The Role of Clinical Lumbo-Pelvic and Hip Tests in the Examination of Gait

by

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A thesis submitted in partial fulfilment for the requirements for the degree of Doctor of Philosophy at the University of Central Lancashire

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and Hip Tests in the Examination of Gait

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Supervisory Team:

Prof James Selfe & Prof Jim Richards

Student Declaration

Student Declaration

Concurrent registration for two or more academic awards

*I declare that while registered as a candidate for the research degree, I have not been a registered candidate or enrolled student for another award of the University or other academic or professional institution

Material submitted for another award

*I declare that no material contained in the thesis has been used in any other submission for an academic award and is solely my own work

Signature of Candidate

Type of Award **PhD**

School **School of Sport, Tourism and the Outdoors**

Abstract

The majority of musculoskeletal patients attend with Lumbo-Pelvic and Hip dysfunction complaining of difficulty during walking and running. Clinicians commonly use weight bearing tests to examine the components of walking and running but these tests use postures and movements that are different to those found during gait. Few studies have examined the relationship between these tests and gait. The aim of this study was to investigate the validity of the Trendelenburg Test, Single Leg Squat and Corkscrew Test as measures of dynamic stability of the Lumbo-Pelvic and Hip region in healthy participants and professional football players during gait. This was a laboratory based study using an experimental, repeated measures design. 18 full time professional football players and 14 healthy participants were recruited. Movement data was captured using a ten camera system using the CAST technique. This study found that for walking there should be observable movement of all the regions and in all planes except at the: lumbar spine; thoracic spine ; trunk in the sagittal plane and lumbar spine; pelvis in the coronal plane. For running there should be observable movement of all the regions and planes. Recommendations are made for changes in the interpretation of the Trendelenburg Test and Single Leg Squat. New values for the interpretation of the Corkscrew Test were also established. Professional football players exhibited differences in their movement patterns at the hip, pelvis and trunk when compared to the healthy participants. Using the Corkscrew and Single Leg Squat Tests in combination allows clinicians to comprehensively examine the sagittal and coronal plane range of movement of the lumbar and thoracic spine relevant to walking. Similar movements occurred during the tests and both walking and running, but the similarities occurred only in specific regions and planes. Hence the tests were found to be task, region and plane specific. A greater understanding of the clinical tests and their relationship to gait may help clinicians to implement evidence based examination, sub-classify and treat Lumbo-Pelvic and Hip dysfunction. This will be of greatest

use when examining and treating populations who have been found to have Lumbo-Pelvic and Hip dysfunction such as young males and professional football players.

During this study two papers were published in peer reviewed journals;

- Bailey, R., Selfe, J., & Richards, J. 2009, "The role of the Trendelenburg Test in the examination of gait", Physical Therapy Reviews, vol. 14, pp. 190-197.
- Bailey, R., Richards, J., & Selfe, J. 2011, "The Single Leg Squat Test in the Assessment of Musculoskeletal Function: a Review", Physiotherapy Practice and Research, vol. 32, no. 2, pp. 18-23.

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To my mum, Edith, who encouraged me to start my career many years ago.

To my Dad, Eric, who inspired me to challenge my boundaries, to touch them, feel them, explore them and push them. You taught me that a man can only be judged by how he responds to the challenge. Your memory will live forever in my heart.

To my wife, Emma, who showed complete faith in me, you never asked how or why, you just told me I could and I would.

To my children, Jessica and Thomas, your love is the flame that burned the midnight oil during the long nights and short days.

This thesis is about underpinning clinical practice, without these keystones there would be no thesis.

Glossary

Term	Definition
AIM model	Automatic Identification of Markers - AIM The AIM model is created from an identified file and can then be applied to any measurement that captures similar motions compared to the model or just a part of the motions in the model
Ascii file	The Visual3D pipeline command exports ASCII data to one of 2 formatted data files (Visual3D default and P2D)
Assess	Estimate or judge the value of
Bonferroni's adjustment	A method used to counteract the problem of multiple comparisons
Central locomotor command	The neurological activity that defines movement generated in the CNS
Centre	Centre of an object is a point in some sense in the middle of the object. If geometry is regarded as the study of isometry groups then the centre is a fixed point of the isometries.
Clinical tests	Trendelenburg Test, Single Leg Squat and Corkscrew Test
CI	An interval estimate of a population parameter and is used to indicate the reliability of an estimate
Coronal plane	Movement in the plane that runs through the body from the head to the feet, and divides the body into front and rear halves.
Cross talk	A phenomenon by which a signal transmitted on one circuit or channel of a transmission system creates an undesired effect in another circuit or channel
Curvilinear	Curvilinear coordinates are a coordinate system for Euclidean space in which the coordinate lines may be curved
Cut-off frequency	The frequency above which the output of the filter is reduced to
Data	Values of variables belonging to a set of items (singular)
Datum	A single value of variables belonging to a set of items (pleural)
Df (Degrees of freedom)	Degrees of freedom are the number of values in the final calculation of a statistic that are free to vary
EMG	Electromyography (EMG) is a technique for evaluating and recording the electrical activity produced by skeletal muscles
Estimated marginal means	In an analysis of covariance model, they are the group means after having controlled for a covariate (i.e. holding it constant at some typical value of the covariate, such as its mean value)

Examine	To observe test or evaluate or determine the cause of ill health
Extension	Movement posterior to the midline
External rotation	Movement in the transverse plane away from the midline
Face validity	The validity of a test at face value. In other words, a test can be said to have face validity if it "looks like" it is going to measure what it is supposed to measure
Flexion	Movement anterior to the midline
Functional tests	Walking and running
Gait cycle	An interval of time during which one sequence of regularly recurring succession of events is completed e.g. heel strike to heel strike
Good trial	A trial which was shown to possess the desired movement characteristics
Healthy participants	Healthy individuals participating within the study
Hip	The movement of the femur relative to the pelvis
Ilio-tibial band syndrome	A syndrome thought to be caused by the Ilio-tibial band frictioning on the lateral tibial epicondyle
Internal rotation	Movement in the transverse plane towards the midline
L shaped reference structure	A set square used to orientate the laboratory axes in QTM
Lowpass second order Butterworth Bi-directional filter	The number of bidirectional passes specified determines the order of the filter (e.g. 1 bidirectional pass results in a fourth order filter). The cut-off frequency takes into account the number of bidirectional passes through the signal. For the lowpass filter the slope of the signal is removed before filtering the data, then replaced after filtering
Lumbar Spine	The movement of the lumbar spine relative to the pelvis
Lumbo-Pelvic and Hip	Lumbar spine, pelvis and hip
Movement maximum	The maximum angular displacement between two segments
Movement minimum	The minimum angular displacement between two segments
Non-weight bearing	A limb not sustaining weight
Oblique sling	Myofascial structures running obliquely in the body
Paradigms	A pattern or model
Peak value	The maximum angular displacement between two segments
Pelvic	The movement of the pelvis relative to the floor
Pelvic obliquity (also known as pelvic list)	The pelvic coronal plane maximum angular displacement
Pelvic anterior tilt	The pelvis is rotated anteriorly relative to the weight bearing limb
Pelvic posterior tilt	The pelvis is rotated posteriorly relative to the weight bearing limb

Pelvic protraction	The pelvis is rotated inwards relative to the weight bearing limb
Pelvic retraction	The pelvis is rotated away relative to the weight bearing limb
Professional Football Players	Football players paid to play football by a professional club
Range of movement	The difference between the minimum and maximum displacement of a segment
Repeated measures design	A repeated measures design is when each individual participant is exposed to the same condition of the experiment, this is useful to decrease the participant variability as all the participants perform in all the same tasks
Repeated measures analysis of variance (ANOVA), with pairwise comparisons	A measure that maybe used when the same parameter has been measured under different conditions on the same participants, comparing entities in pairs to judge which of each entity is preferred
Retroreflective	A marker that reflects light back to its source with a minimum scattering of light
Rotation	Movement in the transverse plane
Sagittal plane	Movement in the plane that runs through the body from the head to the feet, and divides the body into left and right halves.
Same-subject crossover design	A longitudinal study in which participants receive a sequence of different treatments
Sample of convenience	A statistical method of drawing representative data by selecting people because of the ease of their volunteering
Script file	A file created as the first part of the pipeline process
SD	Standard Deviation
Shank	Tibia and fibula
Side flexion	Movement lateral to the midline
Significance level	Probability that the test statistic will reject the null hypothesis when the hypothesis is true
Single limb stance	Standing on one leg
Statistical power	The power of a statistical test is the probability that the test will reject the null hypothesis when the null hypothesis is false (i.e. the probability of not committing a Type II error, or making a false negative decision). The power is in general a function of the possible distributions, often determined by a parameter, under the alternative hypothesis. As the power increases, the chances of a Type II error occurring decrease. The probability of a Type II error occurring is referred to as the false negative rate
Std. Error	The standard error is the standard deviation of the sampling distribution of a statistic
Thigh	Femur
Thoracic Spine	The movement of the thoracic spine relative to the lumbar

	spine
Three cardinal planes	The three imaginary cardinal planes bisect the mass of the body in three dimensions.
Three non-collinear markers	Three markers not lying on the same straight line
Threshold values	A threshold is set to automatically discriminate the marker “pixels” which are the brightest objects in the laboratory
Transverse plane	Movement in the plane that runs left to right through the body and divides it into upper and lower sections.
Tracking markers	Markers that can be retrieved during the study and can be used to calculate the position and orientation of the local co-ordinate system
Trunk	The movement of the trunk relative to the pelvis
Type I error	A type I error, also known as an error of the first kind, occurs when the null hypothesis (H0) is true, but is rejected. It is asserting something that is absent, a false hit. A type I error may be compared with a so called false positive (a result that indicates that a given condition is present when it actually is not present) in tests where a single condition is tested for
Validity	Validity is the extent to which a test measures what it is supposed to measure

1 Introduction

Personal motivation for completing this PhD

The majority of musculoskeletal patients that clinicians treat attend with Lumbo-Pelvic and Hip dysfunction. Clinicians commonly examine the Lumbo-Pelvic and Hip region using both weight bearing and non-weight bearing tests, but there are potential problems within this approach. The non-weight bearing tests are often; single joint, low proprioceptive demand, primarily single muscle group biased and use an inner range movement. They are then being compared to a weight bearing, multiple joint, high proprioceptive demand, multiple muscle group and through range functions such as gait. Many of the clinical examination paradigms, such as Maitland (Maitland, Brewerton, Graham, & Edwards, 1986) or Cyriax (Cyriax, 1944; Cyriax, 2001), refer to the need for normal, symmetrical movement but rarely define what the normal range of movement should be. This study was therefore primarily motivated by the desire to investigate what the normal range of movement is during gait and specific clinical tests, and to create a guide for clinicians to refer to within the clinic.

There are existing weight bearing tests that are available for clinicians to use during the examination process of gait. Whilst these superficially appear more appropriate for the examination of gait, as a group the weight bearing tests use movements and positions that are different to those found during gait. One such contrast is seen when comparing the pelvic obliquity seen during the Trendelenburg Test and walking. By referring to the original paper by Trendelenburg states that the test position is " *… auf dem kranken Bein stehehend, die Gesasshalfte der gesund Seite bis zur Hohe*," (Trendelenburg, 1895), translated as *"… the pelvis is elevated as high as possible and held in this elevated position*," (Peltier, 1998). A focus therefore of this study was to investigate if the movements and positions performed during common weight bearing clinical tests are similar to the movements found during gait.

Clinical observation has also suggested that patients who perform a specific movement frequently enough appear to show changes in their movement patterns. Previous clinical experience with professional football players suggests that they exhibit altered Lumbo-Pelvic and Hip movement patterns. A tertiary motivator was therefore the desire to investigate if professional football players exhibited different Lumbo-Pelvic and Hip kinematics when compared to healthy participants.

1.1 Gait examination

The examination of gait is one of the oldest clinical examination techniques. It is used as an indication of functional ability, to aid diagnosis formation, to monitor rehabilitation and to define the extent of recovery. Despite advances in technology permitting a more advanced examination of walking, clinicians frequently use the oldest method of visual observation to examine it. Their interpretations of these observations are often subjective and based on the clinician's preconceived values. The examination of running gait is more difficult for clinicians than walking due to the faster moving segments. Consequently the accurate clinical interpretation of these observations is more difficult during running than walking.

1.2 Clinical Lumbo-Pelvic and Hip tests

Two common weight bearing tests used by clinicians to examine patients with Lumbo-Pelvic and Hip dysfunction are the Trendelenburg Test and the Single Leg Squat. Recently a novel test, the Corkscrew Test, has been developed by clinicians and is starting to be used in clinical practice. All of these tests are thought to assess Lumbo-Pelvic and Hip position and control of movement by balancing on one leg.

Currently there is limited Lumbo-Pelvic and Hip kinematic data for the Trendelenburg Test, Single Leg Squat and Corkscrew Test. The data that currently exists has been drawn from pathological participants or athletically active students and is limited to the sagittal and coronal planes. Clinical experience has shown that performing a specific movement repetitively may influence an individual's Lumbo-Pelvic and Hip movement pattern even in asymptomatic individuals. Professional football players, for example, perform the dominantly unilateral movement of kicking, repetitively in their training. A priori it was thought that performing this repetitive unilateral movement may change their Lumbo-Pelvic and Hip kinematics. Professional football players would therefore form a clearly defined and easily identifiable specific subgroup of the healthy, asymptomatic population. If this change in the movement pattern was observed in this study it would confirm the clinical belief that performing repetitive movements changes movement patterns. However there is limited existing normative kinematic data for healthy participants or professional football players in three dimensional, six degrees of freedom, and currently no existing studies have investigated if there is a relationship between the Lumbo-Pelvic and Hip kinematics of walking and running when compared to the Trendelenburg Test, Single Leg Squat and Corkscrew Test in these groups.

1.3 Thesis structure

Chapter 1: Introduction

The current, common, clinical process of examining individuals with Lumbo-Pelvic and Hip dysfunction and its relationship to the gait cycle is outlined. A précis of selected common clinical Lumbo-Pelvic and Hip tests follows before a brief description of the research undertaken.

Chapter 2: Background

A synopsis of the definition, phases and events of gait to aid the reader to understand the thesis.

Chapter 3: Review of the literature

In depth review of the current kinematic evidence base relevant to the walking and running gait cycles, Trendelenburg Test, Single Leg Squat and Corkscrew Test highlighting the limitations of the current kinematic data leading to the aims and objectives of the research.

Chapter 4: Methods

The measurement techniques used, experimental procedures and methods of analysis in relation to the study.

Chapter 5: Results

The normative kinematic data recorded are stated. The walking and running gait cycle's kinematic data and the clinical tests data are compared. The differences between healthy participants and the professional football player's kinematic data are also compared.

Chapter 6: Discussion

The relationship between the current kinematic evidence base for walking and running gait cycles, Trendelenburg Test, Single Leg Squat, Corkscrew Test and this study's results are discussed. The differences between the professional football players and healthy participants' data are discussed. The implications of the results of the study for clinicians when examining the Lumbo-Pelvic and Hip region and its role in the gait cycle are stated.

Chapter 7: Conclusion

Conclusions are drawn based on the results of the study, recommendations to clinicians and researchers and future developments in this research are identified.

Chapter 8: Appendices

Additional information that is relevant to, but is not the main focus of the study, is detailed.

1.4 Aims and objectives

1.4.1 Aim

To investigate the validity of the Trendelenburg Test, Single Leg Squat and Corkscrew Test as measures of dynamic pelvic stability in healthy participants and professional football players during gait.

1.4.2 Objectives

- To establish normative Lumbo-Pelvic Hip movement data within healthy participants and professional football players during walking, running, the Trendelenburg Test, the Single Leg Squat and the Corkscrew Test.
- To investigate if there are identifiable similarities between Lumbo-Pelvic and Hip movement during walking, running, the Trendelenburg Test, the Single Leg Squat and the Corkscrew Test.
- To investigate if there is an identifiable difference between Lumbo-Pelvic and Hip movement during walking, running, the Trendelenburg Test and the Single Leg Squat between healthy participants and professional football players.
- To consider the clinical relevance of the Trendelenburg Test, the Single Leg Squat and the Corkscrew Test when examining walking and running gait.

1.5 Scope, boundaries, context and groups

The scope of this study is to generate Lumbo-Pelvic and Hip kinematic data for walking, running, the Trendelenburg Test, Single Leg Squat and Corkscrew Tests for healthy participants and professional football players. It will investigate if there are identifiable similarities between the functional and clinical test Lumbo-Pelvic and Hip kinematic data, and if there are identifiable differences between the groups. The findings will be limited to these particular sub-groups of the general population. The CAST technique used in the "professional football players" study to generate the 13 segment model has received previous validation and is commonly used within the literature. However the 15 segment model (including lumbar and thoracic spine clusters) used in the healthy participants study has not been validated. The Lumbo-Pelvic and Hip kinematic data found in the study are specific to the laboratory environment and not generalizable to external environments including a football pitch. The data found however will be similar to that found in a musculoskeletal clinic and hence this study's findings may be used by clinicians and researchers, examining and treating participants with Lumbo-Pelvic and Hip dysfunction during gait. A priori it was thought that the professional football players would exhibit changes within their Lumbo-Pelvic and Hip kinematics and that the healthy participants would form a matched population exhibiting normal kinematics that these could be compared to.

2 Background

2.1 A description of gait

Gait is the process of locomotion in which the erect, moving body is supported by first one limb and then the other (Rose & Gamble, 2006). As the moving body passes over the supporting limb, the other limb swings forward in preparation for its next support phase. Gait maybe divided into two types; walking gait and running gait. Both walking and running are divided into phases.

