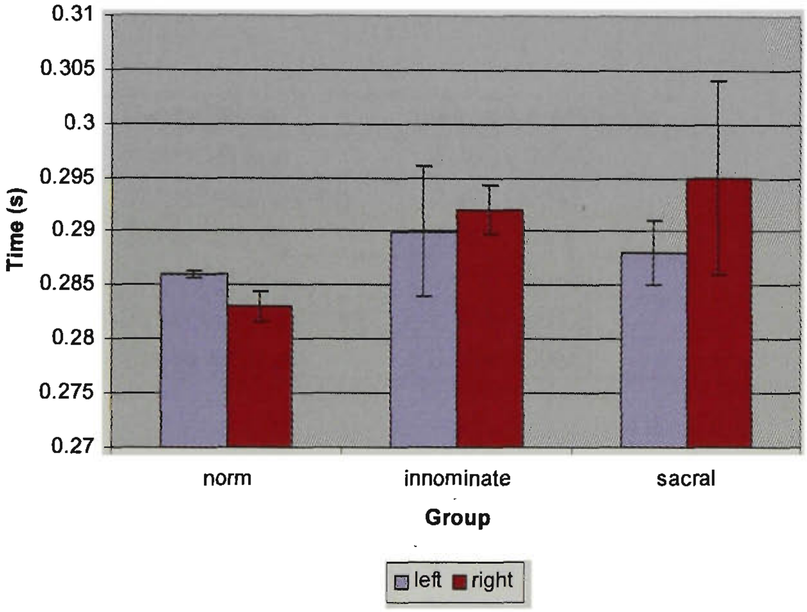
This parameter represents the impulse in Newton seconds up to the trogh of the typically biphasic GRF, normalised to body weight and multiplied by 1000.

The asymmetry between legs in the sacral group was significantly different from the asymmetry between legs in the norm group. The norm group had the right leg less than the left (-0.003N.s/N, 2.4 X SE), whilst the sacral group had the right leg greater than the left (0.005N.s/N, 5 X SE). The innominate group also was significantly different from the norm group, with the right leg higher than the left (.002N.s/N, 2.5 X SE).

The variation of this parameter over time was low (est≥1.96SE), and it accounted for a minor component of this total variance (14%).

### *Fz Min 2 T (s)- time to second trough*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 0.286 (.0007) |
| Innominate left leg | 0.29 (.012) |
| Sacral left leg | 0.288 (.006) |
| Norm right leg | 0.283 (.0029) |
| Innominate right leg | 0.292 (.0046) |
| Sacral right leg | 0.295 (.018) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 0.0053 | 0.0023 | .01 |
| Norm Vs sacral | 0.0092 | 0.0022 | .00003 |
| Innominate Vs sacral | 0.004 | 0.0023 | NA |

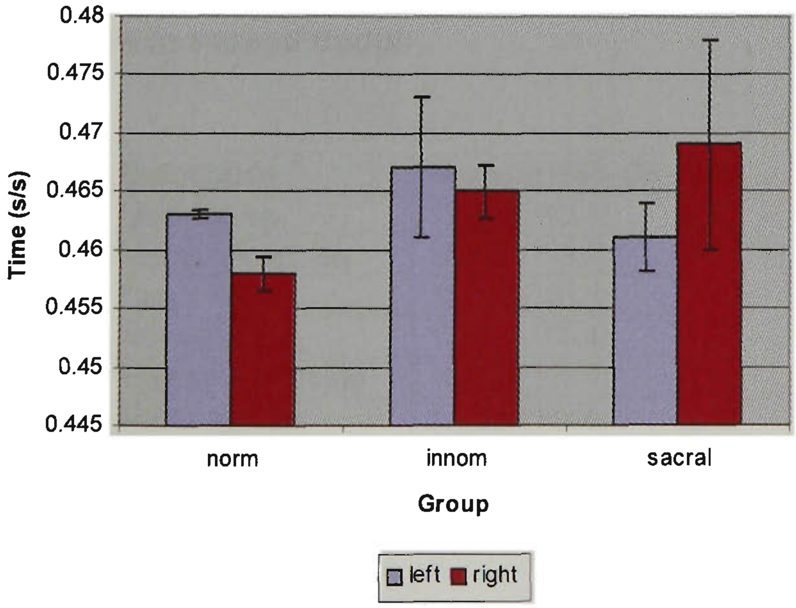
This parameter represents the time of the second trough of the typically biphasic GRF.

The asymmetry between legs in both the innominate group (0.0053s, 2.3 X SE) and the sacral group (0.0092s, 4 X SE) were significantly different to the asymmetry between legs in the norm group, which was insignificant. The right leg was more than the left in both groups, and there was no significant difference between the innominate and sacral groups.

The variation in this parameter over time was low (est≥1.96SE), and it was a minor component of the variance (16%).

### *Fz Min 2 T N (s/s)- normalized time to second trough*

| **Description** | **Measure (95% CI)** |
|---|---|
| Norm left leg | 0.463 (.0094) |
| Innominate left leg | 0.467 (.014) |
| Sacral left leg | 0.461 (.013) |
| Norm right leg | 0.458 (.0048) |
| Innominate right leg | 0.465 (.0072) |
| Sacral right leg | 0.469 (.0068) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 0.0072 | 0.0037 | NA |
| Norm Vs sacral | 0.0118 | 0.0035 | .0001 |
| Innominate Vs sacral | 0.0046 | 0.0037 | NA |

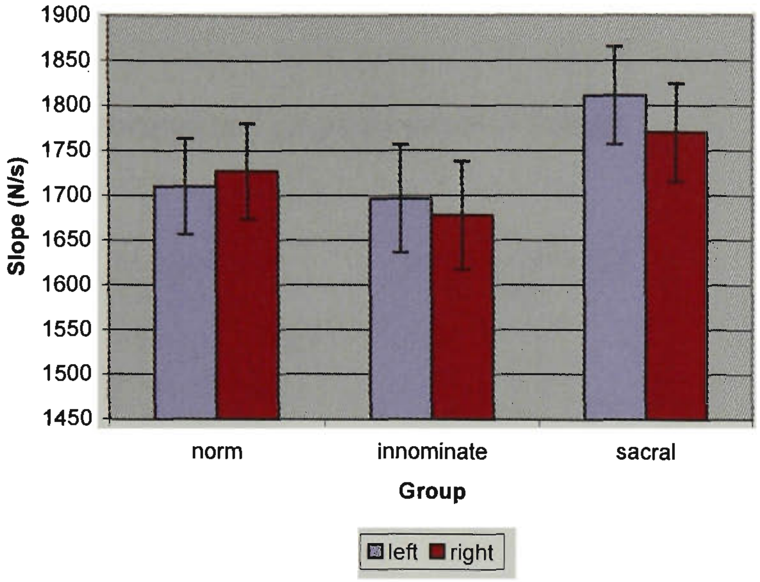
This parameter represents the time of the second trough of the typically biphasic GRF.

The asymmetry between legs in the sacral group (0.0118 s/s, 3.4 X SE) was significantly different to the asymmetry between legs in the norm and innominate groups, which were insignificant. The right leg was higher than the left in the sacral group. There was no significant difference between the innominate and sacral groups.

The variation in this parameter over time was low (est≥1.96SE), and it was a minor component of the variance (21%).

### *Fz SI MIN2 (N/s)- slope to second trough*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 1710.0 (106.4) |
| Innominate left leg | 1696.1 (118.9) |
| Sacral left leg | 1811.2 (108.6) |
| Norm right leg | 1727.1 (106.4) |
| Innominate right leg | 1677.9 (119.0) |
| Sacral right leg | 1770.2 (108.6) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -35.25 | 17.2 | .02 |
| Norm Vs sacral | -57.92 | 16.2 | .0001 |
| Innominate Vs sacral | -22.66 | 17.2 | NA |

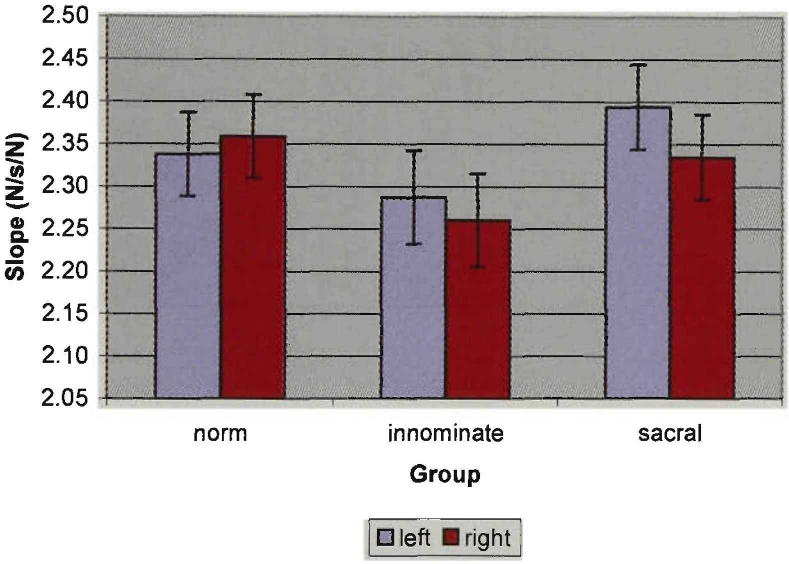
This parameter represents the average slope up to the first minimum peak of the typically biphasic GRF expressed in Newton seconds.

The asymmetry between legs in the sacral group was significantly different from the asymmetry between legs in the norm and innominate groups, which were insignificant. The sacral group had the right leg less than the left (-40.9N/s, 3.5 X SE).

The variation of this parameter over time was low (est≥1.96SE), and it accounted for a minor component of the total variance (25%).

### *Fz SI N MIN2 (N/s/N)- normalized slope to second trough*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 2.338 (.098) |
| Innominate left leg | 2.287 (.110) |
| Sacral left leg | 2.394 (.100) |
| Norm right leg | 2.359 (.098) |
| Innominate right leg | 2.260 (.110) |
| Sacral right leg | 2.335 (.100) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -0.047 | 0.02 | .009 |
| Norm Vs sacral | -0.079 | 0.02 | .00003 |
| Innominate Vs sacral | -0.032 | 0.02 | NA |

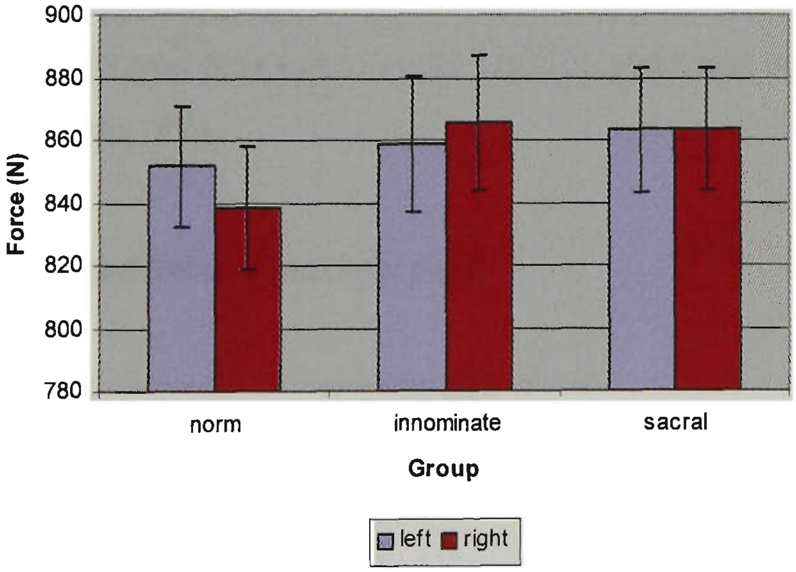
This parameter represents the average slope up to the first minimum peak of the typically biphasic GRF normalised to body weight.

The asymmetry between legs in the sacral group was significantly different from the asymmetry between legs in the norm and innominate groups, which were insignificant. The sacral group had the right leg less than the left (-0.059N/s/N, 3.7 X SE).

The variation of this parameter over time was low (est≥1.96SE), and it accounted for a minor component of the total variance (28%).