2.2 Gait phases

The gait cycle is defined as the interval of time taken for one sequence of regularly recurring events to be completed (Levine, Richards, & Whittle, 2012; Rose et al., 2006). The gait cycle is divided into two phases: stance and swing phases (Karandikar & Vargas, 2011; Levine et al., 2012; Richards, 2008; Rose et al., 2006):

1. Stance phase is the period when the foot is in contact with the ground and is approximately 60% of the walking gait cycle (Levine et al., 2012; Richards, 2008; Rose et al., 2006). This foot contact with the ground constitutes a significant external resistance and hence during the stance phase the lower limb is considered to be in closed kinetic chain (Augustsson, Esko, Thomee, & Svantesson, 1998; Butler & Major, 2003).

2. Swing phase is the period when the foot is not in contact with the ground and is approximately 40% of the walking gait cycle (Levine et al., 2012; Richards, 2008; Rose et al., 2006). Hence during the swing phase the lower limb is considered to be in open kinetic chain (Augustsson et al., 1998; Butler et al., 2003).

2.3 Gait events

The swing and stance phases of gait are sub-divided into events. Whilst there is agreement between authors on the nomenclature that describes the different phases of gait, there is disparity between them on the nomenclature for the events that subdivide the phases of gait. This alternative terminology has developed as different authors felt that in certain types of gait initial contact may not be from the heel (Rose et al., 2006), Table 2.1.

Gait event nomenclature			
Author	(Rose et al., 2006)	(Richards, 2008)	(Levine et al., 2012)
Weight bearing (closed chain)	Stance Phase	Stance Phase	Stance, support or contact phase
Non weight bearing (open chain)	Swing Phase	Swing Phase	Swing Phase
Initial	Foot strike	Heel strike	Initial contact
Final	Foot off	Toe off	Toe off

Table 2.1 Comparison of gait events nomenclature between authors

Rose sub-divides stance phases into; initial double limb support, single limb support and second double limb support. Swing phase is also sub-divided into; initial swing, mid swing and terminal swing (Rose et al., 2006).

Therefore there is agreement between the authors that a weight bearing and non-weight bearing phase of gait exists and that these phases are best described as stance and swing phases (Levine et al., 2012; Richards, 2008; Rose et al., 2006). However there is debate on how best to describe the events that subdivide these two phases of the gait cycle. Furthermore; irrelevant of the nomenclature used it is apparent that these events are not finite points in time; rather they are phases covering a period of time and with the potential to be sub-divided further. However; many of these events are already short periods of time, such as stance phase which lasts approximately 0.6 seconds at self-selected walking speed (Saleh & Murdoch, 1985). This makes observation of these events difficult in clinical practice without the use of video or motion analysis equipment and hence the clinical value of sub-dividing them is debatable.

2.4 Differences between walking and running gait

During the walking gait one foot is always on the ground acting in a closed kinetic chain, and during the period when the support of the body is transferred from the trailing to the leading leg there is a brief period when both feet are on the ground, known as double support. Hence, during double support both lower limbs act in closed kinetic chain. These cyclic alternations of the support function of each leg and the existence of the transfer period when both feet are on the ground form the essential features of the locomotion process known as walking (Rose et al., 2006), Figure 2.1

<table>
<tr><td>Left Heel Strike</td><td>Left Single Limb Stance</td><td>Double Support</td><td>Right Single Limb Stance</td><td>Left Heel Strike</td></tr>
<tr><td colspan="2">Left Stance Phase (closed chain)</td><td rowspan="2">Both limbs closed chain</td><td colspan="2">Right Stance Phase (closed chain)</td></tr>
<tr><td colspan="2">Right Swing Phase (open chain)</td><td colspan="2">Left Swing Phase (open chain)</td></tr>
</table>

Figure 2.1 Phases of walking gait, adapted (Rose et al., 2006)

As a person walks faster, these periods of double support become smaller fractions of the walking cycle reducing the time spent in closed kinetic chain. Eventually as a person starts to run, they disappear altogether and are replaced by a brief periods when neither foot is on the ground, this is termed the double float phase (Mohd Yusof, Sayuti, Salim, & Adilah, 2009; Novacheck, 1998). The difference between the walking gait cycle and running gait cycle therefore is that during running there are periods when neither foot is on the ground (Levine et al., 2012), and hence phases where both lower limbs are in open kinetic chain. Running becomes sprinting when initial contact changes from being on the hindfoot to the forefoot (Novacheck, 1998).

This reduction in stance phase and the development of double float means that a smaller proportion of the gait cycle is spent in closed kinetic chain during running compared to walking. Clinically however this phase of the running gait cycle is critical. It is the only phase of the running gait where the Lumbo-Pelvic and Hip region is weight bearing, transmitting the ground reaction force, which is greater in running (Richards, 2008), through the Lumbo-Pelvic and Hip region. It is also the only phase where an individual is able to use the forward vector of the ground reaction force to propel themselves forward (Novacheck, 1998).

It is clear that neuromuscular control of the Lumbo-Pelvic and Hip region kinetic chain during running; with its relatively high speed joint movement, increased joint and ground reaction forces and reduced closed kinetic chain phase will represent a significant challenge to the central locomotor command. It may therefore be theorized that the potential for loss of control of the kinetic chain is greater during running than walking (Butler et al., 2003; Hoefert, Loomis, Lundberg, & Schmitz, 2003).

One commonly used clinical method for examining control of the kinetic chain during gait is range of movement; this measures the angular displacements of the individual segments. These measurements have great clinical applicability as they help to inform the clinician of the normality of the gait cycle, assist in sub-grouping of the participant, and monitoring of treatment (Rose et al., 2006). Hence a principal task of the researcher or clinician when describing gait is to measure the angular displacements of the various segments (Rose et al., 2006).

2.5 Background summary

The gait cycle maybe divided into walking and running. Both walking and running contain a stance and swing phase. The stance phase starts at heel strike and ends at toe off, forming the closed chain weight bearing phase. The closed chain phase of gait is important for load transmission and the generation of forward propulsion. During running the stance phase is shorter and the loads transmitted are greater than during walking.

3 Literature Review

3.1 Introduction

A search of CINAHL, Google Scholar, Medline, ScienceDirect and SPORTDiscus databases was completed. Using the keywords; orthopaedic, gait, walk, walking, run, running, clinical test, Trendelenburg, Single Leg Squat and Corkscrew, these databases were searched from inception, however the search was limited to publications available in English. This produced 1046 articles, the abstracts of these articles were read and 213 articles were considered relevant and are subsequently referred to within the thesis.

The majority of gait related studies reviewed focused on walking with relatively few papers on running. Twenty studies focused on the pelvis; seventeen on the hip joint; sixteen on the lumbar spine; twelve on the trunk and only one on the thoracic spine. There are currently no studies investigating thoracic spine kinematics during running. The review established that for the clinical tests there are twenty three studies on the Trendelenburg Test and eleven on the Single Leg Squat but no evidence base on the use of the Corkscrew Test. For the Trendelenburg Test; all of the previous studies have been confined to the pelvis coronal plane peak value with no data available for the kinematics of lumbar and thoracic spines or for the hip in any of the three cardinal planes. Similarly for the Single Leg Squat; all of the previous studies have investigated the hip coronal plane peak value with no data available for the pelvis, lumbar or thoracic spine in any of the three cardinal planes. There are currently no existing studies investigating the Corkscrew Test in any segment or plane of movement.

When considering different sub-groups in a healthy population; currently there is no data for Lumbo-Pelvic and Hip kinematics during gait or the clinical tests in professional football players. There is also no evidence to demonstrate if there are any differences between healthy participants and professional football player's Lumbo-Pelvic and Hip kinematics. Professional football players have been found to sustain debilitating and persistent injuries to the Lumbo-Pelvic and Hip region. These gaps in the evidence base limit musculoskeletal clinicians when they attempt to implement a fully evidence based examination into their assessment and treatment of gait (Chan, Fong, Hong, Yung, & Lui, 2008).

3.2 Walking gait

3.2.1 Introduction

The Lumbo-Pelvic and Hip region has a critical role in the production of a normal walking gait. Walking is thought to be amongst the commonest activities performed during daily living (Galli, Sibella, Crivellini, Catalano, Ghetti, Secchi, & Pace, 2001; Winter & Robertson, 1978) and sport (Stolen, Chamari, Castagna, & Wisloff, 2005). In the United Kingdom an individual walks approximately 9-11,000 steps per day on average (Clemes, Matchett, & Wane, 2008; Clemes, Hamilton, & Lindley, 2007; Duncan, Schofield, & Duncan, 2007; Duncan, Al-Nakeeb, Woodfield, & Lyons, 2007; Schneider, Crouter, & Bassett, 2004) and successive United Kingdom governments have encouraged walking as part of a healthier lifestyle (Fitzsimons, Baker, Wright, Nimmo, Thompson, Lowry, Millington, Shaw, Fenwick, & Ogilvie, 2008).

3.2.2 The kinetic chain during normal gait

The Lumbo-Pelvic and Hip region is responsible for creating the limb movements associated with human gait (Vogt & Banzer, 1999) and transmitting the ground reaction force created during stance phase (Anderson, Strickland, & Warren, 2001) between the foot and trunk. During gait the Lumbo-Pelvic and Hip region forms part of a kinetic chain, a chain of articulations (joints) joined by rigid links (bones) and moved by "movement generators" (muscles) (Butler et al., 2003). During the single limb stance phase of gait the weight bearing limb forms a closed kinetic chain with the floor and the non-weight bearing limb forms an open kinetic chain (Karandikar et al., 2011; Mayer, Schlumberger, van Cingel, Henrotin, Laube,

& Schmidtbleicher, 2003). If the two limbs and pelvis are considered as a whole then at the point of single limb stance they are in "controlled open kinetic chain" (Butler et al., 2003), Figure 3.1.

3.2.3 The kinetic chain during abnormal gait

Loss of control at any point in the kinetic chain may cause uncontrolled movement at that particular link in the chain, or at a link proximal or distal to it (Butler et al., 2003; Hoefert et al., 2003; Rothbart & Estabrook, 1988). Any uncontrolled movement may be termed as dysfunction and may cause symptoms or disability (Ellison et al., 1990), Figure 3.1.

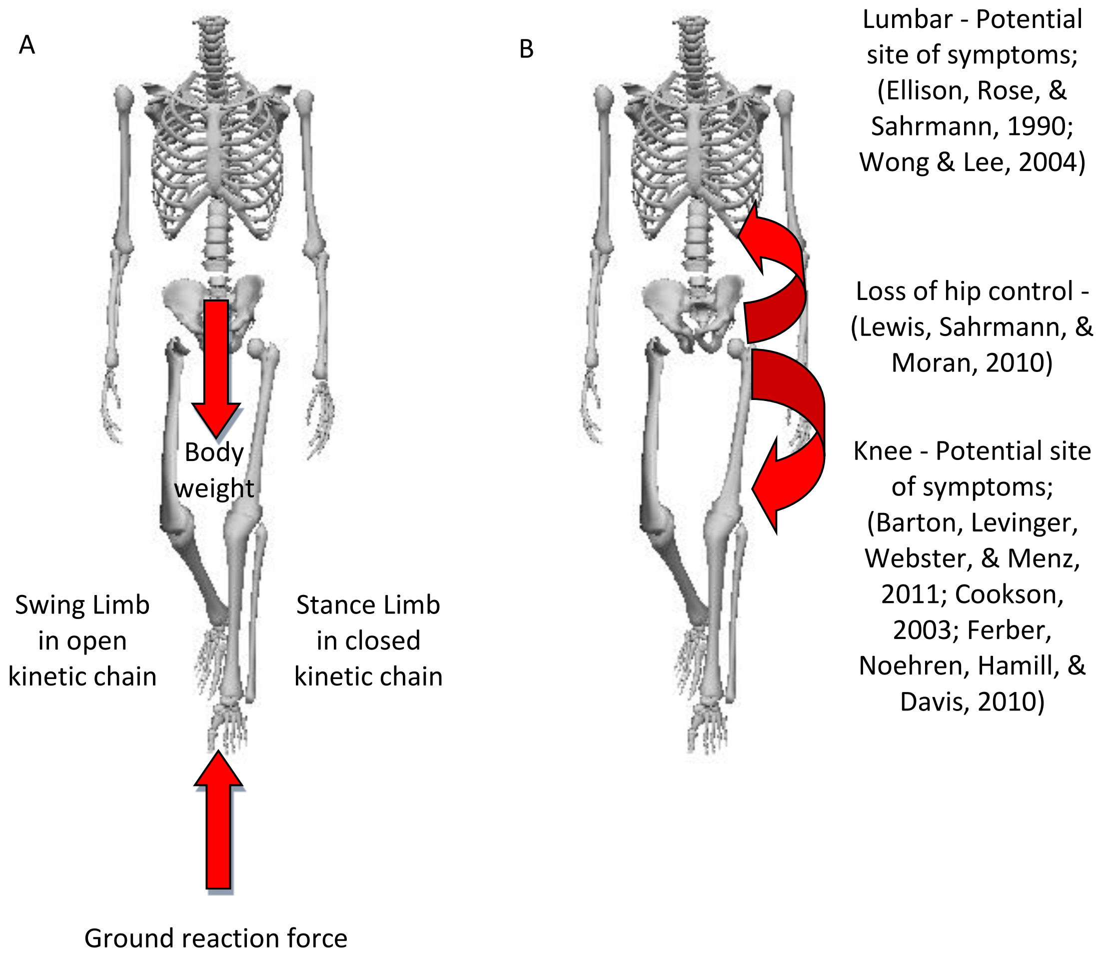


Figure 3.1 Kinetic chain during single limb stance; (A) Normal (B) Abnormal

Abnormal, uncontrolled movements found within the kinetic chain during the gait cycle may further be sub-grouped by clinicians into one of two types; Type 1: Functional movement anomalies are neurological due to abnormal central locomotor command pathway signals or their interpretation (Vaughan, Davis, & O'Connor, 1999). Type 2: Structural movement anomalies are mechanical due to changes in musculoskeletal tissue (Lewis & Sahrmann, 2006), Figure 3.2.

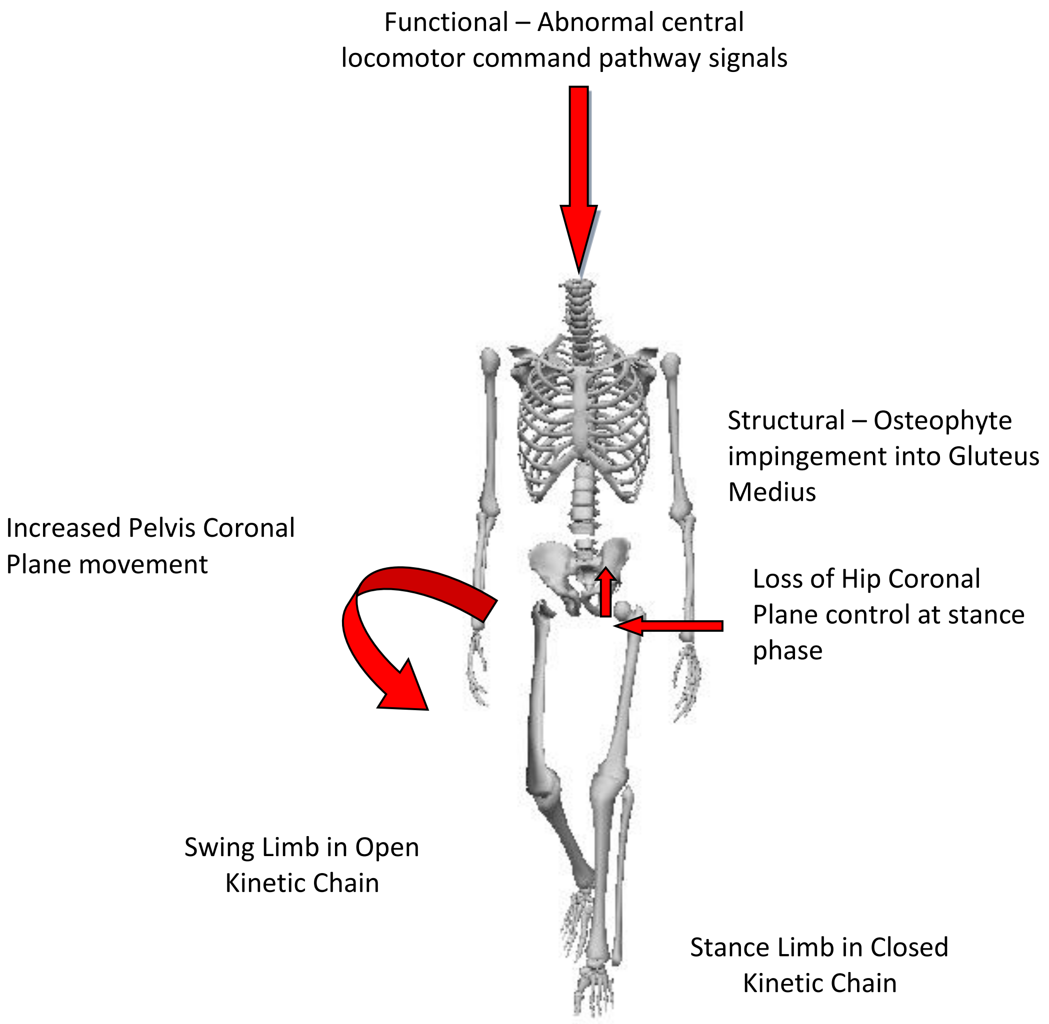


Figure 3.2 Example of loss of hip coronal plane control

3.2.4 Previous studies of the kinetic chain during abnormal walking gait

Ellison, et al. (1990) compared healthy and low back pain participants kinematics during non weight bearing clinical tests and concluded that the low back pain participants exhibited greater lateral hip rotation than healthy participants. Wong, et al. (2004) later compared healthy and low back pain participants during weight bearing clinical tests and concluded that the low back pain participants exhibited reduced hip flexion (39.5^0 versus 72.1^0).