### *Fz MAX3 (N)- second maximal peak*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 851.75 (38.8) |
| Innominate left leg | 858.87 (43.4) |
| Sacral left leg | 863.2 (39.7) |
| Norm right leg | 838.37 (38.8) |
| Innominate right leg | 865.28 (43.5) |
| Sacral right leg | 863.3 (39.7) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 19.78 | 3.65 | .00000003 |
| Norm Vs sacral | 13.46 | 3.43 | .00004 |
| Innominate Vs sacral | -6.31 | 3.67 | NA |

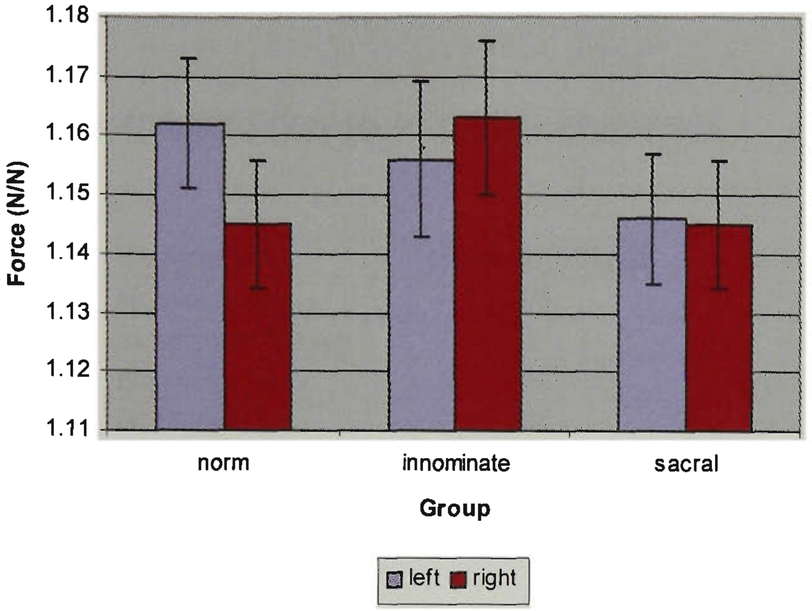
This parameter represents the second peak of the typically biphasic GRF, and is directly related to terminal stance and preswing as the body weight moves anterior to the forefoot. It is expressed in Newtons.

The asymmetry between legs in the innominate group (6.4N, 2.3 X SE), where the right leg was higher than the left, was significantly different from the asymmetry between legs in the norm group, which was significant but in the opposite direction (-13.37N, 5.5 X SE). The right leg in the sacral group was significantly higher than in the norm group, but was not asymmetrical. The innominate and sacral groups were not significantly different from one another.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (3%).

### *Fz MAX3 N (N/N)- normalised second maximal peak*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 1.162 (.022) |
| Innominate left leg | 1.156 (.025) |
| Sacral left leg | 1.146 (.022) |
| Norm right leg | 1.145 (.022) |
| Innominate right leg | 1.163 (.025) |
| Sacral right leg | 1.145 (.022) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 0.023 | 0.004 | .000000004 |
| Norm Vs sacral | 0.016 | 0.004 | .00003 |
| Innominate Vs sacral | -0.006 | 0.004 | NA |

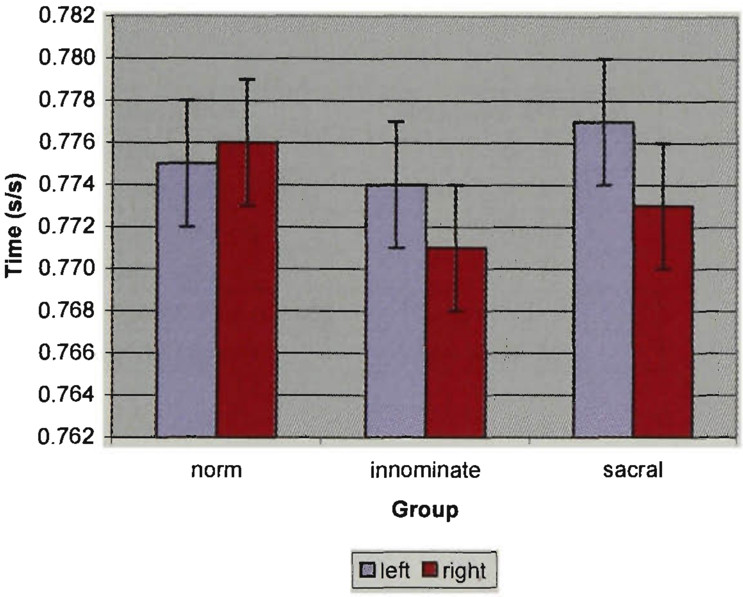
This parameter represents the second peak of the typically biphasic GRF normalized to body weight.

The asymmetry between legs in the norm group (-0.017N/N, 5.3 X SE), where the right leg was lower than the left, was significantly different from the asymmetry between legs in the innominate group (.023N/N, 5.75 X SE), which had the right leg higher than the left. The sacral group was not asymmetrical. The innominate and sacral groups were not significantly different from one another.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (9%).

### *Fz MAX3 TN (s/s) – normalised time to second maximal peak*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | .775 (.006) |
| Innominate left leg | .774 (.007) |
| Sacral left leg | .777 (.006) |
| Norm right leg | .776 (.006) |
| Innominate right leg | .771 (.007) |
| Sacral right leg | .773 (.006) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -0.0039 | 0.002 | NA |
| Norm Vs sacral | -0.004 | 0.001 | .00003 |
| Innominate Vs sacral | -0.00007 | 0.001 | NA |

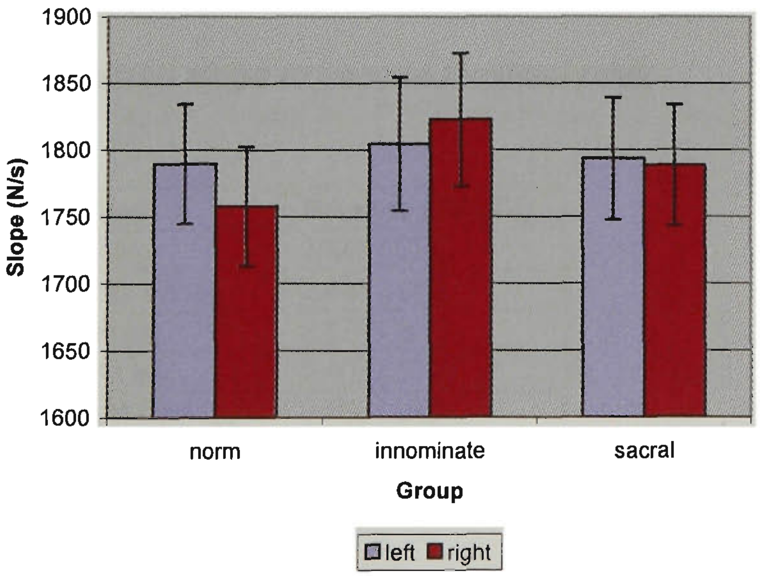
This parameter represents the time of the second maximal peak of the typically biphasic GRF normalised to total stance time.

The asymmetry between legs in both the innominate group (-0.0031s/s, 2.2 X SE) and the sacral group (-0.003s/s, 3 X SE) were significantly different to the asymmetry between legs in the norm group, which was insignificant. The right leg was less than the left in both groups, and there was no significant difference between the innominate and sacral groups.

The variation in this parameter over time was slightly high (est=1.9SE), but it was a minor component of the variance (4%).

### *Fz SI MAX3 (N/s)- slope to second maximal peak*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 1789.6 (89.7) |
| Innominate left leg | 1804.15 (100.3) |
| Sacral left leg | 1793.3 (91.5) |
| Norm right leg | 1757.7 (89.7) |
| Innominate right leg | 1822.4 (100.3) |
| Sacral right leg | 1788.2 (91.5) |



| **Asymmetry comparison** | **Difference between asymmetries** | **SE** | **P** |
|---|---|---|---|
| Norm Vs innominate | 50.11 | 10.67 | .000001 |
| Norm Vs sacral | 26.77 | 10.03 | .003 |
| Innominate Vs sacral | -23.34 | 10.72 | .015 |

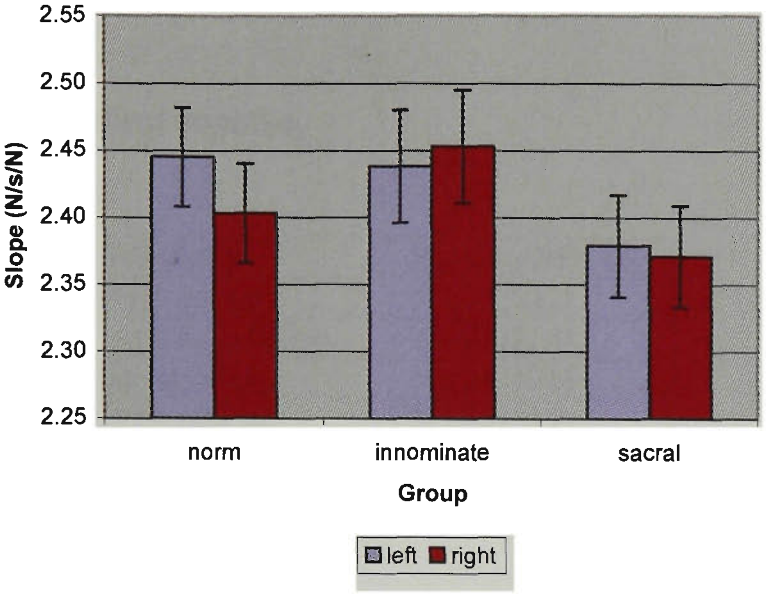
This parameter represents the average slope up to the second peak of the typically biphasic GRF expressed in Newtons per second.

The asymmetry between legs in both the innominate and sacral groups were significantly different to the asymmetry between legs in the norm group, which was significant in that the right leg was less than the left (-31.9N/s, 4.5 X SE). The innominate group was asymmetrical in the opposite direction (18.21N/s, 2.3 X SE), whilst the sacral group was not asymmetrical. The right leg was significantly higher in the innominate group compared to the sacral group (23.34N/s, 2.2 X SE).

The variation in this parameter over time was low (est≥1.96SE), and it accounted for a minor component of the variance (25%).

### *Fz SI N MAX3 (N/s/N)- normalized slope to second maximal peak*

| **Description** | **Measure (95% CI)** |
|---|---|
| Norm left leg | 2.445 (.074) |
| Innominate left leg | 2.438 (.083) |
| Sacral left leg | 2.379 (.076) |
| Norm right leg | 2.403 (.074) |
| Innominate right leg | 2.453 (.083) |
| Sacral right leg | 2.371 (.076) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 0.057 | 0.014 | .00002 |
| Norm Vs sacral | 0.034 | 0.013 | .004 |
| Innominate Vs sacral | -0.022 | 0.014 | NA |

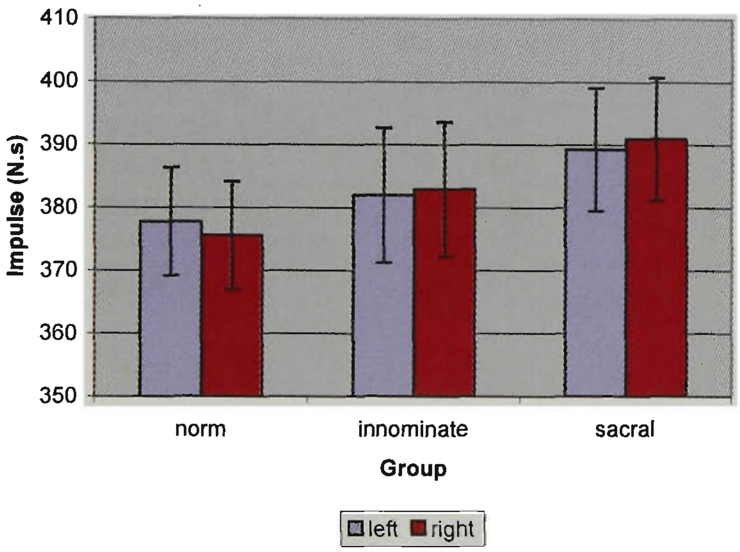
This parameter represents the average slope up to the second peak of the typically biphasic GRF normalised to body weight.

The asymmetry between legs in the norm group (-0.042N/s/N, 4.6 X SE), where the right leg was lower than the left, was significantly different from the asymmetry between legs in the innominate and sacral groups, which were insignificant. The innominate and sacral groups were not significantly different from one another, which does not support the non-normalised findings in the previous parameter. This suggests that body weight was an important factor in that finding.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (7%).

### *Fz Imp (N.s)- total vertical impulse*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | 377.73 (19.2) |
| Innominate left leg | 381.95 (21.4) |
| Sacral left leg | 389.24 (19.5) |
| Norm right leg | 375.53 (19.2) |
| Innominate right leg | 382.9 (21.4) |
| Sacral right leg | 390.95 (19.5) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 3.15 | 1.31 | .008 |
| Norm Vs sacral | 3.90 | 1.24 | .0008 |
| Innominate Vs sacral | 0.75 | 1.32 | NA |

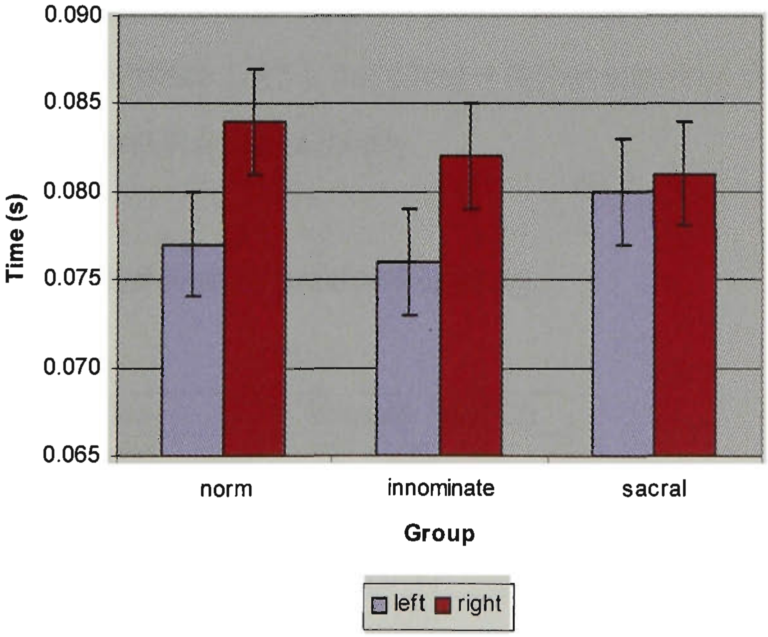
This parameter represents the total impulse of the vertical force in Newton seconds. The asymmetry between legs in the norm group (-2.2N.s, 2.5 X SE), where the right leg was lower than the left, was significantly different from the asymmetry between legs in the innominate and sacral groups, which were insignificant. The innominate and sacral groups were not significantly different from one another.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (3%).

### *8.2.2.2 Anterior-posterior (Fy) parameters*

#### *Max Brake T (s)- time of maximal braking*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | .077 (.005) |
| Innominate left leg | .076 (.006) |
| Sacral left leg | .080 (.006) |
| Norm right leg | .084 (.005) |
| Innominate right leg | .082 (.006) |
| Sacral right leg | .081 (.006) |



| **Asymmetry comparison** | **Difference between asymmetries** | **SE** | **P** |
|---|---|---|---|
| Norm Vs innominate | 0.00006 | 0.002 | NA |
| Norm Vs sacral | -0.005 | 0.001 | .0000002 |
| Innominate Vs sacral | -0.005 | 0.002 | .006 |

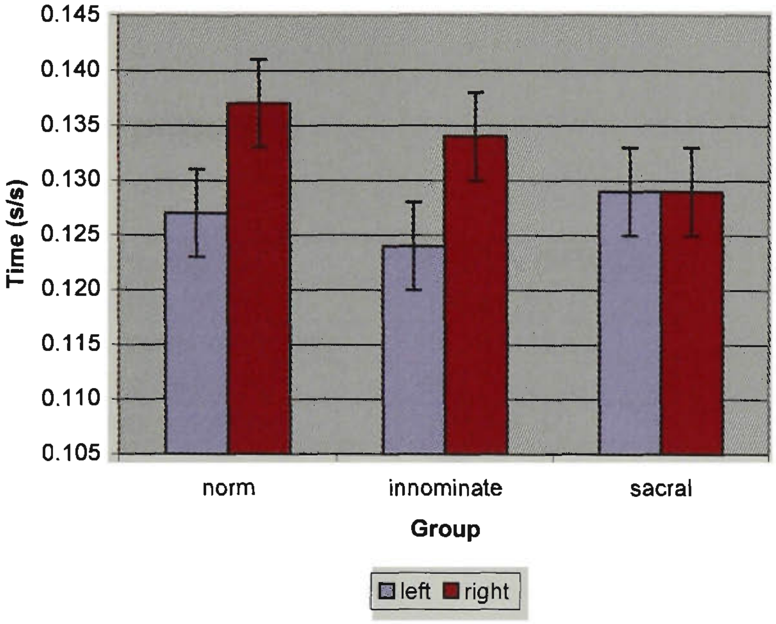
This parameter represents the time of the maximum braking, or posterior (positive) force, and is directly related to initial contact and loading response. It is expressed in seconds.

The asymmetry between legs in the norm and innominate groups is significantly different from the asymmetry in the sacral group, which was not significant. The norm groups (0.007s, 7 X SE) and innominate group (0.006s, 3 X SE) had significant asymmetry, with the right leg higher than the left, and they were similar in this asymmetry.

The variation over time with this parameter was low (est≥1.96SE), it accounted for a minor component of the total variance (24%), but it had a higher inter-trial than inter-subject variability and so has questionable reliability.

***Max Brake TN (s/s)- normalised time of maximal braking***

| **Description** | **Measure (95% CI)** |
|---|---|
| Norm left leg | .127 (.008) |
| Innominate left leg | .124 (.009) |
| Sacral left leg | .129 (.009) |
| Norm right leg | .137 (.008) |
| Innominate right leg | .134 (.009) |
| Sacral right leg | .129 (.009) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | 0.00004 | 0.003 | NA |
| Norm Vs sacral | -0.010 | 0.003 | .0004 |
| Innominate Vs sacral | -0.010 | 0.003 | .0004 |

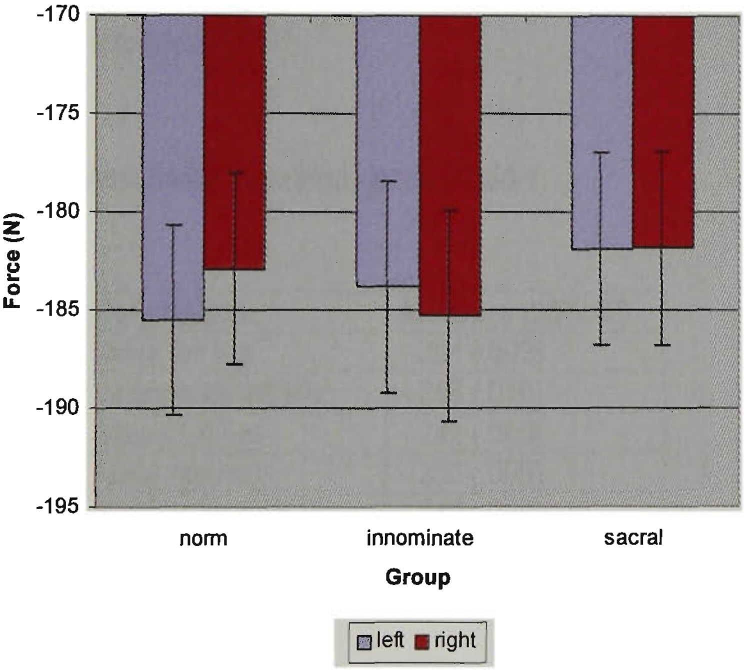
This parameter represents the time of the maximum braking, or posterior (positive) force, normalised to total stance time.

The asymmetry between legs in the norm and innominate groups is significantly different from the asymmetry in the sacral group, which was not significant. The norm (0.01s/s, 5 X SE) and innominate (0.01s/s, 3.3 X SE) groups had significant asymmetry, with the right leg higher than the left, and they were similar in this asymmetry.

The variation over time with this parameter was low (est≥1.96SE), and it was a minimal component of the total variance (10%), but it had a higher inter-trial than inter-subject variability and therefore has questionable reliability.

### *Max Prop (N)- maximal propulsion*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | -185.54 (9.67) |
| Innominate left leg | -183.82 (10.81) |
| Sacral left leg | -181.89 (9.89) |
| Norm right leg | -182.9 (9.67) |
| Innominate right leg | -185.29 (10,81) |
| Sacral right leg | -181.84 (9.86) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -4.10 | 1.72 | .008 |
| Norm Vs sacral | -2.59 | 1.62 | NA |
| Innominate Vs sacral | 1.50 | 1.73 | NA |

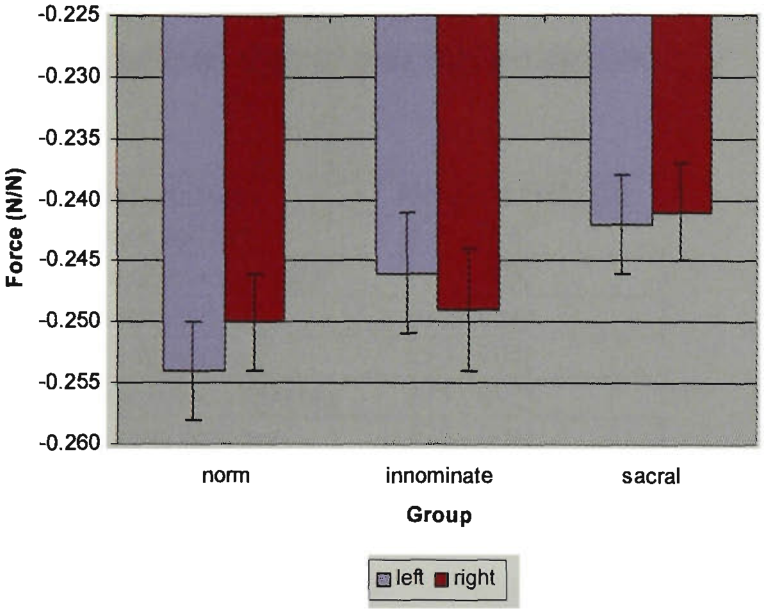
This parameter represents the maximal propulsive, or anterior (negative) force and is directly related to terminal stance. It is expressed in Newtons.

The asymmetry between legs in the norm group (2.63N, 2.3 X SE), where the right leg was higher than the left, was significantly different from the asymmetry between legs in the innominate and sacral groups, which were insignificant. The right leg in the innominate group was significantly lower than in the norm group, but was not asymmetrical. The innominate and sacral groups were not significantly different from one another.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (7%).

### *Max Prop N (N/N)- normalised maximal propulsion*

| **Description** | **Measure (95% CI)** |
|---|---|
| Norm left leg | -.254 (.009) |
| Innominate left leg | -.246 (.010) |
| Sacral left leg | -.242 (.009) |
| Norm right leg | -.250 (.009) |
| Innominate right leg | -.249 (.010) |
| Sacral right leg | -.241 (.009) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -0.006 | 0.002 | .001 |
| Norm Vs sacral | -0.003 | 0.002 | NA |
| Innominate Vs sacral | 0.003 | 0.002 | NA |

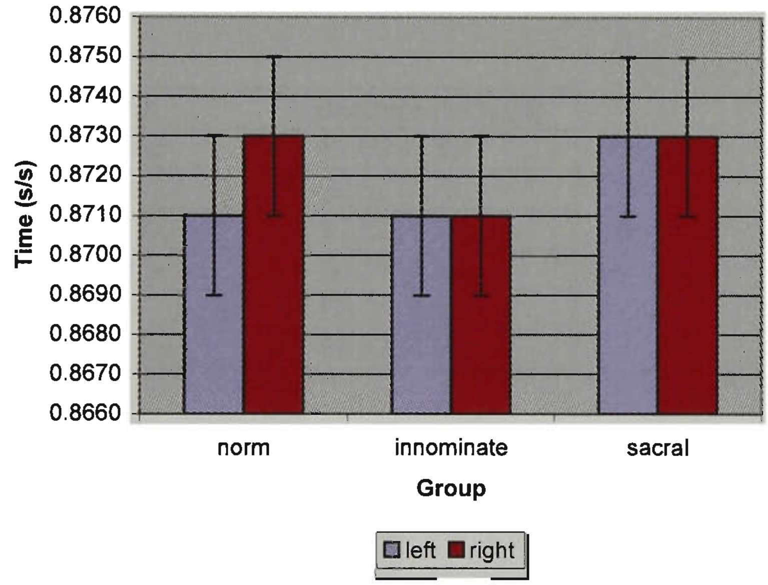
This parameter represents the maximal propulsive, or anterior (negative) force normalized to body weight.

The asymmetry between legs in the norm group (0.0036N/N, 2.4 X SE), where the right leg was higher than the left, was significantly different from the asymmetry between legs in the innominate and sacral groups, which were insignificant. The innominate and sacral groups were not significantly different from one another.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (6%).