Lewis, et al. (2010) compared healthy to anterior hip pain participants and concluded that the anterior hip pain participants demonstrated increased hip extension peak value (13.5^0 versus 11.5^0) during walking. Barton, et al. (2011) compared healthy and patellofemoral pain participants and concluded that the patellofemoral pain participants demonstrated reduced hip internal rotation peak value (7.1^0 versus 11.8^0) during walking.

Iliotibial band syndrome is a pain syndrome caused by friction of the iliotibial band sliding over the lateral femoral epicondyle that is particularly prevalent in runners (Hamill, Miller, Noehren, & Davis, 2008). Ferber, et al. (2010) compared healthy with Iliotibial band syndrome participants hip kinematics and concluded that the Iliotibial band syndrome participants demonstrated significantly greater hip coronal plane peak value adduction (6^0 versus 9^0) during the single limb stance phase of running. Cookson (2003) conducted a single case study and found that in a marathon runner with history of “atypical” knee pain there was a 15^0 reduction in hip internal rotation on the affected side during non weight bearing clinical tests. Treatment to increase the hip internal rotation range of movement was felt to improve the knee pain.

Contemporary research has shown that where patients present with pain syndromes abnormal gait movement patterns are present. When examining gait clinicians are using a functional test for the kinetic chain of joints and their ability to transduce force across them (Winter, 1980). The relevance of these studies was that they demonstrated that a loss of hip control during walking or running may cause symptoms at either the hip or knee. Clinicians should therefore examine the symptomatic joint and both proximally and distally within kinetic chain. By examining for uncontrolled kinetic chain movement during gait they may establish the cause of the symptoms (Butler et al., 2003; Ellison et al., 1990; Hoefert et al., 2003; Rothbart et al., 1988).

3.2.5 Clinical assessment of the pelvis and spine during gait

The management of gait is a common component within musculoskeletal practice. Crucial to the management of gait is examination as this is used to inform diagnosis, treatment planning and a clinician's reflection on treatment efficacy (Churchill, Halligan, & Wade, 2002; Toro, Nester, & Farren, 2003). Historically clinicians have examined gait using an "observational gait analysis" technique (Toro, Nester, & Farren, 2007b). Standard 6 in the Chartered Society of Physiotherapy Core Standards document makes an explicit requirement for members to use published, standardised outcomes (tests) in clinical practice (Chartered Society of Physiotherapy, 2000; Selfe, Harper, Pedersen, Breen-Turner, & Waring, 2001). McDowell states that "An outcome measure should be standardised, with explicit instructions for administration" (McDowell, 2006). However in the UK, physiotherapists do not currently have a standardised clinical protocol or set of instructions for the examination of gait (Toro et al., 2003), and currently, commonly continue to use "observational gait analysis" to examine the gait cycle. This lack of a clear method for performing and interpreting the examination of gait, in combination with the small trunk ranges of movement associated with gait, may explain the conclusion that the clinical examination of gait currently commonly results in; "*poor criterion-related validity, repeatability, specificity, and sensitivity to clinically important changes*" (Toro et al., 2003). Alternative methods to the "observational gait analysis" method of examining gait exist. These methods include the Salford Gait Tool (Toro, Nester, & Farren, 2007a; Toro et al., 2007b) and Gross Motor Function Measure (GMFM) (Palisano, Hanna, Rosenbaum, Russell, Walter, Wood, Raina, & Galuppi, 2000; Russell, Avery, Rosenbaum, Raina, Walter, & Palisano, 2000). Both of these methods have been developed using neurological participants whereby the visual observation of movements and gait were scored using a numerical scale. A key component of both methods is observation of the hip during stance phase. Good inter and intra-observer reliability was found, but these methods were limited to neurological participants and sagittal plane movements (Toro et al., 2007a).

These limitations therefore may explain why clinicians commonly continue to examine gait by visual inspection (Fiona, 1999; Krebs, Edelstein, & Fishman, 1985; Sartor, Alderink, Greenwald, & Elders, 1999; Senden, Meijer, Heyligers, Savelberg, & Grimm, 2011; Toro et al., 2003). Clinicians compare the movements observed to preconceived normal ranges of movement (Krebs et al., 1985) or approximations to an imaginary "perfect" gait. Key movements of gait to be examined are pelvic rotation and pelvic list (also called obliquity).These movements form part of the determinants of gait helping to flatten the trajectory of the body centre of mass during stance phase, and thereby reduce the vertical translation of the body during walking (Rose et al., 2006). However these observations are technically difficult as it requires the clinician to make over thirty observations of the moving segments, including the sagittal, coronal and transverse plane movements of the lumbar and thoracic spines, trunk, pelvis and hips, during a walking gait cycle lasting approximately one second (Saleh et al., 1985). Furthermore, the movements occurring during walking at the pelvis and hip are small and there are currently only limited quantitative, objective, kinematic values for the gait cycle ranges of movement upon which to base these judgments. Therefore a greater understanding of the kinematics of gait, particularly for the pelvis and hip, and of how gait may vary between different populations or in the pathological state would be a valuable aid in the examination of walking (Zarrugh & Radcliffe, 1979). Hence; a reference set of 'normal' gait parameter values, for the Lumbo-Pelvic and hip region, would provide an invaluable tool within the realm of clinical gait examination as a basis of comparison when deciding on treatment of the abnormal (Lelas, Merriman, Riley, & Kerrigan, 2003).

3.2.6 Biomechanical assessment of walking

The earliest biomechanical studies on walking were 2D studies using still cameras performed in the 1870s by Marey in Paris, and Muybridge in California. Considerable improvements followed the development of cine photography, this allowed images to be taken at a higher frequency and consequently studies with greater accuracy could be undertaken. Consequently the first major studies of walking kinematics were completed between 1950 and 1979 by a very active group including; Inman, Ralston, Todd and Lieberman working in the Biomechanics Laboratory at the University of California, Berkeley. This lead to the first book published on gait kinematics “Human Walking” (Inman, Ralston, & Todd, 1981). The late 1970s and early 1980s saw the development of measurement systems based on television cameras, which were linked directly into computers (Cappozzo, 1984; Fiona, 1999; Whittle, 1996; Winter, 1984). This computerization allowed 3D study of walking gait kinematics and made the whole process much quicker and more convenient (Greenberg, Gronley, Perry, & Lawthwaite, 1996; Sutherland, 2002; Whittle, 1982). Since then interest in the kinematic function of the Lumbo-Pelvic and Hip region during walking has continued to develop. Chockalingam explored the Lumbo-Pelvic and Hip kinematics of treadmill and over ground walking (Chatterley, Chockalingam, & Greenhalgh, 2007; Chockalingam, Chatterley, Healy, Greenhalgh, & Branthwaite, 2012). Chockalingam found that the Lumbo-Pelvic and Hip kinematics of walking on a treadmill were different when compared to walking on the ground. The clinical importance of this study was that it illustrated that the Lumbo-Pelvic and Hip kinematics of walking changed dependent on the environment, hence walking kinematics were found to be environment specific. Zhao developed spinal modeling creating a two segment spine (Zhao, Ren, Ren, Hutchinson, Tian, & Dai, 2008). Zhao demonstrated that the trunk could now be successfully subdivided and modeled as a lumbar and thoracic spine. This advance in modeling has generated data that is specific to an individual spinal region rather than the trunk as a single segment. Consequently this has allowed clinicians to consider the movements of the individual spinal regions and hence examine the movements of the trunk in greater detail. Laboratory based kinematic studies of gait are therefore currently the “reference” standard for studying walking and kinematics (Fiona, 1999; Toro et al., 2003).

Contemporary motion analysis studies maybe divided into two areas of study; kinematic and kinetic. Kinematic study is the investigation of joint movement; kinetic study is the study of the joint forces that produce that movement (Rodgers & Cavanagh, 1984). Most physiotherapists do not have access to movement analysis laboratories (Toro et al., 2003). Hence the values derived from kinetic studies maybe difficult to implement into clinical practice. However physiotherapists frequently examine gait using range of movement, hence kinematic data would inform clinical practice more readily than kinetic. Kinematic studies maybe sub-divided into the study of a region of the body; regional kinematics e.g. trunk or lumbar spine, the study of a single joint; arthro-kinematics e.g. L4/5 or the study of one bone relative to another; osteo-kinematics.

Early kinematic walking studies focused upon the lumbar spine and pelvis (Whittle, Levine, & Burke, 1998; Whittle & Levine, 1997; Whittle & Levine, 1999; Whittle & Levine, 1995; Whittle & Levine, 1996). Consequently there has been less evidence generated for the role of the thoracic spine. Initial studies have shown some agreement for the spinal range of movement, but many of these previously accepted values have been derived by measurement techniques which have subsequently been superseded in terms of accuracy and sensitivity. In particular, the methods by which three dimensional movements have been calculated have been imprecise in determining the axes about which the rotations have occurred. Hence, with the development of contemporary measurement systems and improved resolution, the reported values for trunk transverse plane movement during gait have been revised down to nearly half the originally stated values (Krebs, Wong, Jevsevar, Riley, & Hodge, 1992).

3.2.7 Marker based modelling of the Lumbo-Pelvic and Hip region

More recently the research focus for the kinematic function of the Lumbo-Pelvic and Hip region has changed. The current focus is less on the further development of cameras, or greater accuracy in the calculation of axes of rotation, but on the generation of more detailed spinal models (Zhao et al., 2008). Early kinematic studies of the Lumbo-Pelvic and Hip region used comparatively simple models. Often the trunk was modeled as a single segment spine and with a combination of wands and markers being confined to the posterior surface of the body in the coronal plane. This allowed kinematic values to be established but these values were often limited to the sagittal and coronal planes (Schache, Blanch, Rath, Wrigley, & Bennell, 2002a; Whittle et al., 1997; Whittle et al., 1999; Whittle et al., 1995), Figure 3.3.

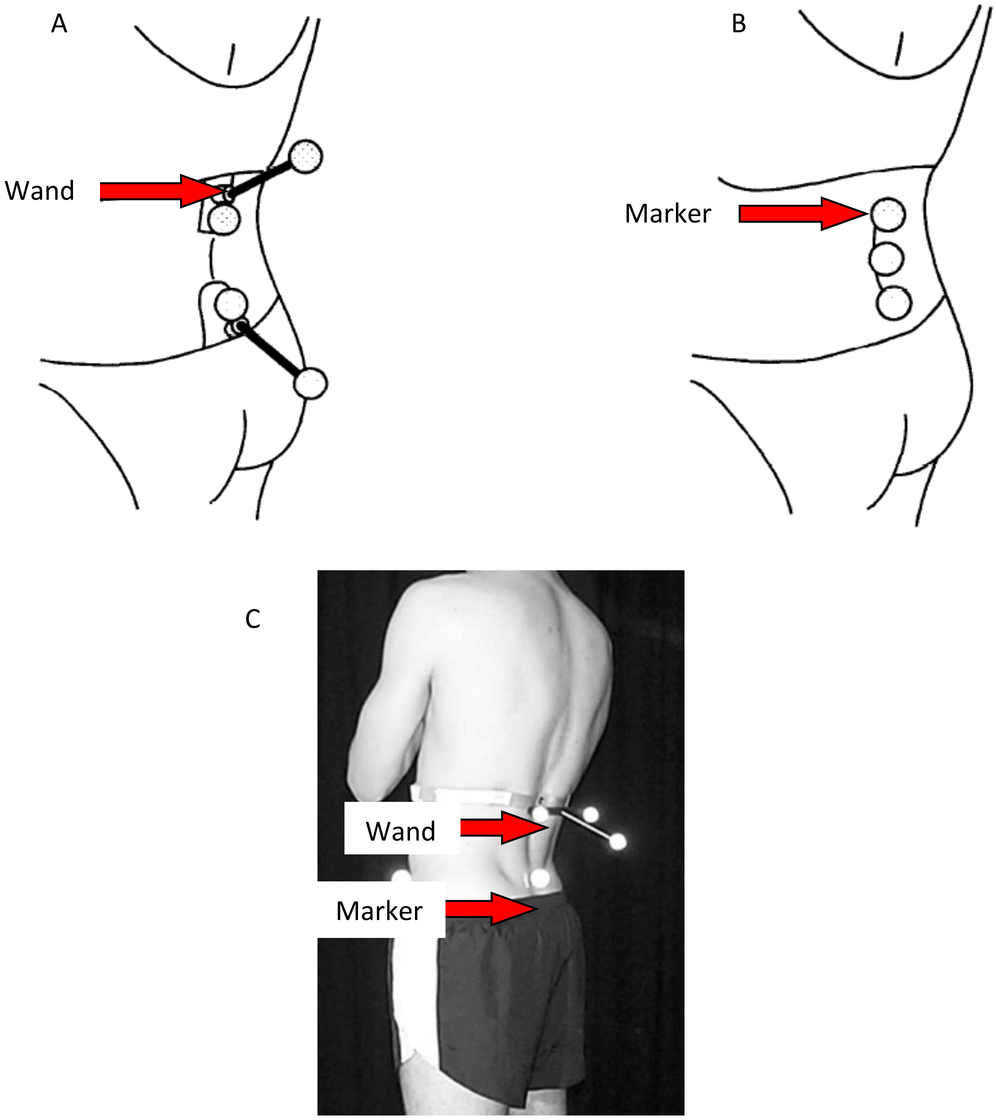


Figure 3.3 Early wand marker set; (A) For examining lumbar sagittal plane range of movement (Whittle et al., 1995), (B) lumbar sagittal plane peak value (Whittle et al., 1997) and lumbar sagittal, coronal and transverse plane range of movement (Whittle et al., 1999) during walking gait and (C) lumbar sagittal plane range of movement during running gait (Schache et al., 2002a)

Subsequent studies have tended not to use wands as the accuracy of their data was questioned (Wren, Do, Hara, & Rethlefsen, 2008), but more skin markers have been used to develop these models, Figure 3.4.

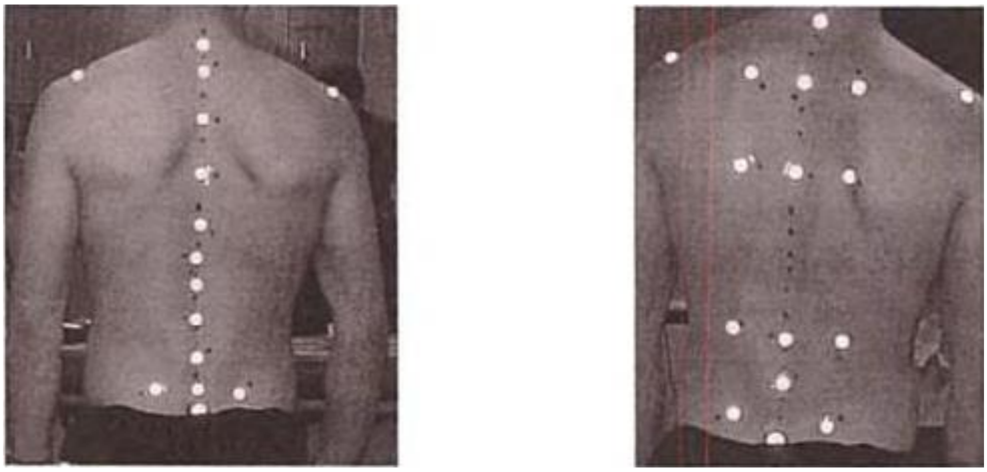
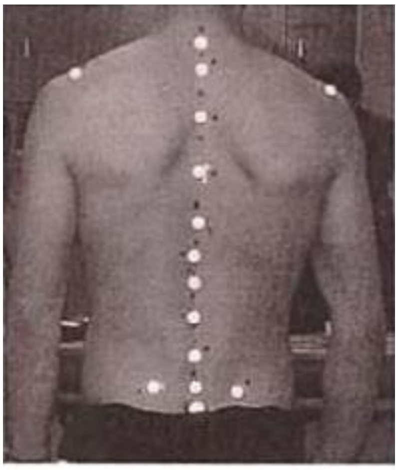


Figure 3.4 Marker set used for examining trunk coronal and sagittal physiological range of movement during standing (Chockalingam, Dangerfield, Giakas, & Cochrane, 2002)



Marker set used for examining relative movement of the trunk compared to the lower limbs during trunk coronal and sagittal plane movements during standing (Chockalingam, Dangerfield, Giakas, Dorgan, & Cochrane, 2002)

The increase in the number of markers used has enabled the trunk to be subdivided into the lumbar and thoracic spine (Zhao et al., 2008). This subdivision of the spine from a single segment spine into a two segment spine has been highly significant to clinicians as it has allowed the generation of more detailed kinematic data, specific to individual regions of the spine. Contemporary models have also started to include clusters. Clusters have the advantage of being able to detect transverse plane movement and hence their use has started to increase the evidence base of transverse plane movement data, Figure 3.5 and Figure 3.6.