### *Max Prop TN (s/s)- normalised time of maximal propulsion*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | .871 (.004) |
| Innorninate left leg | .871 (.005) |
| Sacral left leg | .873 (.004) |
| Norm right leg | .873 (.004) |
| Innominate right leg | .871 (.005) |
| Sacral right leg | .873 (.004) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -0.0027 | 0.001 | .003 |
| Norm Vs sacral | -0.0024 | 0.001 | .008 |
| Innominate Vs sacral | 0.0003 | 0.001 | NA |

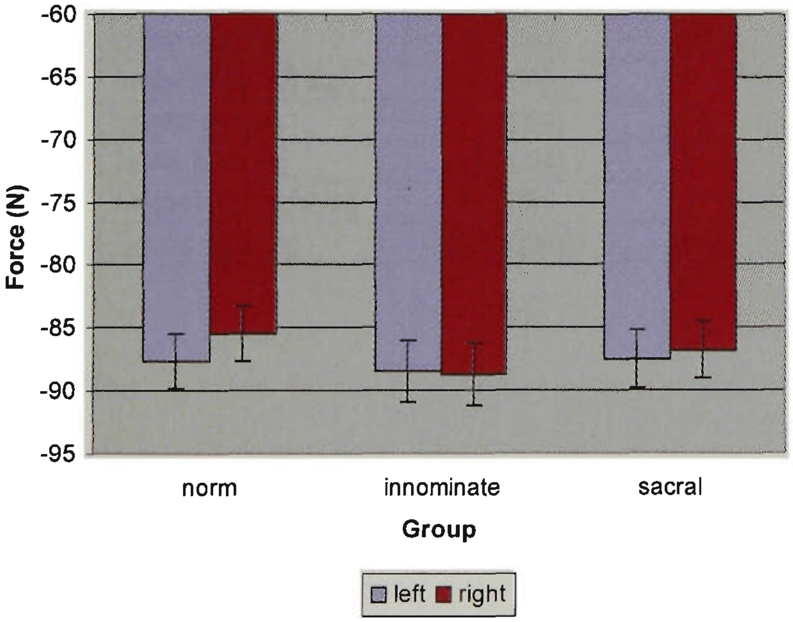
This parameter represents the time up to the maximal propulsive, or anterior (negative) force normalized to total stance time.

The asymmetry between legs in the norm group (0.002s/s, 2.2 X SE), where the right leg was higher than the left, was significantly different from the asymmetry between legs in the innominate and sacral groups, which were insignificant. The innominate and sacral groups were not significantly different from one another.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (12%).

### *Ave Prop (N)- average propulsion*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | -87.69 (4.36) |
| Innominate left leg | -88.52 (4.88) |
| Sacral left leg | -87.52 (4.51) |
| Norm right leg | -85.51 (4.36) |
| Innominate right leg | -88.79 (4.88) |
| Sacral right leg | -86.83 (4.49) |



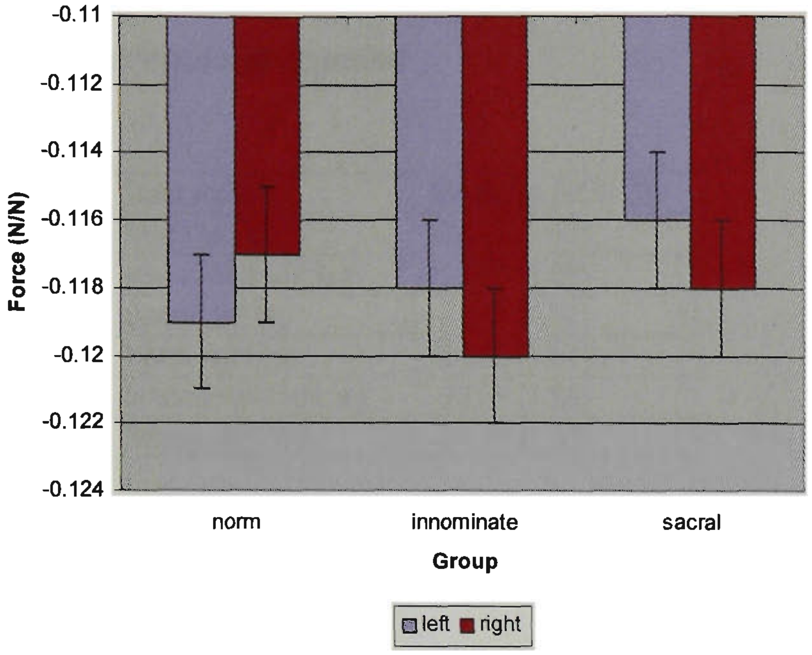
| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -2.45 | 0.79 | .0009 |
| Norm Vs sacral | -1.49 | 0.75 | .02 |
| Innominate Vs sacral | 0.96 | 0.80 | NA |

This parameter represents the average propulsive, or anterior (negative) force. The asymmetry between legs in the normal group (2.18N, 4.12 X SE), where the right leg was lower than the left, was significantly different from the asymmetry between legs in the innominate group where the right leg was higher (-2.45N, 3 X SE), and the sacral group, which was insignificant. The innominate and sacral groups were not significantly different from one another.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (8%).

### *Ave Prop N (N/N)- normalised average propulsion*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | -.119 (.004) |
| Innominate left leg | -.118 (.005) |
| Sacral left leg | -.116 (.004) |
| Norm right leg | -.117 (.004) |
| Innominate right leg | -.12 (.005) |
| Sacral right leg | -.118 (.004) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -0.003 | 0.001 | .001 |
| Norm Vs sacral | -0.001 | 0.001 | NA |
| Innominate Vs sacral | 0.001 | 0.001 | NA |

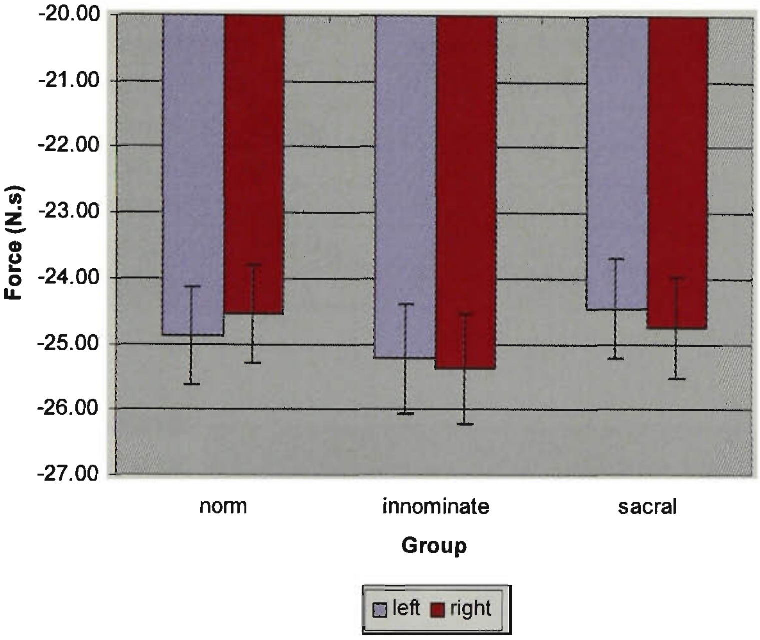
This parameter represents the average propulsive, or anterior (negative) force normalized to body weight.

The asymmetry between legs in the norm group (0.003N/N, 4.3 X SE), where the right leg was lower than the left, was significantly different from the asymmetry between legs in the innominate group where the right leg was higher (-0.003N/N, 3 X SE) and the sacral group, which was insignificant. The innominate and sacral groups were not significantly different from one another.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (7%).

### *Prop Imp (N.s)- total propulsive impulse*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | -24.89 (1.50) |
| Innominate left leg | -25.23 (1.68) |
| Sacral left leg | -24.46 (1.54) |
| Norm right leg | -24.55 (1.51) |
| Innominate right leg | -25.38 (1.68) |
| Sacral right leg | -24.75 (1.54) |



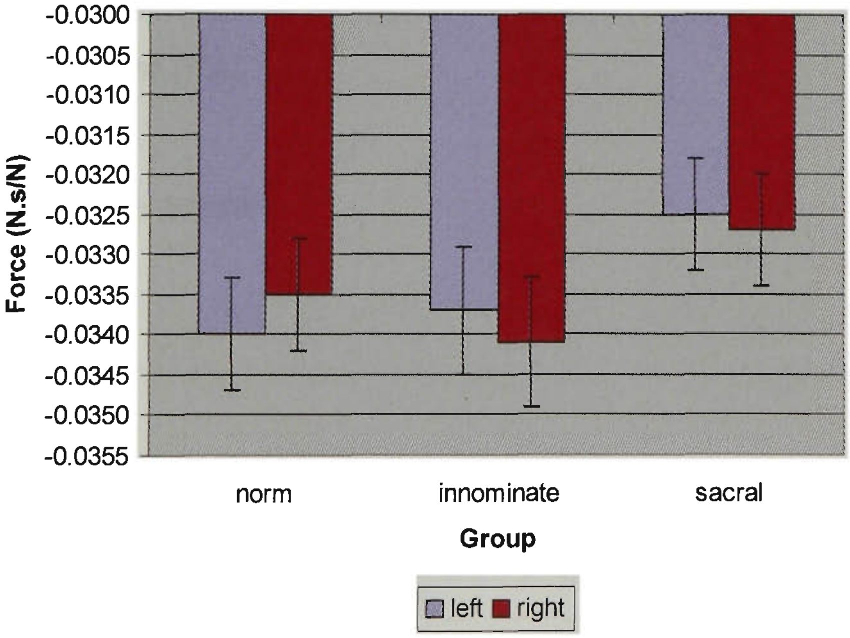
| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -0.498 | 0.25 | .02 |
| Norm Vs sacral | -0.63 | 0.24 | .004 |
| Innominate Vs sacral | -0.14 | 0.26 | NA |

This parameter represents the total propulsive, or anterior (negative) impulse expressed in Newton seconds. The asymmetry between legs in the norm group (0.349N.s, 2 X SE), where the right leg was higher than the left, was significantly different from the asymmetry between legs in the innominate and sacral groups, which were insignificant. The innominate and sacral groups were not significantly different from one another.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (6%).

### *Prop mNI (N.s/N)- normalised total propulsive impulse*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | -0.034 (.0014) |
| Innominate left leg | -0.0337 (.0016) |
| Sacral left leg | -0.0325 (.0014) |
| Norm right leg | -0.0335 (.0014) |
| Innominate right leg | -0.0341 (.0016) |
| Sacral right leg | -0.0327 (.0014) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -0.0007 | 0.0003 | .01 |
| Norm Vs sacral | -0.0006 | 0.0003 | .02 |
| Innominate Vs sacral | 0.00008 | 0.0003 | NA |

This parameter represents the propulsive, or anterior (negative) force normalised to body weight and multiplied by 1000.

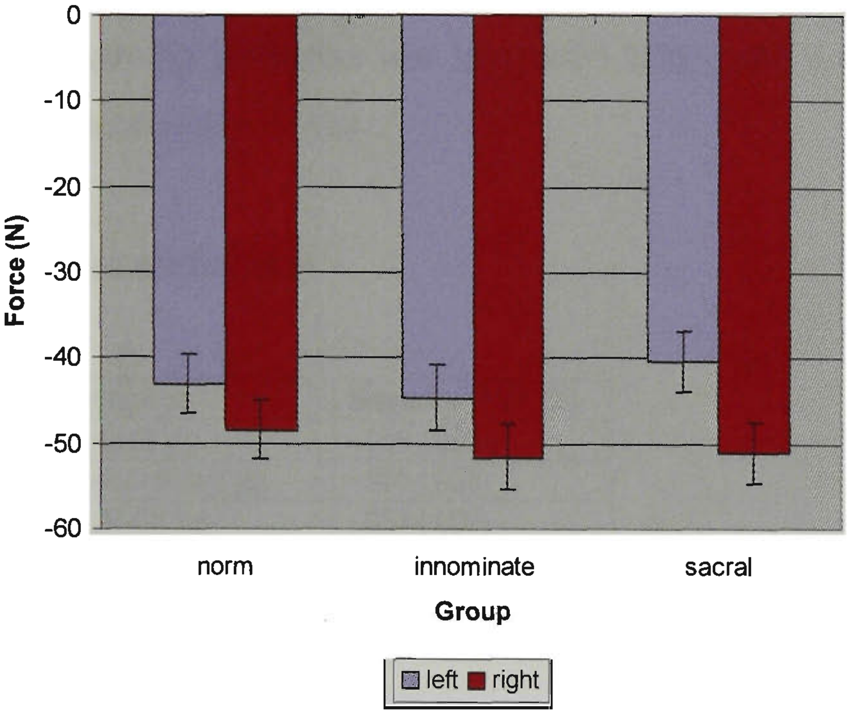
The asymmetry between legs in the norm group (0.00048N.s/N, 2.2 X SE), where the right leg was higher than the left, was significantly different from the asymmetry between legs in the innominate and sacral groups, which were insignificant. The innominate and sacral groups were not significantly different from one another.