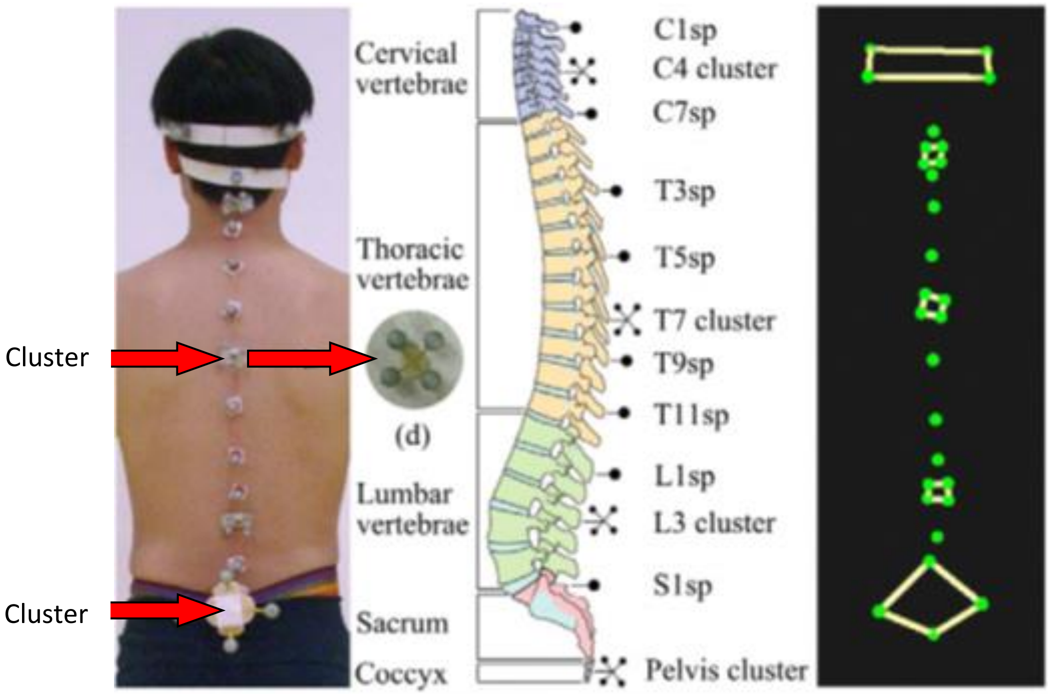


Figure 3.5 Marker set used for examining lumbar spine, thoracic spine and pelvic range of movement in the sagittal, coronal and transverse planes during walking (Zhao et al., 2008)

Figure 3.6 Marker set used for examining pelvic sagittal and coronal range of movement during walking over ground and on a treadmill (Chatterley et al., 2007; Chockalingam et al., 2012)

3.2.8 Bone pin modelling of the Lumbo-Pelvic and Hip region

Bone pin methods are an alternative method to skin marker based studies. They are currently thought to avoid the problem of skin marker movement associated with skin marker based studies, but generally produce larger ranges of movement than skin marker studies (Rozumalski, Schwartz, Wervey, Swanson, Dykes, & Novacheck, 2008). Whilst there are fewer of this type of study that have been completed, as a group the bone pin studies provide values that are similar to each other and have therefore started to generate a body of evidence specific to this method. However, the values are different from the more common skin marker based studies, inter-study comparison of values is virtually impossible and the future generation of a large evidence base maybe slow as ethical approval for bone pin studies is more difficult. Hence, if research participants are to suffer pain then the evidence gained from these studies must make a significant contribution to knowledge, Figure 3.7. Therefore; kinematic modeling of the spine has developed greatly over the last 17 years. Contemporary kinematic models have the potential to generate data for a two segment spine in the three dimensional, six degrees of freedom.

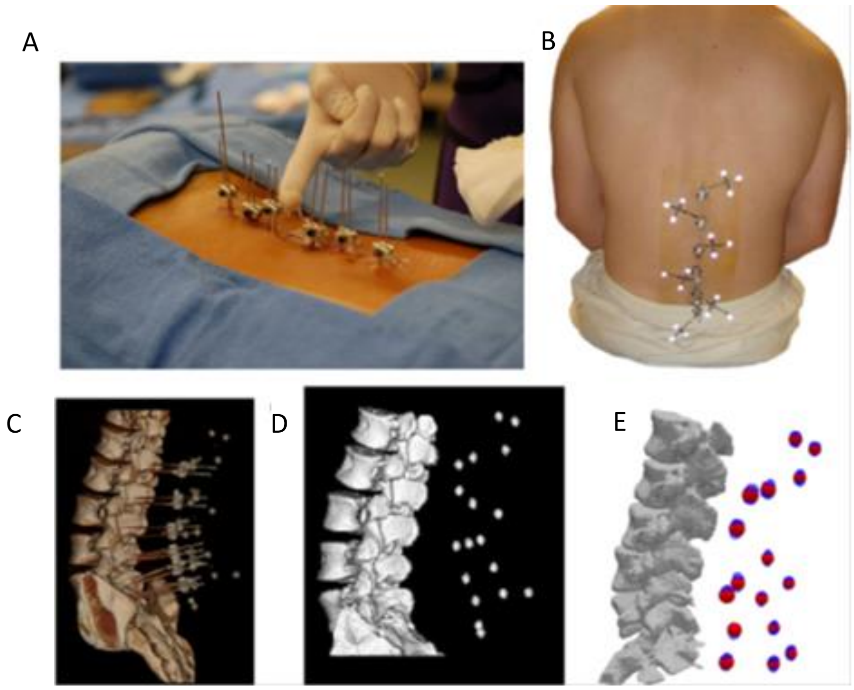


Figure 3.7 Study protocol; (A) insertion of Kirshner wires in the operating room, (B) attachment of marker triads, (C) full lumbar CT scan, (D) digitization and segmentation of the CT scan, and (E) synchronization of the CT data with the motion capture data (Rozumalski et al., 2008)

3.2.9 Assessment of lumbar spine during walking

During walking the lumbar spine in the sagittal plane (flexion-extension) shows “negligible range of movement ... with no particular change of the spinal shape” (Zhao et al., 2008). Most of the evidence is in agreement that the range of movement is small lying between; 3.0^0 and 10.7^0 (Crosbie, Vachalathiti, & Smith, 1997a; Saunders, Schache, Rath, & Hodges, 2005; Taylor, Evans, & Goldie, 1996; Whittle et al., 1999; Whittle et al., 1996), Table 3.1. All of the evidence is in agreement that the peak value is between; 3^0 and 17^0 (Fowler, Rodacki, & Rodacki, 2006; Saunders et al., 2005; Whittle et al., 1999), Table 3.1. The small lumbar spine sagittal plane movements found during walking may explain why clinicians often find this movement difficult to observe.

The lumbar spine in the coronal plane (side flexion) shows; “obvious cyclic changes during (walking) gait ... and high variability. At heel strike, the spine leans toward the trailing limb, and then changes to vertical at mid-stance.,” (Zhao et al., 2008). Vaughan, et al. (1999) found that the direction of lumbar spine movement in the coronal plane during walking differed between individuals. The majority of the evidence is in agreement that the range of movement is small but slightly larger than the sagittal plane movement lying between; 3^0 and 12.8^0 (Crosbie et al., 1997a; Rowe & White, 1996; Saunders et al., 2005; Taylor et al., 1996; Whittle et al., 1998; Whittle et al., 1999), Table 3.1. The evidence for the peak value varies very little with values ranging between; 5^0 and 7^0 (Fowler et al., 2006; Saunders et al., 2005; Whittle et al., 1999; Zhao et al., 2008), Table 3.1. A potential explanation of why this movement is so small may be that sagittal plane movement is primarily guided by the intervertebral joints. These joints are extremely stable and thus relatively immobile. However; coronal plane movement is primarily guided by the zygapophyseal joints. Zygapophyseal joints are less stable and hence more mobile (Moffat & Mottram, 1987). Normal lumbar spine coronal plane movement is thought to be needed for efficient transmission of load (Lee, 2004). These loads include the ground reaction force generated during the stance phase of gait. This may explain why patients with lumbar spine coronal plane dysfunction commonly fail to transmit ground reaction forces and consequently exhibit a weight bearing limp.

The lumbar spine in the transverse plane (rotation) shows; “a uni-phasic pattern with only one peak value near heel strike or at opposite heel strike. The movement pattern is consistent during gait with the minimum angle being at heel strike and the peak value angle at opposite heel strike” (Zhao et al., 2008). Most of the range of movement values are small ranging between; 4^0 and 8.3^0 (Crosbie et al., 1997a; Rowe et al., 1996; Saunders et al., 2005; Taylor et al., 1996; Whittle et al., 1998; Whittle et al., 1999), Table 3.1. The peak values are also small and spread only between 2^0 and 4^0 (Rowe et al., 1996; Saunders et al., 2005; Whittle et al., 1999), Table 3.1.

The lumbar spine transverse plane range of movement during walking is small but similar to the values found in both the coronal and sagittal planes. Thus the ranges of movement observed in the lumbar spine during walking are similar in the sagittal, coronal and transverse planes. However most of the lumbar spine treatment techniques commonly described are for the sagittal (McKenzie & Van Wijmen, 1988) and transverse planes (Cyriax, 2001; Maitland et al., 1986) with few focusing upon the coronal plane. It maybe suggested that musculoskeletal treatment techniques that address lumbar spine coronal plane dysfunction during walking are equally important and further research of evidence based techniques is required for this plane.

The current evidence base has also described anomalous values lying outside of one standard deviation from these lumbar spine studies. One study reported a lower lumbar spine sagittal plane (flexion-extension) range of movement; 2^0 and lower lumbar spine coronal plane peak value; 2^0 (SD=0.26) (Rowe et al., 1996). A potential explanation of this is that the participants were nurses returning to work following low back pain. Clinically it might be expected that they would exhibit a reduced range of movement due to residual soft tissue tension or muscle guarding. In contrast, other studies have reported higher values for lumbar spine sagittal plane range of movement; 21^0 (Schwartz, Rozumalski, Wervey, Novacheck, Swanson, & Dykes,

2007) and 21.5^0 (Rozumalski et al., 2008); coronal plane range of movement; 17.1^0 (SD= average of 2) (Rozumalski et al., 2008), 18^0 (Schwartz et al., 2007) and transverse plane range of movement; 22.8^0 (SD= average of 2) (Rozumalski et al., 2008) and 22^0 (Schwartz et al., 2007), Table 3.1. These studies were methodologically different to previous studies as they used bone pins, Figure 3.7.

A marker study established higher values for lumbar coronal plane range of movement; 9^0 (SD=2), transverse plane range of movement, 25^0 (SD=2) and transverse plane peak value, 15^0 (Zhao et al., 2008). A potential explanation for this is that this study used a "novel marker set" consisting of a sacral cluster and single markers over the spinous processes, Figure 3.5. A second study established a higher lumbar spine coronal plane range of movement value; 9^0 (Fowler et al., 2006). A possible explanation for this is that this study was of gait whilst walking on a treadmill. A previous study comparing treadmill walking to walking on the ground established that there is a difference in Lumbo-Pelvic and Hip kinematics during treadmill walking when compared to walking on the ground (Chatterley et al., 2007; Schache, Blanch, Rath, Wrigley, Starr, & Bennell, 2001), Table 3.1.

Lumbar spine				
Plane of movement	Range of movement		Peak value	
	Value	Author	Value	Author
Sagittal	2^0	(Rowe et al., 1996)	3^0	(Whittle et al., 1999)
	3.0^0	(Whittle et al., 1999)	6^0	(Rowe et al., 1996) (low back pain)
	3.2^0	(Taylor et al., 1996)	13^0	(Fowler et al., 2006)
	3.5^0	(Crosbie et al., 1997a) (difference between standing and walking)	17^0	(Saunders et al., 2005)
	4.0^0	(Whittle et al., 1999)		
	10.7^0	(Whittle et al., 1996)		
	21^0	(Schwartz et al., 2007)		
	21.5^0	(Rozumalski et al., 2008)		
Coronal	3^0	(Whittle et al., 1998)	2^0	(Rowe et al., 1996)
	4^0	(Rowe et al., 1996) (low back pain)	5^0	(Zhao et al., 2008)
	6.0^0	(Saunders et al., 2005)	5^0	(Whittle et al., 1999)
	7.6^0	(Whittle et al., 1999)	6^0	(Saunders et al., 2005)
	9.0^0	(Crosbie et al., 1997a)	7^0	(Fowler et al., 2006)
	9^0	(Zhao et al., 2008)		
	9^0	(Fowler et al., 2006)		
	12.8^0	(Taylor et al., 1996)		
	17.1^0	(Rozumalski et al., 2008)		
	18^0	(Schwartz et al., 2007)		
Transverse	4^0	(Whittle et al., 1998)	2^0	(Saunders et al., 2005)
	4.0^0	(Saunders et al., 2005)	3^0	(Whittle et al., 1999)
	4.5^0	(Crosbie et al., 1997a)	4^0	(Rowe et al., 1996) (low back pain)
	6^0	(Rowe et al., 1996)	15^0	(Zhao et al., 2008)
	6.4^0	(Taylor et al., 1996)		
	8.3^0	(Whittle et al., 1999)		
	22^0	(Schwartz et al., 2007)		
	22.8^0	(Rozumalski et al., 2008)		
	25^0	(Zhao et al., 2008)		

Table 3.1 Summary of previously published lumbar spine movements during walking

Patients often present to clinicians with lumbar symptoms when walking. The evidence reviewed has established that the normal range of movement in the lumbar spine during walking is small for the three planes of movement. As these movements are observed whilst the patient is walking, the clinical observation of these movements is very difficult for clinicians in the lumbar spine. This evidence reviewed established that there is an existing evidence base of normative Lumbo-Pelvic and Hip movement data for healthy participants, however there is no existing evidence base for the lumbar spine kinematics during walking gait in professional football players.

3.2.10 Assessment of thoracic spine during walking

In the sagittal plane (flexion-extension) the thoracic spine quickly extends during double support and then slowly flexes forward during single limb support (Stokes, Andersson, & Forssberg, 1989). The evidence reviewed is in accord that the range of movement is small lying between; 1^0 and 4.4^0 (Crosbie et al., 1997a; Fowler et al., 2006; Stokes et al., 1989; Vogt et al., 1999; Vogt, Pfeifer, & Banzer, 2002), Table 3.2. The peak value is similarly small lying between; 5^0 and 7^0 (Fowler et al., 2006; Vogt et al., 1999), Table 3.2.

The thoracic spine coronal plane (side flexion) movement is a biphasic rotational pattern with reversal points directly after foot-off. The right shoulder is elevated (with respect to the left) in synchrony with the forward swing of the left leg (Stokes et al., 1989). Most of the evidence is in agreement that the range of movement is small lying between; 3.9^0 and 8^0 (Crosbie et al., 1997a; Fowler et al., 2006; Stokes et al., 1989; Vogt et al., 2002; Zhao et al., 2008), Table 3.2. The peak value is between 1^0 and 5^0 (Fowler et al., 2006; Vogt et al., 1999; Zhao et al., 2008), Table 3.2.

Thoracic spine transverse plane (rotation) movement is easily seen during walking. At moderate speeds thoracic rotation is approximately 180° out of phase with the pelvic rotation. Contralateral rotation of the pelvis with the shoulders appears to provide a balancing effect that smooths the forward progression of the body as a whole (Rose et al., 2006; Stokes et al., 1989). As walking speed increases there is a small but statistically significant reduction in thoracic rotational range of movement and the segments become out of phase (Kubo, Holt, Saltzman, & Wagenaar, 2006). The current evidence for range of movement is in agreement; the range of movement is larger than that seen in the lumbar spine and that this clinically observable movement lies between; 4.0^0 and 8.2^0 (Crosbie et al., 1997a; Stokes et al., 1989; Vogt et al., 1999; Vogt et al., 2002; Zhao et al., 2008), Table 3.2. The peak values are smaller but almost in agreement being between 2^0 to 3^0 (Vogt et al., 1999; Zhao et al., 2008), Table 3.2.

Some studies have described anomalous values lying outside of one standard deviation. One study reported a lower values for thoracic coronal plane range of movement, 2.8^0 (Vogt et al., 1999). A potential explanation for this is that this study used a treadmill. Previous evidence established that the lumbar and pelvic kinematics found during treadmill walking were reliable after four minutes of walking, therefore studies using a treadmill may provide reliable Lumbo-Pelvic and Hip kinematic data (Taylor et al., 1996). However a subsequent study found a reduction in the range of movement of the thoracic spine and pelvis in both the coronal and sagittal planes when walking on a treadmill compared to the ground (Vogt et al., 2002). The author draws a logical conclusion; "*This* (if the data is from a treadmill or ground) *should be taken into account when comparing treadmill to over ground readings*" (Vogt et al., 2002). A recent study established lower thoracic spine coronal plane range of movement, 4^0 (SD=2) (Zhao et al., 2008). This study used walking on the ground, not a treadmill. A potential explanation for this lower value is that this study used a "novel marker set" consisting of a sacral cluster and single markers over the spinous processes. Higher transverse plane ranges of movement have been found but these were at fast walking speeds; 11^0-13^0 (Wu, Meijer, Jutte, Uegaki, Lamoth, Sander de Wolf, van Dieen, Wuisman, Kwakkel, de Vries, & Beek, 2011) and in pregnant participants; 11^0-15^0 (Wu et al., 2011), Table 3.2.