The variation of this parameter over time was low (est>1.96SE), and it was a minimal component of the total variance (7%).

#### *8.2.2.3 Medial-lateral (Fx) parameters*

#### *Fx Min (N)- medial peak*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | -43.08 |
| Innominate left leg | -44.61 |
| Sacral left leg | -40.26 |
| Norm right leg | -48.39 |
| Innominate right leg | -51.57 |
| Sacral right leg | -50.98 |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -1.65 | 1.44 | NA |
| Norm Vs sacral | -5.41 | 1.36 | .00003 |
| Innominate Vs sacral | -3.75 | 1.44 | .004 |

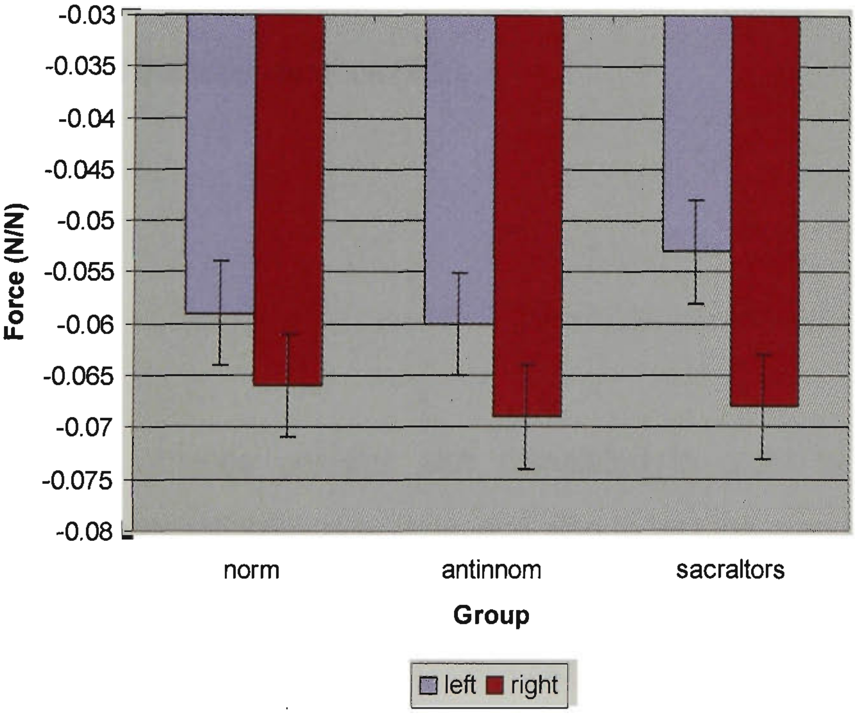
This parameter represents the minimum (negative) Fx force, which is medially directed and is directly associated with initial contact and loading. It is expressed in Newtons.

The asymmetry between legs in the sacral group is significantly different to the asymmetry between legs in the norm and innominate groups. The norm group (-5.31N, 5.5 X SE), innominate group (-6.96N, 6.4 X SE) and sacral group (-10.7N, 11 X SE) all had significant asymmetries between legs with the right larger than the left, although the asymmetry between legs in the norm and innominate groups were not significantly different from one another.

The variation over time with this parameter was low (est≥1.96SE), and it was a minimal component of the total variance (8%).

### *Fx Min N (N/N)- normalised medial peak*

| Description | Measure (95% CI) |
|---|---|
| Norm left leg | -.059 (.009) |
| Innominate left leg | -.060 (.008) |
| Sacral left leg | -.053 (.009) |
| Norm right leg | -.066 (.009) |
| Innominate right leg | -.069 (.008) |
| Sacral right leg | -.068 (.009) |



| Asymmetry comparison | Difference between asymmetries | SE | P |
|---|---|---|---|
| Norm Vs innominate | -0.0017 | 0.0019 | NA |
| Norm Vs sacral | -0.0073 | 0.0018 | .00003 |
| Innominate Vs sacral | -0.0055 | 0.0019 | .001 |

This parameter represents the minimum (negative) Fx force, normalised to body weight, which is medially directed.

The asymmetry between legs in the sacral group is significantly different to the asymmetry between legs in the norm and innominate groups. The norm group (-0.007N/N, 6 X SE), innominate group (-0.009N/N, 6.4 X SE) and sacral group (-0.015N/N, 15 X SE) all had significant asymmetries between legs with the right larger than the left, although the asymmetry between legs in norm and innominate groups were not significantly different from one another.

The variation over time with this parameter was low (est≥1.96SE), and it was a minimal component of the total variance (9%).

# 9 *Discussion*

## *9.1 Reliability*

The week to week variance analysis was completed in order to reveal any parameters that had poor reliability over time, and also to test the manual diagnostic procedure over time. All subjects returned with the same physical examination findings and diagnosis, demonstrating consistency within the one non-blinded examiner. Of 76 parameters tested, 15 demonstrated a high variability between weeks. This week to week variance was considered significant if the estimate was

1.96 or more times its standard error (SE), which is equivalent to $p \leq .05$, and the proportion of total random variance due to weekly variation, obtained by division, was higher than the other variance factors, which were trials and leg. Of these, 13 involved time measures, either directly as a time measure in seconds, or indirectly as part of the impulse or slope calculations. This unreliability could be due to the relatively small degree of measures in these parameters (measured in milliseconds) coupled with the natural variance of normal gait. This issue has been mentioned by other researchers who had found the time measures variable (Robinson et al, 1987; Herzog et al, 1989). To further investigate the reliability of these time measures, increased numbers of subjects and trials should be considered by future researchers.

Previous studies (Robinson et al, 1987; Herzog et al, 1989) had excluded certain parameters in second stage analysis based on two reliability measures: firstly when inter-trial temporal ranges were above 100ms, and secondly when the mean of the absolute values of the variables were small when compared to its variance. As mentioned in Section 8.1, the subject numbers in the week to week analysis were small (ie 6 in the norm group and 3 in each positive group) and the literature is inconclusive regarding variation of gait over time, so in this study all parameters were kept in the main analysis and discussed in the Results section with reference to their week to week variance.

### *9.2 Group differences*

The study compared the asymmetries of GRFs between the right and left legs of normal asymptomatic males, to the asymmetries of GRFs between legs of two symptomatic groups.

The differences between these groups can be explained by sub-dividing them into the various components related to the aims of the study;

- that the innominate group is different to the norm group,
- that the sacral group is different to the norm group, and
- that the innominate group and sacral group are different from one another.

Further explanation is necessary in each of these three sections in order to specify the reasons for the differences, where either:

- the norm group was symmetrical and the innominate and/or sacral groups were asymmetrical, or the
- the norm group and innominate and/or sacral groups were asymmetrical, but different, or the
- the norm group was asymmetrical and the innominate and/or sacral group were symmetrical.

The following discussions are necessarily speculative, as the biomechanical and manual medicine literature has not developed the understanding to explain these associations. Some tentative links are made between the theoretical models of pelvic kinetics and kinematics (covered in Section 4.6), and the results of this study.

### *9.2.1 Differences between the norm and innominate groups*

The innominate group was different from the norm group on eight parameters where the norm group was symmetrical, and the innominate group was asymmetrical. These were all concerning the vertical GRFs - the first and second maxima, the timing of the first and third maxima and second trough, and the slope up to the second maximum. The slope of the second maximum had an apparent discrepancy between the direction of the normalized and non-normalised findings, and should be discounted.

The innominate group was different from the norm group on seven parameters where both groups were asymmetrical, but significantly different. These were concerning the second trough, the third vertical peak force and the timing of the maximal braking. The finding of difference in the slope of the third vertical peak was not supported by the normalized parameter.

The innominate group was different from the normal group on seven parameters where the norm group was asymmetrical and the innominate group was symmetrical. These were concerning the normalised slope of the third maximum vertical peak, the impulse of the vertical force, and the propulsive GRFs. All of these were reliable over time.

In the comparison between the norm and innominate groups, all three maxima of the vertical force profiles were able to characterize the difference. The first is related to heel strike in early initial contact and the positive right side of the innominate group was lower than the norm group. The second and third peaks demonstrated that the positive right leg of the innominate group had higher forces in the loading response and terminal stance phases.

Figure 44 demonstrates the difference in asymmetries between the norm and innominate groups. The vertical force profile of the innominate group is shown, with the right leg (red) and left leg (black) differences outlined.

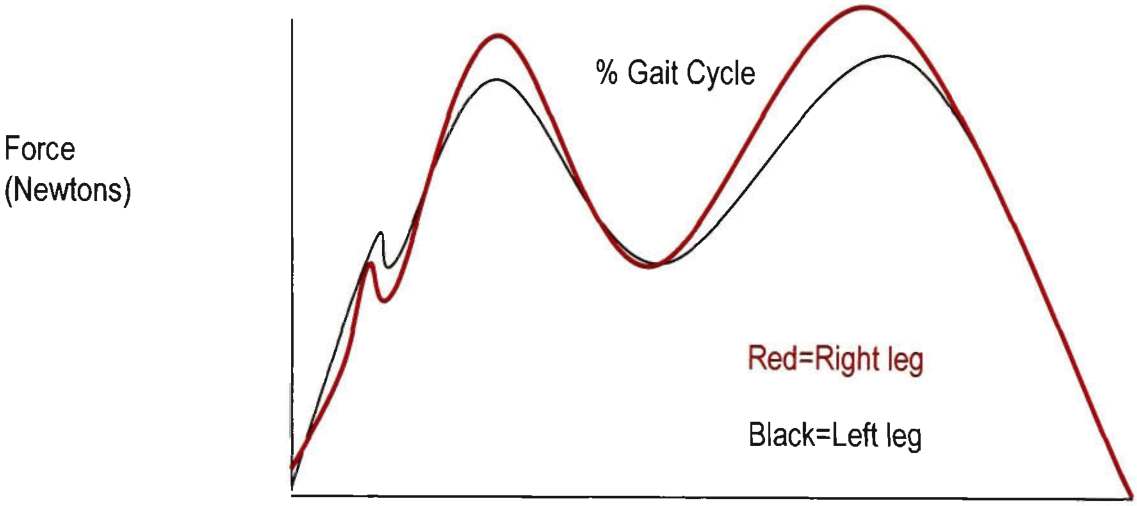


**Figure 44**

**Vertical GRF of innominate group**

**Summary of differences in asymmetries between norm and innominate groups**

The right innominate is thought to rotate posteriorly on the sacrum in the sagittal plane following the hip flexion during right initial contact and loading response (Alderink, 1991; DonTigny, 1997; Greenman, 1990; Lee, 1995; Mitchell et al., 1979). The diagnosis of anterior innominate includes a restricted range of posterior rotation, and also is thought to cause a functional lengthening of the ipsilateral lower limb, measured by the medial malleolus becoming inferior (see Section 6.5.1)(Greenman, 1989). This is thought to occur because of the changed relationship of the acetabulum to the ground when the innominate is anteriorly rotated. It is plausible that both a restricted stride length and a functionally lengthened leg would cause increased vertical acceleration of the COG. This may explain the exaggerated forces on loading response and terminal stance in the positive innominate group on the right side. It is not clear if an altered stride length or functionally longer limb could increase the steepness of slope. The right leg of the innominate group reached the third peak more quickly compared to control, which may represent an inefficient biomechanical transfer of load related to the restrictions of motion in the SIJs in this group.

The findings of significant asymmetry in the norm group for the third vertical maximum and the propulsive parameters may be demonstrating that either:

- normal gait is asymmetrical in these parameters, and therefore symmetry is abnormal (see discussion in Section 9.3); or
- the norm group had other unexcluded conditions creating asymmetrical gait.

The findings that the second and third vertical maxima were higher in an SIJD group agree with a similar previous study (Herzog et al., 1988). These authors' result of the second vertical minima being lower in the positive group was not confirmed in this current study. The previous study did not differentiate the types of SIJD, as in the current study, but used a simple "involved side" for the diagnosis, consistent with a B1 label from section 3.4.1. Therefore, their findings may reflect not only the same dysfunction (anteriorly rotated innominate) but also others that were excluded in the current study. The current study did not confirm the findings of lower propulsive and medial forces in this positive innominate group, but confirmed that the majority of the mediolateral forces were both highly asymmetrical and variable. The findings of differences between groups in the current study contradicts the conclusions of Osterbauer et al (1993) who found no differences in the GRFs between normal and SIJD groups, although again those researchers used the diagnostic category B – that of painful SIJ, and therefore may not have tested the same subject population as the current study tested.