Thoracic spine				
Plane of movement	Range of movement		Peak value	
	Value	Author	Value	Author
Sagittal	1^0	(Fowler et al., 2006)	5^0	(Fowler et al., 2006)
	2.5^0	(Crosbie et al., 1997a)	7^0	(Vogt et al., 1999)
	2.5^0	(Vogt et al., 1999)		
	4^0	(Stokes et al., 1989)		
	4.4^0	(Vogt et al., 2002)		
Coronal	2.8^0	(Vogt et al., 1999)	1^0	(Zhao et al., 2008)
	3.9^0	(Vogt et al., 2002)	2^0	(Vogt et al., 1999)
	4^0	(Zhao et al., 2008)	5^0	(Fowler et al., 2006)
	4.9^0	(Stokes et al., 1989)		
	7.0^0	(Crosbie et al., 1997a)		
	8^0	(Fowler et al., 2006)		
Transverse	4.0^0	(Crosbie et al., 1997a)	2^0	(Vogt et al., 1999)
	5^0	(Stokes et al., 1989)	3^0	(Zhao et al., 2008)
	6.8^0	(Vogt et al., 1999)		
	7^0	(Zhao et al., 2008)		
	8.2^0	(Vogt et al., 2002)		
	11^0-13^0	(Wu et al., 2011) (speed dependent)		
	11^0-15^0	(Wu et al., 2011) (pregnant and speed dependent).		

Table 3.2 Summary of previously published thoracic spine movements during walking

It is apparent that there is far less kinematic data for the thoracic spine than the lumbar spine. In common with the lumbar spine the evidence reviewed has established that the normal range of movement in the thoracic spine during walking is small for the three planes of movement. The combination of small movements and simultaneous overlying scapula movement during walking makes clinical observation of these movements very difficult in the thoracic spine.

3.2.11 Assessment of trunk during walking

The trunk reaches maximum flexion at heel strike, it then extends during single limb stance and then flexes again at the next heel strike (Krebs et al., 1992; Sartor et al., 1999). There are few studies on trunk kinematics in the sagittal plane but the evidence reviewed is in agreement that the range of movement is small lying between; 1^0 and 4^0 (Bianchi, Angelini, Orani, & Lacquaniti, 1998; Fowler et al., 2006; Krebs et al., 1992; Sartor et al., 1999), Table 3.3. The peak value is between; 2^0 and 7^0 (Bianchi et al., 1998; Fowler et al., 2006; Krebs et al., 1992; Sartor et al., 1999), Table 3.3.

Trunk coronal plane (side flexion) movement, relative to the pelvis, tends to occur toward the stance limb, reaching its peak value at the time of opposite side toe-off. That is, at right heel strike, the trunk is midway in its movement from left to right side flexion, and this motion continues until left toe-off, at which time a reversal occurs and the trunk begins to side flex toward the left side. Relative to laboratory vertical, the side flexion amplitude is lower and the curve has fewer inflection points than pelvis referenced motions; in general, pelvis referenced trunk side flexion toward the soon to be stance limb, reverses about 5% of the cycle after ipsilateral foot contact. The greater trunk compared to pelvis range of movement is due to independent pelvis movement moving out of phase with the trunk (Krebs et al., 1992; Sartor et al., 1999). The range of movement is between; 6^0 and 12^0 (Krebs et al., 1992; Sartor et al., 1999; Veneman, Menger, van Asseldonk, van der Helm, & van der Kooij, 2008), Table 3.3. The peak value is between; 3^0 and 6^0 (Krebs et al., 1992; Sartor et al., 1999), Table 3.3.

Trunk transverse plane (rotation) movement, relative to the pelvis, is rotated away from the weight bearing limb (retracted) approximately 8^0 at initial contact. The trunk then rotates towards the weight bearing limb (protraction), relative to the pelvis, and reaches a peak value of approximately 6^0 in terminal stance (48%). Following terminal stance, the trunk changes position relative to the pelvis and reaches approximately 7^0 of retraction by late terminal swing (98%). With respect to the laboratory, the trunk begins in 2^0 of retraction and progresses to 3^0 of protraction at terminal stance (35%). Gradually, the rotation reverses and progresses to a peak value of 3^0 of retraction at mid-swing (74%) and remains retracted throughout the rest of the swing phase (Sartor et al., 1999). Hence, during walking, the transverse trunk rotation relative to room coordinates is 180^0 out of phase with the pelvis (Krebs et al., 1992), Table 3.3. The evidence base is small that the range of movement is between; 10^0 and 14^0 (Krebs et al., 1992; Sartor et al., 1999). The evidence for the peak value is in agreement that it is between; 4^0 and 8^0 (Krebs et al., 1992; Sartor et al., 1999), Table 3.3.

Some studies have described anomalous values lying outside of one standard deviation. One study reported lower values for trunk coronal plane range of movement; 4^0 and trunk coronal plane peak value, 1^0 (Fowler et al., 2006). A potential explanation for this is that this study used a treadmill, as previously discussed in this chapter. Higher values have been found for trunk transverse plane range of movement during faster walking; 8^0-17^0 (Wu et al., 2011) and during pregnancy; 8^0-22^0 (Wu et al., 2011), Table 3.3.

Trunk				
Plane of movement	Range of movement		Peak value	
	Value	Author	Value	Author
Sagittal	1^0	(Fowler et al., 2006)	2^0	(Bianchi et al., 1998)
	2^0	(Bianchi et al., 1998)	2^0	(Krebs et al., 1992)
	2^0	(Sartor et al., 1999)	5^0	(Sartor et al., 1999)
	4^0	(Krebs et al., 1992)	7^0	(Fowler et al., 2006)
Coronal	4^0	(Fowler et al., 2006)	1^0	(Fowler et al., 2006)
	6^0	(Krebs et al., 1992)	3^0	(Krebs et al., 1992)
	8^0	(Veneman et al., 2008)	6^0	(Sartor et al., 1999)
	12^0	(Sartor et al., 1999)		
Transverse	10^0	(Krebs et al., 1992)	4^0	(Krebs et al., 1992)
	14^0	(Sartor et al., 1999)	8^0	(Sartor et al., 1999)
	8^0-17^0	(Wu et al., 2011) (speed dependent)		
	8^0-22^0	(Wu et al., 2011) (pregnant and speed dependent).		

Table 3.3 Summary of previously published trunk movements during walking

The evidence reviewed has established that the normal range of movement in the trunk during walking is small for the three planes of movement but larger than that of the lumbar spine and thoracic spine in isolation. This makes it easier for a clinician to observe the movement of the trunk as a single segment during gait, compared to observing the lumbar or thoracic spine as independent segments. However in the clinical environment, using observation of the trunk as a single segment may lack the clinical detail necessary for optimal examination and treatment of the patient. There is currently no kinematic data for the trunk in the three planes of movement in professional football players.

3.2.12 Assessment of pelvis during walking

The pelvic movement in the sagittal plane (anterior tilt-posterior tilt) is a sinusoidal movement with two peaks and two valleys during which the pelvis is inclined anteriorly. The pelvis is most horizontal (least amount of tilt) at foot-off and opposite foot-off, with peak value flexion occurring in mid-to late stance and terminal swing (Rose et al., 2006). The peak value is approximately 10^0 and minimum value 9^0 with a range of motion approximately 1^0 (Rose et al., 2006). The range of movement is small, consistently throughout the literature and is between; 1^0 and 8^0 (Bianchi et al., 1998; Crosbie et al., 1997a; Franz, Paylo, Dicharry, Riley, & Kerrigan, 2009; Kadaba, Ramakrishnan, Wootten, Gainey, Gorton, & Cochran, 1989; Rose et al., 2006; Stokes et al., 1989; Taylor et al., 1996; Vogt et al., 1999; Vogt et al., 2002), Table 3.4. The peak values are higher lying between; 15^0 and 22^0 (Franz et al., 2009; Novacheck, 1998; Schache et al., 2002a; Schache et al., 2001), Table 3.4.

The pelvic movement in the coronal plane (pelvic obliquity or pelvic list) shows that during early stance phase the non weight bearing side of the pelvis drops downward in the coronal plane (Mackinnon & Winter, 1993; Richards, 2008; Rose et al., 2006; Zijlstra & Hof, 1997), into a positive Trendelenburg position (Rose et al., 2006). Hence when observing walking a key point for clinicians to remember is that the motion classically described as a positive Trendelenburg Test is normal for the single limb stance phase of the walking gait cycle (Rose et al., 2006). During normal walking the pelvis coronal plane peak value is approximately 5^0 at the hip joint (Rose et al., 2006) with a range of movement of approximately 10^0 (Rose et al., 2006). The pelvis coronal plane peak value occurs just after opposite toe off, which corresponds to early stance on the weight bearing limb (Rose et al., 2006). Movement of the pelvis in the coronal plane produces an equivalent relative adduction of the supporting limb and relative abduction of the non weight bearing limb, which is in the swing phase of the gait cycle (Rose et al., 2006). Pelvis coronal plane movement allows shock absorption, limb length adjustments (Richards, 2008; Rose et al., 2006), lowers the centre of mass and contributes to the effectiveness of the abductor mechanism of the hip (Rose et al., 2006). The evidence is extensive that the range of movement is relatively small for the pelvic movement in the coronal plane being between; 3^0 and 8^0 (Crosbie et al., 1997a; Kadaba et al., 1989; Kennedy, Lamontagne, & Beaule, 2009; Rose et al., 2006; Stokes et al., 1989; Vogt et al., 1999; Vogt et al., 2002; Whittle et al., 1999; Zhao et al., 2008), Table 3.4. However the peak value is relatively large and is between; 10.6^0 and 13.6^0 (Schache et al., 2002a; Schache et al., 2001), Table 3.4.

The pelvic movement in the transverse plane (rotation) movement shows that the pelvis rotates about a vertical axis alternately to the left and to the right. This rotation is usually approximately 4^0 (Richards, 2008; Rose et al., 2006) creating a range of movement of 8^0 (Rose et al., 2006), the peak internal rotation occurs at heel strike and the peak external rotation at opposite heel strike. This rotation effectively lengthens the limb by increasing the step length (Sartor et al., 1999), prevents excessive drop of the centre of mass of the whole body, and smooths the vertical excursion of the centre of mass (Richards, 2008; Rose et al., 2006; Stokes et al., 1989) making the walking pattern more efficient. The value for pelvis transverse plane rotation increases markedly as speed increases. Because the pelvis is a rigid structure, the transverse plane movement occurs alternately at each hip joint and requires a deviation from pure sagittal plane movement of the hips (Rose et al., 2006). Most of the evidence is in agreement that the range of movement is between; 4.0^0 and 10.4^0 (Crosbie et al., 1997a; Kadaba et al., 1989; Rose et al., 2006; Stokes et al., 1989; Taylor et al., 1996; Vogt et al., 1999; Vogt et al., 2002; Whittle et al., 1999), Table 3.4. The evidence is extensive and the peak value is relatively small for this plane being between; 3^0 and 9^0 (Kadaba et al., 1989), Table 3.4.

Some studies have described values lying outside of one standard deviation. Two studies reported lower values for pelvis sagittal plane range of movement; 2.87^0 (SD=0.95) (Whittle et al., 1996) and 2.8^0 (SD=0.76) (Whittle et al., 1999). A potential explanation for this is both of these studies used wands for markers. As previously discussed in this chapter, markers are now considered to "wobble" and hence may generate errors within the data (Wren et al., 2008). Higher values for pelvis coronal plane range of movement have been established; 11.7^0 (Taylor et al., 1996) and pelvis coronal plane peak value; 14^0 (Schache et al., 2001). A potential explanation of this is that these studies used a treadmill. A study prior to this had established a lower pelvis coronal plane peak value; 5^0 (Novacheck, 1998) and a subsequent study established both lower pelvis coronal and transverse plane peak value (Chatterley et al., 2007). Higher pelvis transverse plane range of movement have been established; 22^0 (SD=2) (Zhao et al., 2008). A potential explanation for this is that this study used a "novel marker set" consisting of a sacral cluster and single markers over the spinous processes. Higher values for pelvis transverse plane range of movement have been found in faster walking; 9^0-14^0 (Wu et al., 2011) and during pregnancy; 9^0-17^0 (Wu et al., 2011), Table 3.4. This evidence suggests that the pelvic movement in the transverse plane changes in response to both function and health condition. This range of movement is also greater than those found at the lumbar spine. This is of clinical importance as currently there is no evidence to suggest if clinicians should observe the lumbar spine, pelvis or hip first when examining walking. This evidence may suggest that starting the examination of walking by observing the pelvic movement in the transverse plane is optimal as this is the movement that is most likely to demonstrate changes during abnormal function or health condition.

Pelvis				
Plane of movement	Range of movement		Peak value	
	Value	Author	Value	Author
Sagittal	1^0	(Rose et al., 2006)	3^0	(Vogt et al., 1999)
	2^0	(Kadaba et al., 1989)	4^0	(Bianchi et al., 1998)
	2.8^0	(Whittle et al., 1999)	6^0	(Kadaba et al., 1989)
	2.87^0	(Whittle et al., 1996)	6.8^0	(Franz et al., 2009)
	3.5^0	(Crosbie et al., 1997a)	10^0	(Rose et al., 2006)
	3.8^0	(Vogt et al., 1999)	11^0	(Whittle et al., 1999)
	4.3^0	(Taylor et al., 1996)		
	4.9^0	(Vogt et al., 2002)		
	5.0^0	(Franz et al., 2009)		
	7.6^0	(Stokes et al., 1989)		
Coronal	3^0	(Kadaba et al., 1989)	3^0	(Crosbie et al., 1997a)
	5^0	(Zhao et al., 2008)	3^0	(Vogt et al., 2002)
	5^0	(Kennedy et al., 2009)	3^0	(Vogt et al., 1999)
	6.0^0	(Crosbie et al., 1997a)	3^0	(Kadaba et al., 1989)
	6.2^0	(Vogt et al., 2002)	4^0	(Zhao et al., 2008)
	7.7^0	(Whittle et al., 1999)	6^0	(Kennedy et al., 2009)
	7.8^0	(Vogt et al., 1999).	23^0	(Whittle et al., 1999)
	9^0	(Stokes et al., 1989)		
	10°	(Rose et al., 2006)		
	11.7^0	(Taylor et al., 1996)		
Transverse	4.0^0	(Crosbie et al., 1997a)	3^0	(Kadaba et al., 1989)
	5^0	(Kadaba et al., 1989)	3^0	(Whittle et al., 1999)
	6.4^0	(Vogt et al., 1999)	3^0	(Vogt et al., 1999)
	7.7^0	(Vogt et al., 2002)	4^0	(Rose et al., 2006)
	8.5^0	(Taylor et al., 1996)	4^0	(Richards, 2008)
	9^0	(Stokes et al., 1989)	9^0	(Zhao et al., 2008)
	9^0-14^0	(Wu et al., 2011) (speed dependent)		
	9^0-17^0	(Wu et al., 2011)(pregnant and speed dependent)		
	10.4^0	(Whittle et al., 1999)		
	22^0	(Zhao et al., 2008)		

Table 3.4 Summary of previously published pelvis movements during walking

The pelvis is one of the regions that have received the most attention from researchers. The evidence reviewed has established that the normal range of movement in the pelvis during walking gait is small for the three planes of movement. The sagittal plane range of movement is negligible. The coronal plane range of movement is a plane that many clinicians focus their observations on feeling that it is a good indication of pelvis control. In the coronal plane a slightly larger but again clinically very small movement should be seen. The transverse plane demonstrates two important factors; firstly it has the highest values for pelvic range of movement giving the clinician the greatest opportunity of observing the movement. Secondly; it appears to be the plane that is most influenced by changes within the patient including speed and pregnancy. Therefore when examining pelvis movement during walking clinicians may find they gain more information on pelvis control from their observations by focusing away from the coronal plane and onto the transverse plane.

3.2.13 Assessment of hip during walking

Movement of the hip in the sagittal plane (flexion-extension) is an anterior movement forward at the hip joint to take a step and then a posterior extension movement until push off (Rose et al., 2006). Most of the evidence is in agreement that the sagittal plane range of movement is between; 30^0 and 45^0 (Franz et al., 2009; Kadaba et al., 1989; Kennedy et al., 2009; Levine et al., 2012; Ostrosky, VanSwearingen, Burdett, & Gee, 1994; Richards, 2008; Rose et al., 2006; Whittle, 1996), Table 3.5. The peak value is between; 40^0 and 52^0 (Franz et al., 2009; Novacheck, 1998; Schache et al., 2001), Table 3.5.

Movement of the hip in the coronal plane (abduction-adduction) is a lateral movement of the thigh relative to the pelvis (Rose et al., 2006). The evidence reviewed is in agreement that the coronal plane range of movement is between; 7^0 and 15^0 (Kadaba et al., 1989; Kennedy et al., 2009; Richards, 2008; Rose et al., 2006), Table 3.5. The peak value is approximately 50% of the total range being between; 7^0 and 9.1^0 (Novacheck, 1998; Pollard, Davis, & Hamill, 2004), Table 3.5.

Movement of the hip in the transverse plane may be described as internal and external rotation. All of the evidence reviewed is in full agreement that the transverse plane range of movement is; 15^0 (Kadaba et al., 1989; Richards, 2008; Rose et al., 2006), Table 3.5. The peak value lies between; 3.37^0 and 10^0 (Novacheck, 1998; Pollard et al., 2004), Table 3.5.

Some studies have described anomalous values lying outside of one standard deviation. Ostrosky established lower hip sagittal range of movement; 21^0 (Ostrosky et al., 1994). A potential explanation for this is that this study used elderly participants (60-80 years old) as part of this study and concluded that these participants had a reduced hip sagittal plane peak value and increased hip sagittal plane minimum compared to younger participants. Lelas established lower hip sagittal plane range of movement; 27.6^0 (Lelas et al., 2003). This study by Lelas used three different gait speeds and found a significant relationship between gait speed and both hip sagittal plane peak value and hip sagittal plane minimum ($P<0.0001$ for both). Hence this lower value may simply reflect a different gait speed compared to the other studies reviewed. A higher hip coronal plane peak value has been established; 13^0 (Schache et al., 2001) and hip transverse plane peak value; 25^0 (Schache et al., 2001). A potential explanation for this is that this was a treadmill study, Table 3.5.