The finding of Robinson et al (1987) that only a minority of calculated cases (62 out of 198 trials, or 31%) were asymmetrical in their positive group, can be compared to the current study (44 of the 76 parameters, or 57%). A direct comparison of trials could not be done, as the parameter measures in the current study represent the means of trials. The findings demonstrate a higher incidence of asymmetry in the two positive groups studied, and illustrates that SIJD does not appear to affect all parameters of the GRFs.

The same authors found that the parameters that were more than 10% asymmetrical using the symmetry index outlined in section 4.7.2, moved towards symmetry post manipulative treatment. These parameters included five that were asymmetrical on the positive groups in the current study – the second vertical maximum force, the third vertical maximum and its timing, the second vertical minimum, the vertical maximal slope, and the medial peak. The study does not provide details of each parameters result, which makes further direct comparison impossible. The authors used the diagnostic label B2, therefore the results may not be directly comparable to the current study.

### *9.2.2 Differences between groups norm and sacral*

The sacral group was different on five parameters where the norm group was symmetrical and the sacral group was asymmetrical. These were concerning the timing and slope of the second trough as well as the timing of the third maximum of the vertical GRFs.

The sacral group was different from the norm group on nine parameters where both groups were asymmetrical, but different. These were concerning the first minimum, its slope, the second minimum impulse and slope to the third maximum peak of the vertical GRFs and the minimum mediolateral GRF. The slope of the first minimum had high variability from week to week, and the result for the slope of the third maximum peak was not supported by its normalized findings.

The sacral group was different from the norm group on eleven parameters where it was symmetrical and the norm group was asymmetrical. These were concerning the normlaised slope of the third maximum vertical GRF, the vertical impulse, the propulsive GRFs and the timing of the maximum braking. All of these were reliable over time.

In the comparison between the norm and sacral groups, the first and second minima in the vertical GRFs represent the deceleration of the COG, and the sacral diagnosis appeared to alter this – higher on the first minimum and lower on the second. The earlier timing of the third maximum vertical peak may demonstrate inefficient biomechanical function, particularly as the right side of the forward sacral torsion (left on left) is thought to have sacral sidebending to the right (right rotation about the AP x axis) (Greenman, 1990; Mitchell et al., 1979). The right SIJ is thought to be under maximum load during midstance, before it unloads during the transition from left to right axial sacral rotation (DonTigny, 1997; Greenman, 1990; Lee, 1995; Mitchell et al., 1979). Restricted motion in the coupled osteokinematic sacral sidebending and rotation in the sacral group may create the asymmetry notable in these parameters. Figure 46 demonstrates the differences between the legs in the sacral group, after adjustment for the norm group differences.

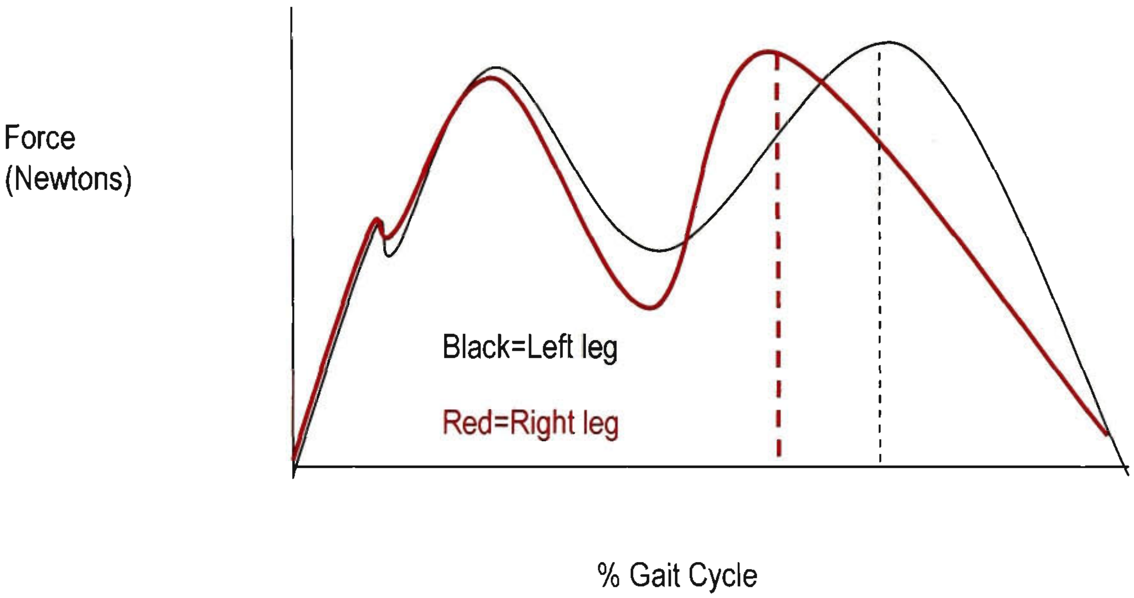


**Figure 45**

**Vertical GRF of sacral group**

### Summary of differences in asymmetries between norm and sacral groups

The increased medial GRF on the right leg in the sacral group (demonstrated in Figure 47) occurred at initial loading. At this phase there is a medial rotation of the hip, a valgus thrust to the knee joint and a medial rotation of the tibia, resulting in passive subtalar pronation. The sacrum and pelvis in general rotates to the left in the transverse plane. As part of the diagnosis in the sacral group, the sacrum is fixed in left rotation, which may exaggerate the amount of left pelvic axial rotation, causing higher acceleration of the COG in the medial direction at the right foot. Imbalance in the muscles of hip rotation (particularly piriformis) is also thought to play a role in this diagnosis (Greenman, 1989; Mitchell et al., 1979), and may also affect medial COG acceleration at the foot in this phase of gait.

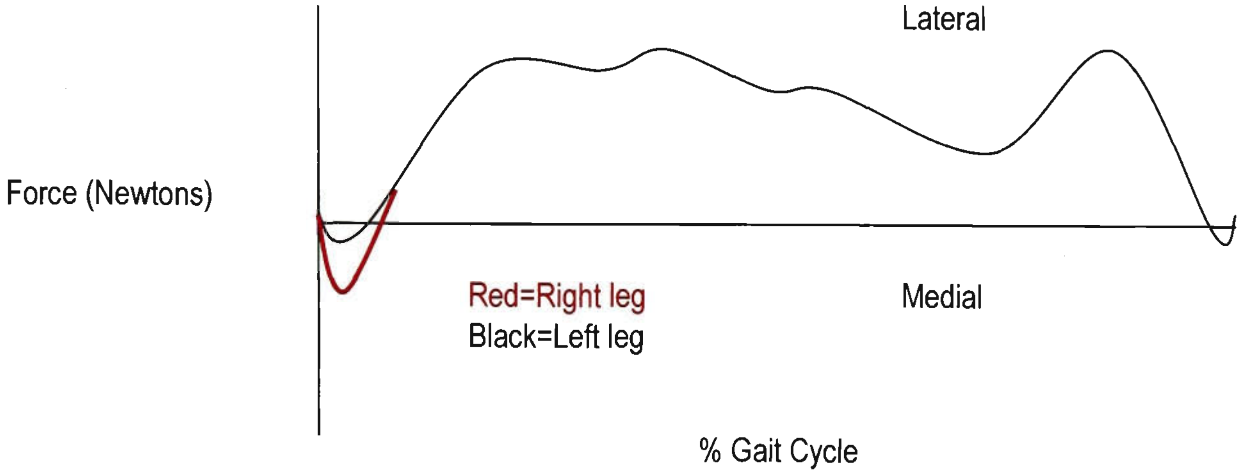


**Figure 46**

**Mediolateral GRF of sacral group**

### Summary of differences in asymmetry between norm and sacral groups

The findings of significant asymmetry in the norm group for the third vertical maximum force, the propulsive and the braking parameters may be demonstrating that either:

- normal gait is asymmetrical in these parameters, and therefore symmetry is abnormal (see discussion in Section 9.3); ori
- the norm group had other unexcluded conditions creating asymmetrical gait.

In one of the very few related studies, Herzog and co-workers (1988) found that the second vertical minima was lower in the positive group; the current study conversely found higher forces on this parameter in the positive sacral group. The previous study did not differentiate the types of SIJD, as done in the current study, but used a simple "involved side" for the diagnosis, consistent with a B1 label from section 3.4.1.

Therefore, their findings may reflect not only the same dysfunction (forward sacral torsion – left on left) but also others that were excluded in the current study.

The same is true for the Robinson et al (1993) study, which used a B2 diagnostic label. Results from this study listed parameters that were asymmetrical before manipulative treatement, and two of them were asymmetrical in the sacral group in this current study (second vertical minimum force and medial peak force). Robinson and co workers defined asymmetry as greater than 10% difference between legs on a Symmetry Index (outlined in section 4.7.2), which is different to the method utilised in this current study, so direct comparisons are difficult.

### *9.2.3 Differences between the innominate and sacral groups*

The innominate group was different on seven parameters where it was asymmetrical and the sacral group was symmetrical. These were concerning the slopes of the first and second maxima of the vertical GRFs, and the timing of maximal braking GRF.

The innominate group was different from the sacral group on six parameters where both groups were asymmetrical, but significantly different. These were the timing and slope of the first minimum trough and the peak medial GRF. The timing of the first trough was variable from week to week. The finding on the slope of the third vertical maximum was not supported by the normalized parameter.

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The sacral group was different from the innominate group on two parameters where the sacral group was asymmetrical and the innominate group was symmetrical. These were regarding the slope of the second minimum of the vertical GRF.

In the comparison between the innominate and sacral groups, the first maximum is related to heel strike in early initial contact, and the innominate group had lower forces compared to the sacral group. The time of maximum braking demonstrated that the innominate group had a delayed peak during initial contact and loading response. This may be related to the proposed functional longer leg in the innominate group. As mentioned in Section 4.6.2, the right innominate is thought to rotate posteriorly on the sacrum in the sagittal plane leading up to initial contact, and it is plausible that a restricted stride length might cause altered vertical and braking GRFs in loading response.

The sacral group was differentiated from a symmetrical innominate group in the second minima. The second minimum is related to midstance when the body weight unloads over the longitudinal arch of the foot. The right SIJ is thought to be under maximum load during midstance, before it unloads during the transition from left to right axial sacral rotation, as mentioned in Section 4.6.3. Restricted motion in the coupled osteokinematic sacral sidebending and rotation in the sacral group may create the asymmetry notable in this second vertical trough.

The medial force also differentiated between the groups, despite the asymmetry of both groups, and demonstrated that the medial acceleration GRF of the right leg of the sacral group was larger than the left, possibly meaning that right leg adduction or foot pronation were involved in creating greater than normal medial reaction force.

The timing of braking, where the right leg of the innominate group was delayed compared to the sacral group, may demonstrate a biomechanical inefficiency. This is demonstrated in Figure 45, showing the right leg reaching the braking peak later than the left leg.