Hip				
Plane of movement	Range of movement		Peak value	
	Value	Author	Value	Author
Sagittal	21^0	(Ostrosky et al., 1994)	10^0	(Ostrosky et al., 1994) (elder)
	27.6^0	(Lelas et al., 2003)	20^0	(Franz et al., 2009)
	36^0	(Ostrosky et al., 1994) (young)	20^0	(Bianchi et al., 1998)
	40^0	(Franz et al., 2009)	23.8^0	(Lelas et al., 2003)
	40^0	(Whittle, 1996)	25^0	(Whittle, 1996)
	40^0	(Kadaba et al., 1989)	26^0	(Ostrosky et al., 1994)(young)
	40^0	(Kennedy et al., 2009)	30^0	(Kadaba et al., 1989)
	45^0	(Rose et al., 2006)	30^0	(Levine et al., 2012; Rose et al., 2006)
	45^0	(Richards, 2008)	30^0	(Kennedy et al., 2009)
	45^0	(Levine et al., 2012)		
Coronal	7^0	(Kadaba et al., 1989)	5^0	(Kadaba et al., 1989)
	10^0	(Kennedy et al., 2009)	6^0	(Rose et al., 2006)
	12°	(Rose et al., 2006)	10^0	(Kennedy et al., 2009)
	15^0	(Richards, 2008)		
Transverse	15^0	(Kadaba et al., 1989)	3.37^0	(Pollard et al., 2004)
	15^0	(Richards, 2008; Rose et al., 2006)	10^0	(Richards, 2008; Rose et al., 2006)
	15^0	(Richards, 2008; Rose et al., 2006)	25^0	(Kadaba et al., 1989)

Table 3.5 Summary of previously published hip movements during walking

The evidence reviewed has established that there is a relatively large evidence base for normative hip kinematics during walking gait. The normal range of movement in the hip during walking is relatively large for the three planes of movement making it easier for the clinician to observe hip movement during walking. The sagittal plane range of movement is the plane that exhibits the greatest range of movement and is most influenced by speed. Therefore when applying the current evidence to the sagittal plane the clinician must be aware of matching the patient's walking speed to the research. The coronal plane range of movement is smaller but remains relatively easy to observe clinically. It is clinically important that in the coronal plane the hip normally moves into an adducted position at mid-stance and therefore a positive Trendelenburg position is normal for the single limb stance phase of gait. The hip also moves in synergy with the pelvis in the coronal and transverse planes, hence of clinical importance is that if a clinician notes abnormal movement of the hip in either the coronal or transverse plane then movement of both the pelvis and hip must be examined to establish which is creating the problem.

3.2.14 Assessment of walking observability

The review of the evidence for the kinematics of walking has shown that the ranges of movement at the hip are large, but relatively small at the lumbar and thoracic spine, trunk and pelvis. Current, clinical practice examines the movements of walking gait by visual observation, but visual observation of gait is prone to error and there are no existing studies to establish how accurate clinical observation of gait kinematics are. A previous study established that clinicians could not detect coronal plane pelvic movements of the Lumbo-Pelvic and Hip region of less than 5^0 during the Trendelenburg Test by visual observation (Youdas, Loder, Moldenhauer, Paulsen, & Hollman, 2006). The Trendelenburg Test is a relatively static test when compared to walking gait and hence clinicians may potentially not be able to detect movements as small as 5^0 during the relatively dynamic activity of gait. However if this 5^0 "level of observability" is applied to the observation of the Lumbo-Pelvic and Hip region during walking then clinicians should be able to perceive the larger ranges of movement of gait by visual observation. Therefore if the clinician observes the patient's walking gait from the side then the hip sagittal plane range of movement should be readily observable. The hip coronal plane range of movement should also be observable when viewed from anterior or posterior. Although the hip transverse plane range of movement is potentially large enough to be observed, viewing the participant from above or below is impractical in most physiotherapy clinics, Figure 3.8. For any range of movement, under 5^0, segments should appear motionless. Hence in the clinic, if clinicians observe movement then it is reasonable to assume that the region is hypermobile which may be indicative of a pathological state, Figure 3.8.

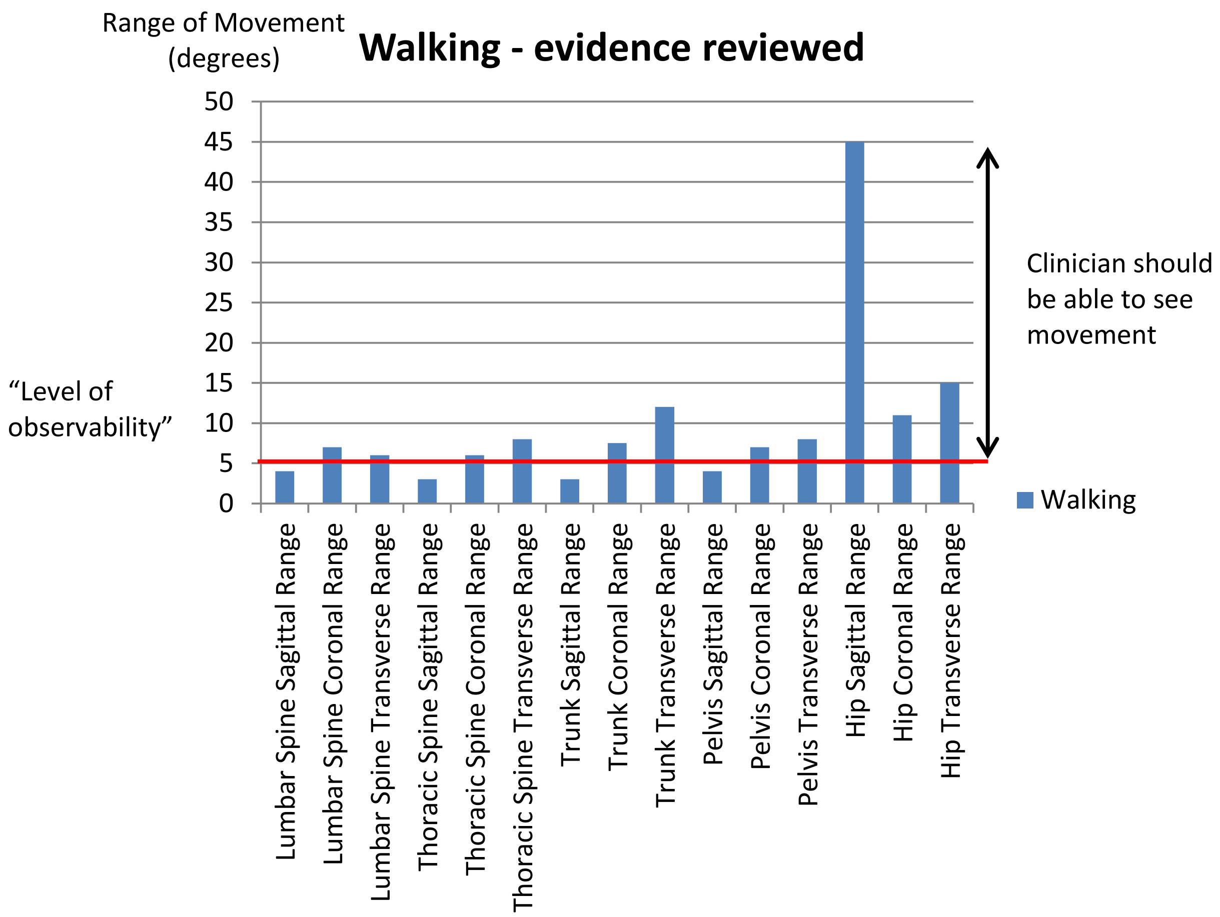


Figure 3.8 Perceivable and unperceivable range of movement during walking gait, median values from evidence reviewed

It is therefore clinically useful to be able to assess the components of walking gait by appropriate clinical tests, particularly where the range of movement is small making visual inspection difficult, such as at the lumbar, thoracic spine, trunk or pelvis. The study of any identifiable similarities between Lumbo-Pelvic and Hip movement during walking, running, the Trendelenburg Test, the Single Leg Squat and the Corkscrew Test would therefore allow clinicians to make evidence based decisions on which clinical tests to use as a proxy for the assessment of the lumbar, thoracic spine, trunk or pelvis.

3.2.15 Assessment of walking summary

This literature review has established that there is an existing evidence base for the Lumbo-Pelvic and Hip kinematics during walking. This evidence base is substantial, describing the kinematics for the pelvis and hip, however there is a lack of evidence describing the kinematics of the trunk, lumbar and thoracic spine. The main limitation of the current literature is that studies have used different age groups, mixed genders, pathologies and study methods. This makes comparison between the studies and clinical application of the data challenging.

3.3 Running gait

3.3.1 Assessment of lumbar spine during running

Lumbar spine in the sagittal plane (flexion-extension) movement is a flexion movement relative to the pelvis occurring twice, firstly just before mid-stance and secondly before late stance phase. It then moves into extension in late stance phase (Saunders et al., 2005). The range of lumbar flexion-extension increases minimally with speed of running but not reaching levels of statistically significant difference (Saunders et al., 2005). The evidence is in agreement that the range of movement is between; 7^0 and 14.5^0 (Saunders et al., 2005; Schache et al., 2002a; Schache, Blanch, Rath, Wrigley, Starr, & Bennell, 2002b; Schache et al., 2001), Table 3.6. The peak values are between 15^0 and 20^0 (Saunders et al., 2005; Schache et al., 2002a; Schache et al., 2001), Table 3.6. This would suggest that Lumbar spine movement in the sagittal plane is more easily observed during running than walking. However clinicians frequently find this movement difficult to observe due to the increased speed of the moving segments.

Lumbar spine in the coronal plane (side flexion) movement displays a biphasic curve for one complete running cycle. The lumbar spine coronal plane peak value occurs shortly after heel strike. As running speed increases, the lumbar spine coronal plane peak value reduces but is not statistically significantly different to walking ($p<0.0001$) (Saunders et al., 2005). The direction of lumbar spine coronal plane movement during running is variable (Saunders et al., 2005). The range of movement is approximately; 6^0 (Saunders et al., 2005), Table 3.6. Most of the evidence is in agreement that the peak value is; 10^0 (Schache et al., 2002a; Schache et al., 2001), Table 3.6. Therefore; at the lumbar spine the range and movement pattern in the coronal plane was similar for walking and running. During running however the speed of movement makes clinical observation more difficult. Hence clinicians may find it easier to observe a participant's lumbar spine movement in the coronal plane during walking and use these findings as a measure of how the participant moves during running.

Lumbar spine in the transverse plane (rotation) movement displays a single peak value during a complete running cycle. The peak value occurs shortly after heel strike. Moving from walking into running causes a tendency towards a lower peak value (Saunders et al., 2005). The evidence states that the range of movement is; 10^0 (Saunders et al., 2005), Table 3.6. The evidence is in agreement that the peak value is between; 8^0 and 10^0 (Saunders et al., 2005; Schache et al., 2002a; Schache et al., 2001), Table 3.6. This was a larger range of movement in the lumbar spine during running than walking. Hence clinicians will have a greater opportunity to observe the movement of the lumbar spine movement in the transverse plane during running than walking. However the faster movements occurring during running may make this difficult to observe clinically.

Elevated lumbar spine coronal plane ranges of movement have been stated lying between; 18.5^0 (SD=3.9) (Schache et al., 2002a), 22^0 (Schache et al., 2001) and 22.5^0 (SD=4.2) (Schache et al., 2002b). Also higher values for lumbar transverse plane range of movement have been established; 20^0 (Schache et al., 2001), 23.0^0 (SD=3.9) (Schache et al., 2002a) and 24.3^0 (SD=4.4) (Schache et al., 2002b). A potential explanation for this is that all of these studies used a combination of wands and markers to model the lumbar spine, Table 3.6. Lower values for lumbar coronal plane peak value have been found; 5.8^0 (0.8^0) (Saunders et al., 2005). A possible explanation for this is that this study was a treadmill study, Table 3.6.

Lumbar spine				
Plane of movement	Range of movement		Peak value	
	Value	Author	Value	Author
Sagittal	7^0	(Schache et al., 2001)	15^0	(Schache et al., 2001)
	10^0	(Saunders et al., 2005)	17^0	(Saunders et al., 2005)
	13.3^0	(Schache et al., 2002a)	20^0	(Schache et al., 2002a)
	14.5^0	(Schache et al., 2002b)		
Coronal	6^0	(Saunders et al., 2005)	5.8^0	(Saunders et al., 2005)
	18.5^0	(Schache et al., 2002a)	10^0	(Schache et al., 2001)
	22^0	(Schache et al., 2001)	10^0	(Schache et al., 2002a)
	22.5^0	(Schache et al., 2002b)		
Transverse	10^0	(Saunders et al., 2005)	8^0	(Saunders et al., 2005)
	20^0	(Schache et al., 2001)	10^0	(Schache et al., 2001)
	23.0^0	(Schache et al., 2002a)	10^0	(Schache et al., 2002a)
	24.3^0	(Schache et al., 2002b)		

Table 3.6 Summary of previously published lumbar spine movements during running

3.3.2 Common injuries of the lumbar spine during running

Patients often present to clinicians with lumbar symptoms that occur during running. The evidence reviewed has established that the normal ranges of movement in the lumbar spine during running are small for the three planes of movement. In combination with viewing these movements whilst the patient is actually running, where the segments are moving faster than during walking, this makes clinical observation of these movements very difficult for clinicians in the lumbar spine. This review of the literature for the lumbar spine kinematics during running gait has also established that there is an established evidence base of normative

Lumbo-Pelvic and Hip movement data for healthy participants. Despite lumbar spine injuries accounting for 22% of career ending injuries in professional football (Drawer & Fuller, 2001), there is no existing evidence base for the lumbar spine kinematics during running gait in professional football players. Greater understanding of lumbar spine kinematics during running may help to understand the lumbar pain syndromes suffered by professional football players (Drawer et al., 2001), which may help to reduce such injuries.

3.3.3 Assessment of thoracic spine during running

A review of the evidence has established that there is currently no description of how the thoracic spine moves during running. This lack of evidence for the kinematic values for the range of movement or peak value in the sagittal, coronal and transverse planes of movement represents the single largest gap in the current evidence base for running. Although the incidence of thoracic pain is relatively low in professional football players (Drawer et al., 2001), increasing understanding of thoracic kinematics is important as abnormal movement within the thoracic spine may cause symptoms remotely within the kinetic chain (Butler et al., 2003; Hoefert et al., 2003; Rothbart et al., 1988). This evidence gap therefore challenges clinicians in their examination and treatment of patients and researchers studying the role of clinical tests or treatment effectiveness.

3.3.4 Assessment of trunk during running

For trunk sagittal plane (flexion-extension) the movement displays a regular pattern of two full oscillations per running cycle. The point about which this movement occurs is essentially the mean angle of trunk rotation about a medial–lateral axis (average degree of trunk inclination with respect to the vertical) over the running cycle. Previous studies have considered the trunk to be a single segment and have measured with respect to an external, vertical reference (global co-ordinate system) finding that there was no clear relationship between running speed and trunk sagittal plane range of movement (Schache et al., 2002a). A search of the literature established that there is only one paper reporting a trunk sagittal plane range of movement; 9.6^0 (Schache et al., 2002b), Table 3.7. The trunk sagittal plane range and pattern of movement is similar during running and walking, but clinically more difficult to observe during running due to the faster movements involved. The clinical relevance of this is that clinicians may therefore consider using trunk sagittal plane range of movement during walking as a proxy measure for running.

The trunk coronal plane (side flexion) is more subtle than sagittal plane movement. Only one paper reporting a trunk coronal plane range of movement was found; 9.1^0 (Schache et al., 2002b), Table 3.7. The trunk coronal plane movement is nearly reciprocal to the pelvic movement. Hence the trunk compensates for the movement of the upper body, shoulders and head. It forms one of the most clinically important mechanisms for decoupling the intense lower extremity movement. This results in relatively minimal head and trunk movement allowing balance and equilibrium to be maintained during running (Novacheck, 1998).

For trunk transverse plane (rotation); the range of movement is large in magnitude compared to the sagittal plane. Joint rotations in this plane may be the most difficult to examine clinically because they are difficult to see (Novacheck, 1998). It is thought that the lower trunk rotates backward during an extension of the trailing leg while, simultaneously, the upper trunk rotates forward synchronously with the arm on the same side to maintain equilibrium during running (Schache, Bennell, Blanch, & Wrigley, 1999). The literature search established that there is only one paper reporting a trunk transverse plane range of movement; 23.8^0 (Schache et al., 2002b), Table 3.7. The trunk movement in the transverse plane is therefore greater during running than walking. This may explain why participants with trunk pain are able to walk without pain but not run. This review of the literature established that there is currently no evidence for the trunk peak value in the sagittal, coronal or transverse planes. This represents another large gap in the current evidence base.

Trunk		
Plane of movement	Range of movement	
	Value	Author
Sagittal	9.6^0	(Schache et al., 2002b)
Coronal	9.1^0	(Schache et al., 2002b)
Transverse	23.8^0	(Schache et al., 2002b)

Table 3.7 Summary of previously published trunk movements during running

The evidence reviewed has established that the normal range of movement in the trunk during running gait is greatest in the transverse plane and whilst this would give the clinician the greatest opportunity to observe this movement, it is the most difficult plane to observe visually in the clinic. There is existing evidence for each plane of trunk movement but this is based on one paper.

3.3.5 Assessment of pelvis during running

The pelvis sagittal plane (anterior tilt-posterior tilt) movement displays a biphasic curve for one complete running cycle. The pelvis sagittal plane range of movement during running is similar to the pelvis sagittal plane range of movement in normal walking, which has been found to be approximately 11^0 (Whittle et al., 1996). The pelvis sagittal plane range of movement is similar during running and walking, but clinically more difficult to observe during running due to the faster movements involved. The clinical relevance of this is that clinicians may therefore consider using walking as a proxy measure of pelvis sagittal plane range of movement during running. As running speed increases, the pelvis sagittal plane peak value (anterior pelvic tilt) increases very little (Novacheck, 1998). The movement of the pelvis in the sagittal plane anteriorly acts to lower the centre of mass, maximise the horizontal force and therefore increase forward propulsion (Novacheck, 1998). The biphasic oscillation for one running cycle can be described as follows; during the absorption period of stance the pelvis posteriorly tilts slightly to reach a position of pelvis sagittal plane minimum, or relative posterior tilt. After mid-stance, the pelvis then anteriorly tilts, reaching a pelvis sagittal plane peak value at approximately toe off, or anterior tilt. The pelvis then posteriorly tilts slightly during initial swing before anteriorly tilting again during terminal swing. This second posterior and anterior tilt during swing is produced by the stance phase forces of the contralateral lower limb. The pelvis sagittal plane range of movement appears to increase very little with faster running velocities. It is thought that pelvis sagittal plane movement needs to be minimized to conserve energy and maintain efficiency in running (Novacheck, 1998). Most of the evidence is in agreement that the range of movement is between 5^0 and 8.6^0 (Franz et al., 2009; Novacheck, 1998; Schache et al., 2002a; Schache et al., 2002b; Schache et al., 2001), Table 3.8. The literature stating a peak value shows little disparity with values between; 15^0 and 22^0 (Franz et al., 2009; Novacheck, 1998; Schache et al., 2002a; Schache et al., 2001), Table 3.8.

For pelvis coronal plane (pelvic obliquity or pelvic list) movement during stance phase, the pelvis drops until the start of double float where it is the most oblique. The clinical relevance of this is that a positive “Trendelenburg position” is normal for the stance phase of the running gait. As the limb begins swing phase, the movement reverses and the pelvis elevates to obtain foot clearance, returning to its starting position (Novacheck, 1998). This nearly reciprocal movement of pelvis and hip in the coronal plane, combined with slight Lumbo-Pelvic movement is one of the most important mechanisms for decoupling the intense lower extremity movements. The result is relatively minimal head and trunk movement allowing balance and equilibrium to be maintained during running (Novacheck, 1998). This review of the literature found two studies for the range of movement with values of; 6^0 (Novacheck, 1998) and 10.6^0 (Schache et al., 2002a), Table 3.8. Pelvis coronal plane peak value lies between; 10.6^0 and 13.6^0 (Schache et al., 2002a; Schache et al., 2001), Table 3.8.

The pelvis transverse plane (rotation) movement is very different in walking compared to running and sprinting. In walking, pelvic rotation is an important method of lengthening the stride by maximally rotating forward at initial contact to achieve a longer step length. The result of this rotation however is a decrease in horizontal velocity. During running and sprinting pelvis internal rotation peak value occurs in mid-swing to lengthen the stride, but by the time of initial contact, the pelvis has rotated externally. This maximizes the horizontal propulsion force and velocity. The pelvis in running and sprinting also functions as a pivot between the counter-rotating shoulders and legs (Novacheck, 1998). There are more studies for transverse plane range of movement than sagittal or coronal and most of the evidence is in agreement that the range of movement is between; 10^{0} and 16.2^{0} (Novacheck, 1998; Schache et al., 2002a; Schache et al., 2001), Table 3.8. The evidence is in agreement that the peak value is; 5^{0} (Novacheck, 1998; Schache et al., 2002a), Table 3.8.

A higher value for the pelvis coronal plane range of movement has been established; 14^{0} (Schache et al., 2001). A potential explanation for this is that this study used a combination of wands and markers to model the lumbar spine, Figure 3.3. A lower value for the pelvis coronal plane peak value has been found, 5^{0} (Novacheck, 1998). However this was a literature review and the source of the data is not stated. One higher pelvis transverse plane peak value has been stated; 14^{0} (Schache et al., 2001), Table 3.8, however this study used a treadmill.

Pelvis				
Plane of movement	Range of movement		Peak value	
	Value	Author	Value	Author
Sagittal	5^{0}	(Novacheck, 1998)	15^{0}	(Franz et al., 2009)
	7^{0}	(Schache et al., 2001)	17^{0}	(Schache et al., 2002a)
	7.4^{0}	(Franz et al., 2009)	18^{0}	(Schache et al., 2001)
	7.6^{0}	(Schache et al., 2002a)	22^{0}	(Novacheck, 1998)
	8.6^{0}	(Schache et al., 2002b)		
Coronal	6^{0}	(Novacheck, 1998)	5^{0}	(Novacheck, 1998)
	10.6^{0}	(Schache et al., 2002a)	10.6^{0}	(Schache et al., 2002a)
	14^{0}	(Schache et al., 2001)	13.6^{0}	(Schache et al., 2001)
Transverse	10^{0}	(Novacheck, 1998)	5^{0}	(Novacheck, 1998; Schache et al., 2002a)
	13.9^{0}	(Schache et al., 2002a)	5^{0}	(Novacheck, 1998)
	14^{0}	(Schache et al., 2001)	14^{0}	(Schache et al., 2001)
	16.2^{0}	(Schache et al., 2002a)		

Table 3.8 Summary of previously published pelvic movements during running

The pelvis is one of the regions that have previously received the most attention in kinematic studies. This has been noted previously in this chapter with respect to walking and this is equally relevant for running. The evidence reviewed has established that the normal range of movement in the pelvis during running in the sagittal plane is small. The coronal plane range of movement is a plane that many clinicians focus their observations on feeling that it is a good indication of pelvic control. In the coronal plane a slightly larger but clinically moderate movement should be seen. The transverse plane shows the highest values for pelvic range of movement, giving the clinician the greatest chance of observing the movement. Furthermore pelvic transverse plane movement timing is different during walking and running illustrating the importance of neuromuscular control within this plane. Therefore when examining pelvic movement during running gait clinicians may find they gain most information by focusing on the transverse plane.

3.3.6 Assessment of hip during running

Hip sagittal plane (flexion-extension) movement is essentially sinusoidal during running. In running the hip extension peak value is similar to walking, but occurs slightly later in the gait cycle, at mid to late stance phase during toe off. During initial swing, the hip reverses direction and begins to rapidly flex. As gait velocity increases, so does the hip sagittal plane peak value leading to a longer step length. The range of movement of hip flexion movement increases consistently with faster running (Novacheck, 1998; Schache et al., 1999). During the second half of swing phase, in running unlike walking, the hip extends in preparation for initial contact. The hip starting to extend in this manner is thought to help avoid the excessive deceleration that would occur at the time of initial contact if the foot is too far ahead of the centre of mass of the body, creating a braking force on forward progression of the body (Novacheck, 1998). Most of the evidence is in accord that the range of movement is between; 50^0 (Franz et al., 2009) and 55^0 (Novacheck, 1998), Table 3.9. The peak value is between; 40^0 and 52^0 (Franz et al., 2009; Novacheck, 1998; Schache et al., 2001), Table 3.9.

Hip coronal plane (abduction-adduction) movement is more subtle than sagittal plane movement. It is however, important in minimizing upper body movement because in this plane, motion of the knee and ankle is restricted by the collateral ligaments. In contrast, the movement of the hip is relatively unconstrained allowing significant movement to occur (Novacheck, 1998). The hip adducts relative to the pelvis during stance, acting as a shock absorbing mechanism similar to that seen in the sagittal plane at the knee in running and the ankle in sprinting (Novacheck, 1998), and abducts during swing phase returning to the start position (Novacheck, 1998). A review of the current literature established that there is limited evidence for the range of movement; 14^0 (Novacheck, 1998), Table 3.9. The hip coronal plane peak value is consistent within the literature lying between; 9.1^0 (males) (whilst cutting) (Pollard et al., 2004) and 13^0 (Schache et al., 2001), Table 3.9.

In the transverse plane (internal rotation-external rotation); during running the hip rotates reciprocally with the pelvis hence hip transverse plane peak value (external rotation) occurs at heel strike and it internally rotates during stance phase (Novacheck, 1998). A review of the current literature established that there is little evidence for this range of movement; 7^0 (Novacheck, 1998), Table 3.9. There are a few studies for peak value with values between; 3.37^0(females), 3.58^0 (males) (Pollard et al., 2004), and 10^0 (Novacheck, 1998), Table 3.9.

A higher hip sagittal plane range of movement has been established; 68.2^0 (Schache et al., 2001). However hip sagittal plane peak value (hip flexion) has been found to increase consistently with faster running (Novacheck, 1998; Schache et al., 1999). Therefore this high range of movement may simply be due to the different running speeds of these studies. Higher values for hip coronal plane range of movement; 26^0 (SD=6), hip transverse plane range of movement; 31.1^0 (SD=5.2) and hip transverse plane peak value; 25^0 (Schache et al., 2001) have been found potentially due to the marker set of wands and markers used. A lower value for pelvis coronal plane peak value was found; 7^0 (Novacheck, 1998), but the data source of this literature review was not stated, Table 3.9.

Hip				
Plane of movement	Range of movement		Peak value	
	Value	Author	Value	Author
Sagittal	50^0	(Franz et al., 2009)	40^0	(Franz et al., 2009)
	55^0	(Novacheck, 1998)	50^0	(Schache et al., 2001)
	68.2^0	(Schache et al., 2001)	52^0	(Novacheck, 1998)
Coronal	14^0	(Novacheck, 1998)	7^0	(Novacheck, 1998)
	26^0	(Schache et al., 2001)	9.1^0	(Pollard et al., 2004)
			13^0	(Schache et al., 2001)
Transverse	7^0	(Novacheck, 1998)	3.37^0(females)	(Pollard et al., 2004)
	31.1^0	(Schache et al., 2001)	3.58^0 (males)	(Pollard et al., 2004)
			10^0	(Novacheck, 1998)
			25^0	(Schache et al., 2001)

Table 3.9 Summary of previously published hip movements during running

The evidence reviewed has established that there is a strong evidence base for normative hip kinematics during running gait. The normal range of movement at the hip during running is relatively large for the three planes of movement making it relatively easy for the clinician to observe hip movement during gait. The sagittal plane range of movement is the plane that exhibits the greatest range of movement and is most influenced by speed. Therefore when applying the current evidence to the sagittal plane the clinician must be aware of matching the patient's running speed to the research. The coronal plane range of movement is smaller but remains relatively easy to observe clinically. It is clinically important that in the coronal plane the hip normally moves into an adducted position at mid-stance and therefore a positive Trendelenburg position is normal for this phase of gait. The hip also moves in synergy with the pelvis in the coronal and transverse planes. In common with walking it is important that if a clinician notes abnormal movement of the hip in either the coronal or sagittal planes that movement of both the pelvis and hip must be examined to establish which is creating the problem.

The evidence base for running is far smaller than for walking. The running and walking evidence base suffers from similar problems when comparing the studies, primarily based around study design. Different studies have used different populations (Schache et al., 2002b), gait speed (Queen, Gross, & Liu, 2006), ages (Schache et al., 2002a), genders (Pollard et al., 2004; Willson & Davis, 2008), and surfaces (Schache et al., 2002a; Schache et al., 2001), all of which have been shown to generate different kinematics values. Hence the clinician should interpret running data carefully and apply it to the appropriate populations and environments.

3.3.7 Assessment of running observability

The existing kinematic evidence for running gait has shown that the range of movement at the Lumbo-Pelvic and Hip region is relatively small, in each of the three cardinal planes. Walking and the Trendelenburg Test are both less dynamic than running gait, where the segments are moving at higher speeds, and hence clinicians may not be able to observe movements as small as 5^0. However if the 5^0 "level of observability" is applied to the observation of the Lumbo-Pelvic and Hip region during running gait then clinicians should be able to assess Lumbo-Pelvic and Hip movement by visual observation. Hence if a clinician is unable to perceive movement in any of the regions in any single plane these could be interpreted as hypomobile, Figure 3.9.

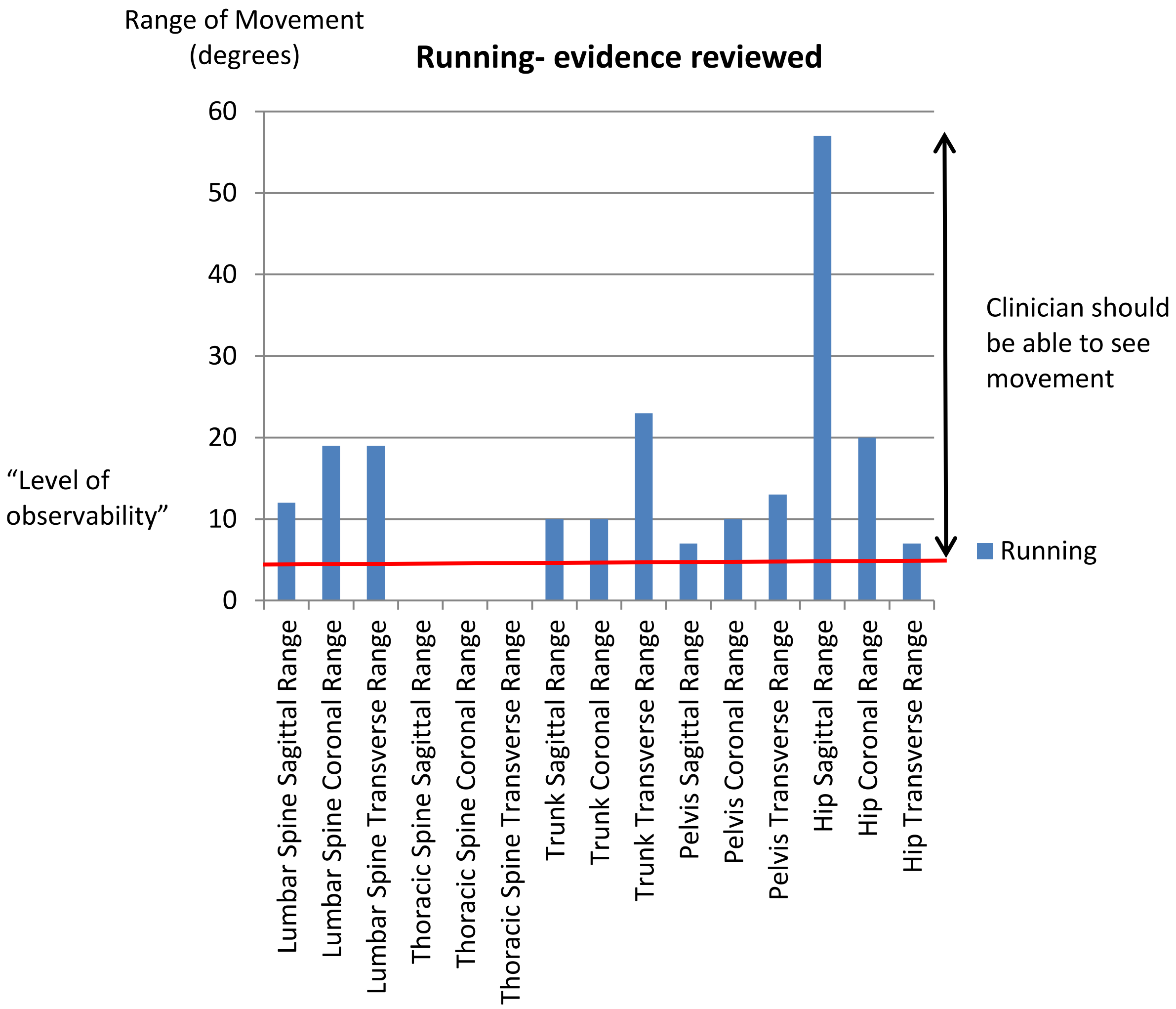


Figure 3.9 Perceivable and unperceivable movements during running gait, median values from evidence reviewed

It is therefore clinically useful to be able to examine the components of running gait by appropriate clinical tests, particularly where the range of movement is small making visual inspection difficult, such as at the pelvis, lumbar spine or trunk in the sagittal plane of movement. The study of any similarities between Lumbo-Pelvic and Hip movement during clinical and functional tests for these parameters would have great utility allowing clinicians to make evidence based decisions as to which tests to use particularly in the anatomical regions and planes exhibiting the smallest movements.

3.3.8 Assessment of running summary

The aim of this literature review was to explore the existing evidence base for the Lumbo-Pelvic and Hip kinematics of running. This evidence base is substantial for the pelvis and hip and small for the lumbar spine, but there is currently no evidence for the thoracic spine. However the current literature has used participants with different ages ranging between 23.5 and 29.8 years, different genders and study methods including participants wearing shoes and barefoot. This makes comparison between the studies difficult. The clinical application of the current data is problematic as there are gaps within the current evidence particularly for young males under the age of 23.