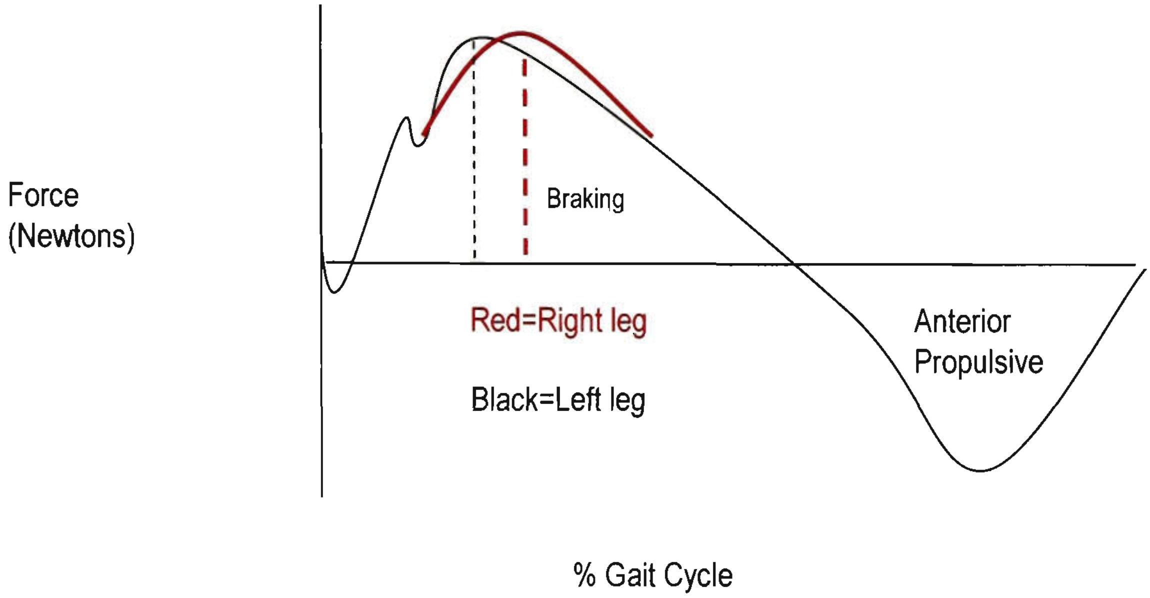

**Figure 47**

**Anteroposterior GRF of innominate group**

**Summary of differences in asymmetries between innominate and sacral groups**

### *9.3 Asymmetry in normal gait*

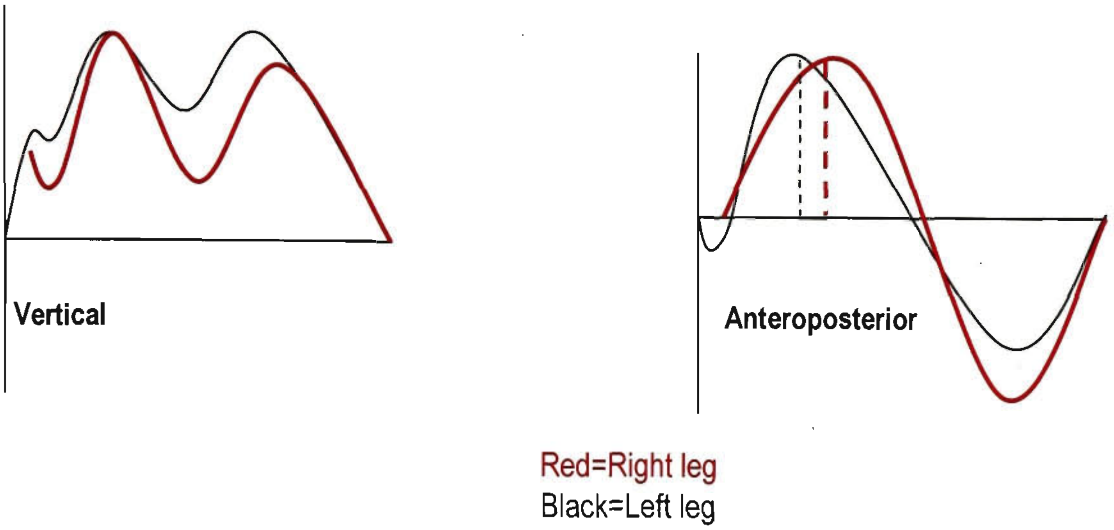

**Figure 48**

**Asymmetry between legs in norm group**

The asymmetry between legs in the normal group in this study concerns the first and second troughs as well as the third maximum peak of the vertical force, the time of maximal braking and the propulsive forces in the anteroposterior measures, and the medial force (see Figure 48). These findings appear to contradict the preconception present in the literature that normal gait is symmetrical, and that altered gait becomes normal as it regains asymmetry. This may be true in the extremes of pathological gait, for instance measuring the gait of amputee subjects following prosthesis. In contrast, this study suggests that normal gait has asymmetrical GRFs, due to an unknown effect, but possibly due to leg dominance. Gait has never been reported as perfectly symmetrical, but claims of non-preference have been made based on less than 4% deviation from zero using a symmetry index (Herzog et al, 1989).

In a recent review, gait is described as naturally asymmetrical, based possibly on a neurophysiological lateralisation where one limb is used for support and body weight transfer and the other limb for mobility, predominantly propulsion (Sadeghi et al, 2000). These reports help to explain some of the findings in this study with regards to the asymmetry of normal subjects; propulsion was the most asymmetrical parameter in the normal group, with the right leg being higher in propulsive parameters.

The question arises that if normal gait is asymmetrical in part, then are findings of symmetry in a patient population suggestive of dysfunction? This would challenge the literature (Giakas & Baltzopouolos, 1997; Herzog et al., 1989; Osterbauer et al., 1993; Robinson et al., 1987; White et al., 1999) that utilised gait analysis to measure clinical improvement as symmetry returns. This then becomes a question of degree, in that normal gait may have minor asymmetries, but severe pathological gait has major differences between legs, and still may return to normal with some measure of, but not perfect, symmetry.

## *10 Limitations of the study and future directions*

As part of this discussion, it is vital to consider the validity of these findings. This can be divided into internal and external validity (DePoy and Gitlin, 1994, p96). Internal validity refers to the ability of the research design to answer the research question, whereas external validity refers to the capacity to generalise findings and develop inferences from the sample to the study population.

### *10.1 Internal validity*

The design of this study included a set of exclusion criteria that may appear to be excessively stringent. The clinical reality with diagnoses like SIJD is that many conditions are excluded before the clinician depends upon a procedure like the one used in this study. Ensuring that there were no pathologies or dysfunctions apart from what was being studied, as well as screening for false positives in the testing, has resulted in a more homogeneous group, and increased confidence in the results.

Building a methodology that aims to test clinical practice observations should always include procedures that mimic practice as much as possible. This is particularly true with manual medicine practice where palpatory tests are utilised within a larger framework of exclusion and differential diagnosis. There may have been undiagnosed pathologies in the subject population that had not caused acute pain, and screening with radiological and serum analyses would be necessary to exclude this possibility.

### *10.2 External validity*

This study had a subject population of volunteer adult males aged from 18-55 years of age. This precluded the variability in the female, child and aged populations that may alter the gait. Studies need to be completed on these sections of the broader population in order to generalise about the gait of subjects with SIJD, with careful selection within these groups necessary to explain the variations associated with hormonal action, stages of development and degeneration. The gait of subjects with pathologies of the lower limbs, pelvis and lumbar spine were not studied, and the methodology excluded these groups from the study as far as possible.

As mentioned in Section 7.3, the possibility of a Type 1 statistical error exists in this study because of the high number of tests completed. The ability to generalize findings from this study alone is therefore diminsished, although of the 66 significant findings in the comparison between groups, only one finding had an alpha of higher than 0.02. In this study, the goal was to explore the data, looking for credible relationships to be confirmed in future research, and to put some restriction on which relationships would be worthy of further study.

### *10.3 Diagnostic procedure*

A limitation of this study was that the diagnostic procedure was carried out by just one examiner, although experienced. This reduces the strength of the findings because of the question about the inter examiner reliability of the testing used, as the diagnostic procedure used has not been formally tested for reliability. The standing and seated flexion tests have both been reported as having poor to fair inter-examiner reliability (Cibulka, et al, 1988; Potter & Rothstein, 1985; Van Deursen et al, 1990), and their continued use within the manual medicine community will depend on the whole diagnostic procedure being exposed to further research. As mentioned in 3.4.3 and 3.4.4, the studies into these tests had deficiencies that can be improved upon. The retest group did return with the same diagnoses after one week, although tested by the same examiner. The modified procedure needs to be examined for reliability, and then applied to a larger and more varied population to generalise the findings.

### *10.4 Natural variability of gait*

Like many physiological parameters, gait has a natural variability and an individual character. Analysing conditions like SIJD, researchers must satisfy themselves that the differences in gait are due to the condition and not natural variance. Studies suggest that it is first necessary to quantify the repeatability of each subject by multiple trials before biomechanical comparisons can be made (Herzog, 1989b). This supports the methodology in this study where 10 trials on each leg were completed, and where a Multilevel statistical model was utilised to explain the sources of variance.

## *11 Conclusions*

A relationship was found in 37 of 76 parameters studied between the ground reaction forces measured on a force platform during gait and the osteopathic diagnoses of anteriorly rotated innominate and anterior sacral torsion (left on left).

Gait, as measured by ground reaction forces, of symptomatic male subjects aged between 18-55 years of age who were diagnosed using a modified osteopathic procedure with two variants of sacroiliac joint somatic dysfunction, was significantly different to a comparable group of asymptomatic subjects who did not have sacroiliac joint somatic dysfunction.

The differences between the normal and anteriorly rotated innominate groups that were most relevant for further study were of the three vertical maximal peaks. The positive right leg had decreased heelstrike forces, but conversely had increased forces in loading in both of the peaks in the typical biphasic pattern.

The differences between the normal and anterior sacral torsion (left on left) groups that were most relevant for further study were of the three minimal vertical troughs. The right leg of the positive group had increased force in the heelstrike trough, as well as increased impulse in, and increased time to the second trough. Also significant was the increased medial force in the right leg of this group.

The most relevant differences between the two positive groups were where the innominate group had higher force in, and longer time to the heelstrike transient, as well as longer time to the maximal braking peak.

Significant asymmetry was found in the normal group with a number of variables. This may be due to leg dominance, but there is a paucity of literature about this asymmetry of function of the lower limbs. As mentioned in section 9.3, lateralization of limb function and its relationship to dominance is not clear, and this is an area demanding further research. The significant findings in the positive groups in this study took into account these asymmetries in the normal group.

These findings represent the first time there has been objective evidence of these osteopathic diagnoses, and take one preliminary step in revealing the effect they may have on gait and motion dysfunction. The diagnoses appeared stable over time, as did the diagnostic procedure carried out by the lone examiner. 15 of the 76 GRF parameters demonstrated excessive variability over time.

The use of GRF measured on force platforms to objectively analyse biomechanical dysfunctions of the lower limbs and pelvis appears to be a reasonable method for future research. The transfer of load from the lower limbs through the pelvis into the vertebral structures and trunk is an emerging area of interest in low back and pelvic pain, and the study of GRF with clinical application may be productive for future research on painful conditions in these regions.

A new classification system of the definitions and diagnostic criteria for the various conditions under the broad label Sacroiliac Joint Dysfunction was proposed, clarifying the field of study for future research.

# *12 APPENDICES*

## *12.1 APPENDIX 1 Questionnaire and Informed Consent*

***VICTORIA UNIVERSITY***
***CENTRE FOR REHABILITATION, EXERCISE AND SPORT SCIENCE***
***Biomechanics Unit***

### ***Lower Back Function in Walking***

### ***Informed Consent and Information form***

This study invoves being examined for stiff joints in the lower back by Dr Paul Orrock, a registered Osteopath, and then comfortable walking 20 times over plates in the floor.

The back tests are simple motion tests. They are painless. They involve feeling for movement in the joints of your lower back in standing, sitting and lying positions. This should take 20 minutes. Some subjects may be asked to return in one week to check the consistency of the findings.

***Please answer yes or no to the following questions:***

Have you had:

Previous **fracture/accident** in the lower back, pelvis, hip, knee or ankle?
Previous **surgery** in the low back, pelvis or lower limbs?
Any organ **disease** in the pelvis (eg bowel, prostate)?
**Arthritis** in the lower back or limbs?
Diagnosed **short leg** requiring shoe inserts?
Current (ie in the lasts 6 months) **pain** in the lower back, limbs or pelvis?
    Please describe the features of this pain.

***I understand that I can withdraw from this study at any time, and that this testing will not interfere with any treatment I am receiving.***

***I have been informed of all the procedures, have had any questions answered, and I consent to participate in this study.***

***Name ....................................................................................***
***Signed .......................................................Date.......................***

## 12.2 APPENDIX 2 *Week to week reliability table*

| Number | Parameter | Variance component attributed to week | Standard error SE | Total variance | % of total attributed to week |
|---|---|---|---|---|---|
| 1 | FzMAX 1 | 1143.359 | 402.523 | 13979.201 | 8.179 |
| 2 | FzMAX 1N | .0019 | .0007 | .0218 | 11.47 |
| 3 | FzMAX1 I | 0 | 0 | 2.5661 | 0 |
| 4 | FzMAX1 MnI | .005 | .0008 | 0.326 | 1.5 |
| 5 | FzMAX T | 0 | 0 | 2.23 | 0 |
| 6 | FzMAXTN | .0087 | .017 | .7196 | 1 |
| 7 | FzSI MAX 1 | 14493420 | 5751327 | 155419450 | 9 |
| 8 | FzSIN MAX1 | 24.510 | 9.713 | 237.425 | 10 |
| 9 | Fz MIN1 | 269.346 | 111.750 | 4165.353 | 6 |
| 10 | Fz MIN1N | 0.04 | 0.01 | .87 | 4.5 |
| 11 | Fz MIN1I | 1.005 | 0.534 | 10.834 | 9 |
| 12 | Fz MIN1Mni | 0.011 | .007 | .14 | 7.8 |
| 13 | Fz MIN1T | 0.006 | .014 | .507 | 1 |
| 14 | Fz MIN1TN | 0.046 | .046 | 1.319 | 3.4 |
| 15 | Fz MIN1SI | 930276.6 | 507779.6 | 20015834 | 4.6 |
| 16 | Fz MIN1SIN | 1.608 | 0.883 | 37.122 | 4.3 |
| 17 | Fz MAX2 | 858.018 | 277.172 | 4345.851 | 19 |
| 18 | Fz MAX2N | 10.348 | 3.481 | 50.985 | 20 |
| 19 | Fz MAX2I | 7.666 | 3.351 | 77.772 | 9 |
| 20 | Fz MAX2MnI | 0.078 | .044 | .858 | 9 |
| 21 | Fz MAX2T | 0.117 | .059 | 1.612 | 7.2 |
| 22 | Fz MAX2TN | 0.0149 | .01 | .4779 | 3 |
| 23 | Fz MAX2SI | 89661.96 | 41499.7 | 928678.2 | 9 |
| 24 | Fz MAX2SIN | 17.740 | 3.628 | 18.254 | 97 |
| 25 | Fz MIN2 | 327.894 | 107.732 | 2345.91 | 13 |
| 26 | Fz MIN2N | .659 | 0.212 | 2.504 | 26 |
| 27 | Fz MIN2I | 53.967 | 18.466 | 451.826 | 11 |
| 28 | Fz MIN2MnI | 0.057 | .0217 | .384 | 14 |
| 29 | Fz MIN2T | 0.0848 | .0319 | .506 | 16 |
| 30 | Fz MIN2TN | 0.197 | .0749 | .926 | 21 |
| 31 | Fz MIN2SI | 8694.745 | 2950.85 | 34135.84 | 25 |
| 32 | Fz MIN2SIN | .019 | .006 | .066 | 28 |
| 33 | Fz MAX3 | 200.645 | 77.173 | 5242.836 | 3 |
| 34 | Fz MAX3N | 0.2553 | 0.1062 | 2.8626 | 9 |
| 35 | Fz MAX3I | 47.777 | 15.931 | 1058.158 | 4 |
| 36 | Fz MAX3MnI | 0.031 | 0.012 | .934 | 3 |
| 37 | Fz MAX3T | 0.033 | 0.013 | .94 | 3.5 |
| 38 | Fz MAX3TN | 0.019 | .01 | .51 | 4 |
| 39 | Fz MAX3SI | 8694.745 | 2950.85 | 34405.84 | 25 |
| 40 | Fz MAX3SIN | .003 | .001 | .042 | 7 |
| 41 | Fz Imp | 48.771 | 15.788 | 1250.96 | 3 |
| 42 | Max Prop | 47.377 | 16.603 | 635.299 | 7 |
| 43 | Max Prop N | 0.06 | 0.02 | 1.029 | 6 |
| 44 | Max Prop T | 0.032 | 0.012 | .728 | 4 |
| 45 | Max Prop TN | 0.159 | 0.065 | 1.299 | 12 |
| 46 | Avg Prop | 13.263 | 4.473 | 154.41 | 8 |
| 47 | Avg Prop N | 0.017 | 0.0064 | .24 | 7 |
| 48 | Prop Imp | 1.052 | 0.370 | 16.142 | 6 |
| 49 | Prop Imp MnI | 0.025 | .011 | 0.369 | 7 |
| 50 | Max Brake | 162.4 | 54.1 | 659.285 | 24 |
| 51 | Max Brake N | 0.263 | 0.088 | 1.27 | 20 |
| 52 | Max Brake T | 0.0386 | 0.016 | .257 | 15 |
| 53 | Max Brake TN | 0.075 | .033 | 0.695 | 10 |
| 54 | Avg Brake | 29.897 | 9.501 | 109.97 | 27 |
| 55 | Avg Brake N | 0.0438 | .0145 | .21 | 20 |
| 56 | Avg Brake Imp | 4.585 | 1.466 | 25.812 | 17 |

| Number | Parameter | Variance component | Standard error SE | Total variance | % of total as week |
|---|---|---|---|---|---|
| 57 | Brake Mnl | 0.077 | .026 | .464 | 16 |
| 58 | Fy Avg | 14.531 | 4.918 | 61.82 | 23 |
| 59 | Fy Avg N | 0.264 | .093 | 1.238 | 21 |
| 60 | Fy Imp | 5.573 | 1.883 | 23.151 | 24 |
| 61 | Fx Max (lateral) | 50.437 | 23.62 | 232.191 | 21.72 |
| 62 | Fx Max N | .083 | .039 | .382 | 21.72 |
| 63 | Fx Max T | .11 | .054 | .912 | 12 |
| 64 | Fx Max TN | .272 | .135 | 2.44 | 11 |
| 65 | Fx Min (medial) | 33.606 | 17.53 | 523.476 | 6.4 |
| 66 | Fx Min N | .062 | .031 | .754 | 8.2 |
| 67 | Fx Min T | .276 | .12 | 2.36 | 12 |
| 68 | Fx Min TN | .069 | .031 | .604 | 11 |
| 69 | Fx Avg | 71.266 | 22.908 | 176.194 | 40 |
| 70 | Fx Avg N | .136 | .044 | .325 | 41 |
| 71 | Fx Imp | 27.574 | 8.864 | 67.443 | 40 |
| 72 | Fx Mnl | .625 | .2 | 1.355 | 46 |
| 73 | X excur | 1.12 | 0,5 | 9.507 | 11 |
| 74 | 30 Force | 43.879 | 14.925 | 161.425 | 27 |
| 75 | 30 Force N | .856 | .286 | 2.765 | 30 |
| 76 | 30 excur | .393 | .136 | 1.788 | 21 |

## 12.3 APPENDIX 3 Statistical Analyses

The statistical approach utilised was a multilevel analysis, a form of multiple regression designed for repeated measures data sets. The four models used (week to week model and the three models of the main analysis, see Section 7) are detailed here, in order to explain the calculations. The first parameter, Fz Max 1, is used as an example in the models following.

First was the week to week analysis, which included three levels of variance - trial, week and subject.

$$\text{fzmax1}_{ijk} \sim \mathrm{N}(XB,\ \Omega)$$

$$\begin{aligned}\text{fzmax1}_{ijk} = {} & \beta_{0ijk}\text{cons} + \text{-}74.299(75.422)\text{g2}_k + \text{-}55.839(75.449)\text{g3}_k + \text{-}5.831(61.590)\text{rl}_k + \\ & \text{-}2.674(106.681)\text{g2rl}_k + 14.762(106.716)\text{g3rl}_k\end{aligned}$$

$$\beta_{0ijk} = 576.151(43.547) + v_{0k} + u_{0jk} + e_{0ijk}$$

$$\left[v_{0k}\right] \sim \mathrm{N}(0,\ \Omega_v) : \Omega_v = \left[10686.730(3278.344)\right]$$

$$\left[u_{0jk}\right] \sim \mathrm{N}(0,\ \Omega_u) : \Omega_u = \left[1143.359(402.523)\right]$$

$$\left[e_{0ijk}\right] \sim \mathrm{N}(0,\ \Omega_e) : \Omega_e = \left[2149.112(156.529)\right]$$

$$-2{*}log(like) = 4611.282$$

**Figure 49**

**Multilevel week by week model and estimates for the variable fzmax1**

The first line of Figure 49 describes the distributional assumptions of the model, that the residuals in fzmax1 for trial *i*, week *j* and subject *k*, are normally distributed about the fixed part of the model *XB* and are collected in the matrix $\mathbf{\Omega}$.

The fixed part of the model, *XB,* is presented next. $\beta_{0ijk}$cons is the overall intercept, g2 and g3 are dummy coded variables representing the *group* variable with group 1 (control) as the reference category, rl is a dummy coded variable representing the *leg* variable with the left leg as the reference category, and g2rl and g3rl represent *group by leg* interaction effects. In this example, only the intercept ($\beta_{0ijk}$) (576.15) is significant ($p \leq .05$), being more than 1.96 times its SE (in brackets, 43.55).

$\mathbf{\Omega}$ contains the three residual variance estimates of the three levels of variance, $\Omega_e$, $\Omega_u$, $\Omega_v$, for *trials (within weeks), weeks (within subjects)* and *subjects* respectively. In this example, the variance from week to week (1143.4) is significant ($p \leq .05$), being more than 1.96 times its SE (402.5), and is 8.18% of the total residual variance (the specific variance component divided by the total of all three components: 1143.36/(10686.7+1143.4+2149.1)). This proportion of total variance is smaller than the variance attributable to trial within week (15.4%). The number –2*log(like) stands for 'minus 2 loglikelihood', or -2LL, and is a measure of how far the data are from the model on average. The week to week results for all parameters are shown in Appendix 2.

Following is the three models used to compare groups, which had two level of variance – trial and subject.

$$\text{fzmax1}_{ij} \sim \text{N}(XB,\ \Omega)$$
$$\text{fzmax1}_{ij} = \beta_{0ij}\text{cons}$$
$$\beta_{0ij} = 542.607(14.652) + u_{0j} + e_{0ij}$$

$$\begin{bmatrix} u_{0j} \end{bmatrix} \sim \text{N}(0,\ \Omega_u)\ :\ \Omega_u = \begin{bmatrix} 14644.840(2520.152) \end{bmatrix}$$

$$\begin{bmatrix} e_{0ij} \end{bmatrix} \sim \text{N}(0,\ \Omega_e)\ :\ \Omega_e = \begin{bmatrix} 3133.851(126.575) \end{bmatrix}$$

$-2*loglikelihood(IGLS) = 14408.030(1295 \text{ of } 1295 \text{ cases in use})$

**Figure 50**

**Multilevel model 1 (variance components) in the main analysis**

$$\text{fzmax1}_{ij} \sim \text{N}(XB,\ \Omega)$$
$$\text{fzmax1}_{ij} = \beta_{0ij}\text{cons} + -13.877(37.120)\text{g2}_j + -2.434(35.358)\text{g3}_j + 0.172(5.156)\text{rl}_{ij} + -21.872(7.789)\text{g2rl}_{ij} + 7.014(7.323)\text{g3rl}_{ij}$$
$$\beta_{0ij} = 549.239(24.745) + u_{0j} + e_{0ij}$$

$$\begin{bmatrix} u_{0j} \end{bmatrix} \sim \text{N}(0,\ \Omega_u)\ :\ \Omega_u = \begin{bmatrix} 14977.530(2569.480) \end{bmatrix}$$

$$\begin{bmatrix} e_{0ij} \end{bmatrix} \sim \text{N}(0,\ \Omega_e)\ :\ \Omega_e = \begin{bmatrix} 3101.445(125.294) \end{bmatrix}$$

$-2*loglikelihood(IGLS) = 14391.820(1295 \text{ of } 1295 \text{ cases in use})$

**Figure 51**

**Multilevel model 2 (g2g3) in the main analysis**

$$\mathrm{fzmax1}_{ij} \sim \mathrm{N}(XB,\ \Omega)$$

$$\mathrm{fzmax1}_{ij} = \beta_{0ij}\mathrm{cons} + 13.876(37.120)\mathrm{g1}_j + 11.441(37.462)\mathrm{g3}_j + -21.700(5.839)\mathrm{rl}_{ij} + 21.872(7.789)\mathrm{g1rl}_{ij} + 28.886(7.819)\mathrm{g3rl}_{ij}$$

$$\beta_{0ij} = 535.363(27.668) + u_{0j} + e_{0ij}$$

$$\left[u_{0j}\right] \sim \mathrm{N}(0,\ \Omega_u) : \Omega_u = \left[14977.410(2569.508)\right]$$

$$\left[e_{0ij}\right] \sim \mathrm{N}(0,\ \Omega_e) : \Omega_e = \left[3101.446(125.294)\right]$$

*-2*loglikelihood(IGLS)* = **14391.810(1295 of 1295 cases in use)**

**Figure 52**

**Multilevel model 3 (g1g3) in the main analysis**

The first line of Figure 52, 53 and 54 describes the distributional assumptions of the model, that the residuals in fzmax1 for trial *i* and subject *j*, are normally distributed about the fixed part of the model *XB* and are collected in the matrix **Ω**.

*XB* is presented next. Cons is the overall intercept, and in this example is significant (542.607) ($p \leq .05$), being more than 1.96 times its SE (in brackets, 14.652). **Ω** contains the two residual variance estimates, $\Omega_e$, $\Omega_u$, for *trials (within weeks)* and *subjects* respectively.

The calculation to measure the difference in asymmetry between groups starts with cons (norm in model 2 and innominate in model 3), and adds each component of variance. For example, to find the measure of the right leg in the sacral group, in order to compare the asymmetries between groups, the calculation would be:

Model 2: Cons (549.239)(norm left leg) + -2.434 g3 (sacral left leg) + 0.172 rl (norm right leg) + 7.014 g3rl (sacral right leg) = 553.99 (measure of sacral right leg). See Section 8.2.2.1 where this finding is recorded and not considered significant due to its high Standard Error.

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