3.3.9 Assessment of walking and running summary

There have been a large number of papers published with data for walking but fewer on running (Schache et al., 1999). For both walking and running; the majority of Lumbo-Pelvic and Hip studies have focused on the pelvis and hip, there are fewer studies on the trunk and virtually none of the lumbar or thoracic spines. There are currently no studies investigating thoracic spine kinematics during running, Figure 3.10. A potential explanation of this maybe that until recently technology was not sufficiently advanced to track spinal markers accurately and yield meaningful data, particularly during the running gait cycle. When considering the planes of movement; most of the evidence has been for the sagittal plane of movement, less evidence exists for the coronal and transverse planes during either gait cycle. There is currently no normative data for walking or running Lumbo-Pelvic and Hip kinematics within professional football players. Furthermore there is no evidence to demonstrate if there are any differences between healthy participants and professional football player's Lumbo-Pelvic and Hip kinematics, despite this population commonly sustaining Lumbo-Pelvic and Hip injuries (Merron, Selfe, Swire, & Rolf, 2006). There are also very few studies comparing the kinematics observed during gait with common Lumbo-Pelvic and Hip clinical tests (Hindle, Pearcy, Cross, & Miller, 1990). These gaps in the evidence base, limit clinicians when attempting to implement evidence into the examination of gait and in the selection of appropriate clinical tests for the examination of specific components of walking and running (Chan et al., 2008). This illustrates a clinical need to establish normative Lumbo-Pelvic and Hip kinematic data for professional football players in the three cardinal planes, and establish if this data is different to healthy participants. A greater understanding of the relationship between the kinematics of gait and the clinical tests will help the clinician to select appropriate tests to examine the components of gait.

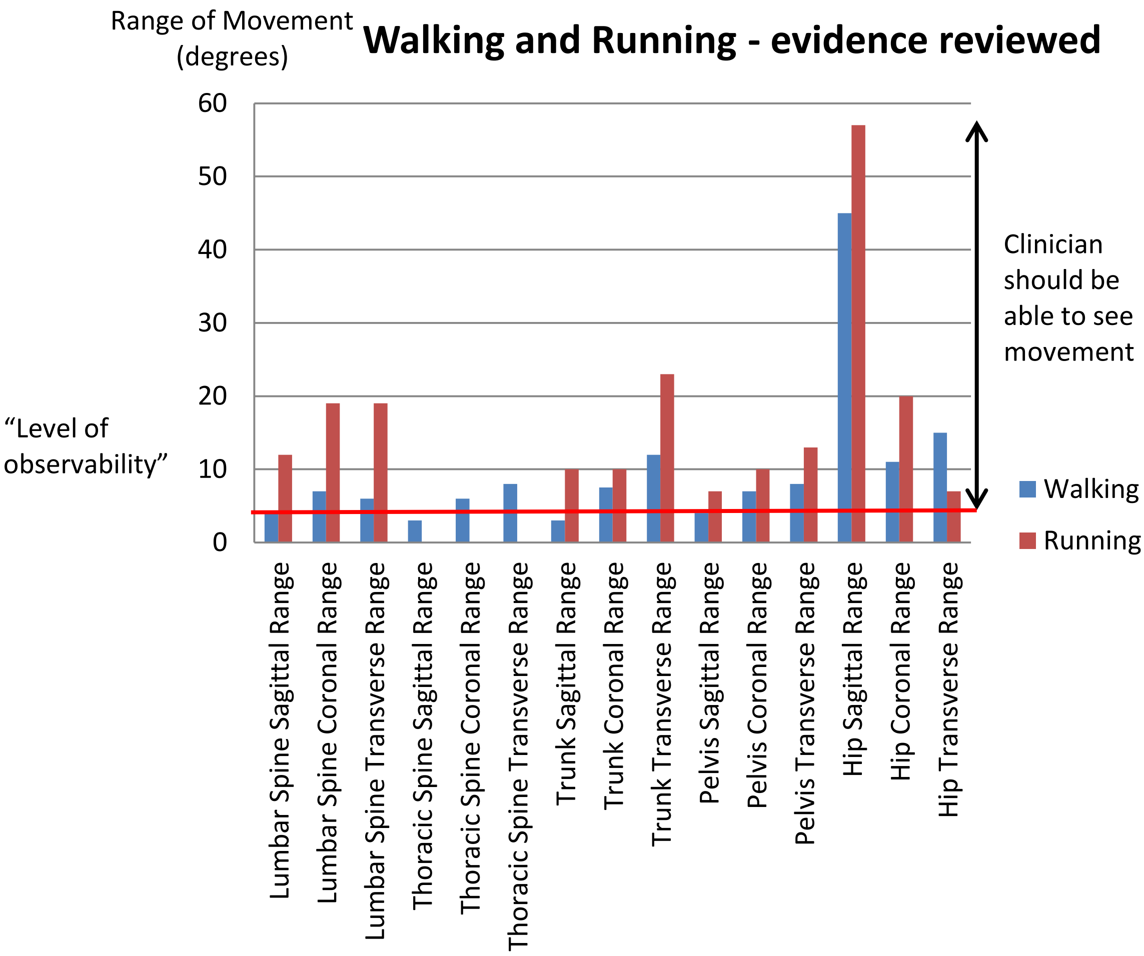


Figure 3.10 Perceivable and unperceivable movements during walking and running gait, median values from evidence reviewed

It is of clinical interest that the current evidence indicates that the range of movement is similar, in most of the Lumbo-Pelvic and Hip region during both gait cycles, Figure 3.10. The literature has shown that the greatest changes in movement occurred at the hip when comparing walking to running, Figure 3.10. However the observation of running is harder due to the faster moving segments. This evidence suggests that clinicians may be able to use the Lumbo-Pelvic and Hip movements observed during walking as surrogate measures of those expected during running except at the hip. However during running the ranges of movement at the hip are large and hence clinicians may be able to observe this movement despite the increased speed of movement. Alternatively clinicians may wish to examine the hip component of running by using a clinical test as a proxy measure.

3.4 The Lumbo-Pelvic and Hip region in professional football players

3.4.1 Common injuries of the Lumbo-Pelvic and Hip in professional football players

The evidence related to the overall injury prevalence within professional football players indicates that professional football players in the English Premier League sustain 1.3 injuries per player per year on average with each injury leading on average to 24.2 days absence. 78% of these injures lead to one competitive match being missed (Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001). Therefore it is estimated that the overall cost of injuries for a professional football club is £630,000 per season per player.

In English professional football injuries of the Lumbo-Pelvic and Hip region occur at a lower frequency than injuries to the lower extremities (Anderson et al., 2001; Merron et al., 2006), However these injuries can result in extensive rehabilitation time (Anderson et al., 2001) and form a major diagnostic (Fogel & Esses, 2003) and therapeutic dilemma (Fon & Spence, 2000). Lumbar injuries accounted for 6% of injuries from July 1997 to May 1999 (Hawkins et al., 2001) and 3% in 2006 in English professional football players (Merron et al., 2006). A similar incidence is seen within European professional football with lumbar injuries accounting for 9% of Swedish elite football injuries in 2001 (Hagglund, Walden, & Ekstrand, 2006) and 5% of injuries sustained in the 50 top European football clubs (Ekstrand, Hagglund, & Walden, 2009). Pelvic injuries accounted for 3% of injuries between 2003 and 2006 in English professional football players (Merron et al., 2006). Pelvic injuries in particular are thought to be an economic and personal burden in terms of absence from sport with the potential to result in chronic disability and early retirement (Cunningham, Brennan, O'Connell, MacMahon, O'Neill, & Eustace, 2007; Fon et al., 2000). The hip joint exhibits the highest rate of arthritis per 10000 hours of playing time in English professional football players (Drawer et al., 2001) and joint pain score (static activities, 0.06, dynamic activities 0.09) (Drawer et al., 2001). In English professional football players the hip appears to provide the highest rates of joint pathology and pain. As a group the Lumbo-Pelvic and Hip region accounts for one the highest percentage of career ending injuries in English professional football (31% total, 22% lumbar spine, 9% hip) (Drawer et al., 2001), Figure 3.11.

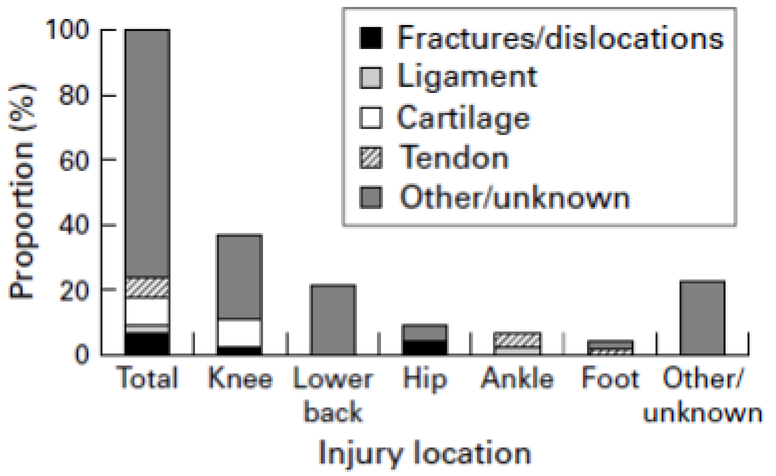


Figure 3.11 Location and nature of career ending chronic injuries (Drawer et al., 2001)

When considered as a region, Lumbo-Pelvic and Hip injuries accounted for 36% of the injuries sustained in English professional youth academy football, 35% of the injuries in English professional football (Hawkins et al., 2001), 81% of recurrent injuries in English professional youth academy football (Hawkins et al., 2001), and 31% of the career ending injuries in English professional football players (Drawer et al., 2001). Injury data for English professional football club's youth team players has established that there is a higher incidence of spinal and pelvic related injuries, with equivocal rates in the hip, amongst youth players when compared with the senior squad (Merron et al., 2006). This highlights the need to develop diagnostic algorithms for this particular group of players (Mayer, Geibler, Schneider, Ishak, & Schneider, 2012). An increased knowledge therefore of the Lumbo-Pelvic and Hip kinematics of this particular group may help provide an insight into the patho-biomechanics of this unique problem. It may be speculated that emphasis on control of the Lumbo-Pelvic and Hip region by core stability training and muscle imbalance around the pelvis may be important for injury prevention and treatment of these younger players.

3.4.2 Current conservative treatment of Lumbo-Pelvic and Hip injuries in professional football players

Contemporary evidence suggests that the cause for many insidious injuries of the Lumbo-Pelvic and Hip region is a change within the central locomotor command (Smith, Russell, & Hodges, 2009). This change leads to mis-selection of appropriate movement patterns (Latash, Scholz, & Schoner, 2002), sub-optimal movement patterns during functional activities (Carson & Collins, 2011), reduced performance and eventually pain or pathology (Comerford & Mottram, 2001a; Comerford & Mottram, 2001b). Many Lumbo-Pelvic and Hip problems are managed conservatively. All of the conservative management paradigms aim to reverse this process, starting with an examination of the patient and using exercises to treat movement dysfunction. Interestingly these contemporary paradigms use different postures and types of contractions during the patient’s rehabilitation.

Comerford and Mottram developed a hypothetical paradigm for the treatment of the Lumbo-Pelvic and Hip region. They advocate exercises in non-functional positions using low threshold contractions (Comerford et al., 2001a; Comerford et al., 2001b). O’Sullivan described a similar regime for the treatment of lumbar segmental instability and recommended that exercises should be direction specific to the patient (O'Sullivan, 2000). However how these types of exercises are able to create a change within the central locomotor command has been challenged. Lederman questioned the concept that pre-conceived, low threshold contractions, in a non-functional position could evoke a desirable change in central locomotor command when function frequently required sub-conscious, high threshold contractions, in functional positions (Lederman, 2010).

“Pilates” and “core stability” programmes use similar exercises to those advocated by Comerford, Mottram and O’Sullivan. Both paradigms have been developed within the health and fitness industry, and are commonly used within sports rehabilitation (Akuthota, Ferreiro, Moore, & Fredericson, 2008; Hibbs, Thompson, French, Wrigley, & Spears, 2008). They also use pre-conceived contractions in a non-functional position, but “Pilates” and “core stability” often use a high threshold contraction. Interestingly another paradigm developed in the sports industry is the “Specific Adaptation to Imposed Demands” (SAID) principle. It states that adaptation will be specific to the demand imposed upon the body during exercise (Mathews, Fox, & Close, 1976). This is a similar paradigm to the medical paradigms of Wolff’s and Davis’s laws which states that the bone and muscle adapts to the manner in which it is used. A study by Stanton of young male athletes (n=18) established that 6 weeks of seated core stability training improved core stability of the participants but did not significantly improve their running posture or economy (Stanton, Reaburn, & Humphries, 2004). Therefore both hypothetical principles, and research, suggest that adaptations created by exercises in one posture may not lead to changes in another. Hence it is suggested that exercises prescribed by clinicians for any specific problem within the Lumbo-Pelvic and Hip region should be specific to the posture and type of contraction required for that function. Thus rehabilitation should be load, speed, joint, plane and movement specific.

3.4.3 The Lumbo-Pelvic and Hip region in professional football players conclusion

Football players form a large part of the athletic population, run long distances, and sustain significant injuries to the Lumbo-Pelvic and Hip region. These injuries often require significant input from clinicians (Rodriguez, Miguel, Lima, & Heinrichs, 2001) and frequently lead to retirement from the sport. Geraci, et al. (2005) stated that athletes who run are especially at risk of the development of hip and pelvis injuries due to chronic repetitive microtrauma. Geraci states that the key to treatment is identifying the kinematic dysfunction within the kinetic chain that contribute to this repetitive microtrauma. Moreover that a long-term successful outcome and prevention of re-injury is more likely if the focus of rehabilitation is on the restoration of normal kinematic function of the kinetic chain, rather than on a specific injured tissue (Geraci & Brown, 2005; Nuesch, Huber, Romkes, Gopfert, & Camathias, 2010). The identification therefore of the normal Lumbo-Pelvic and Hip kinematics in the healthy population and professional football players may aid the implementation of evidence based injury prevention programmes (Willems, De Clercq, Delbaere, Vanderstraeten, De Cock, & Witvrouw, 2006), and help to improve the clinical examination and treatment of these injuries (Geraci et al., 2005; Nuesch et al., 2010).

3.5 Trendelenburg Test

3.5.1 Introduction

The Trendelenburg Test was developed by Friedrick Trendelenburg, an orthopaedic surgeon, in Bonn, Germany in 1895 (Mercer Rang, 1966; Peltier, 1998; Powell, 2001; Shampo, 2001; Trendelenburg, 1895; Vasudevan, Vaidyalingam, & Nair, 1997). It was a progression of previous work by Dupytren on " glissement vertical," (Peltier, 1998). The Trendelenburg Test was created to assist doctors in examining the gait of patients with congenital dislocation of the hip (CDH) and progressive muscular atrophy (Mercer Rang, 1966; Peltier, 1998). The Trendelenburg Test is conducted in the position of single limb stance (Hoefert et al., 2003). This position is seen in many daily functions such as walking and running, or in sports such as football, rugby, hockey, gymnastics and skiing. Therefore single limb stance is a position both normal and sporting individuals go into repetitively and frequently.

During the Trendelenburg Test the weight bearing limb forms a closed kinetic chain with the floor and the non weight bearing limb forms an open kinetic chain (Mayer et al., 2003). If the two limbs and pelvis are considered as a whole then during the Trendelenburg Test they are in "controlled open kinetic chain" (Butler et al., 2003). Loss of control during the test may cause uncontrolled movement of the pelvic link in the chain (Butler et al., 2003; Hoefert et al., 2003), potentially leading to dysfunction, symptoms or disability (Kinetic Control, 2002) at the site of dysfunction during the test, proximal or distal to it. Therefore the Trendelenburg Test is a clinical test for the lower limb kinetic chain of joints and their ability to transduce force across them in a functional manner.

3.5.2 The Trendelenburg Test

Originally Trendelenburg described his test as "*standing on the treated (affected) leg and raising the buttock of the other side up to or above the horizontal line*," (Mercer Rang, 1966; Peltier, 1998), Figure 3.12. Trendelenburg stated that the test was positive if the patient was unable to stand on the treated (affected) leg and raise the buttock of the other side up to or above the horizontal line (Mercer Rang, 1966; Peltier, 1998), Figure 3.12. Trendelenburg felt that this indicated *"… that the abductors of the standing leg cannot keep the pelvis horizontal*", (Mercer Rang, 1966; Peltier, 1998). Equally the ability to maintain the test position indicated a negative test and should be interpreted as a normal hip abductor mechanism.

A B

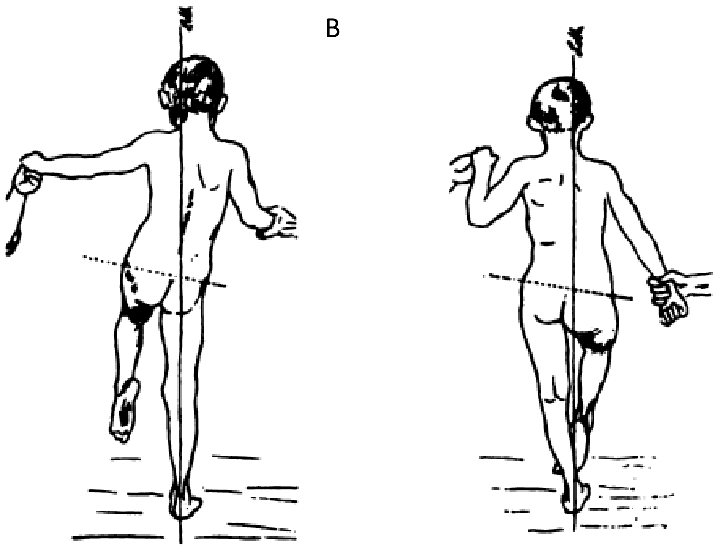


Figure 3.12 Literature review Trendelenburg Test method; (A) Normal (i.e. the test is "negative") (B) Abnormal (i.e. the test is "positive") (Mercer Rang, 1966; Peltier, 1998)

Trendelenburg described the effect that this hip abductor weakness had upon the patient's gait. "*The opposing swings* (seen in the Trendelenburg gait) *meet between the sacrum and lumbar spine: this is the pivot of the movements. It looks as if almost a hinge were inserted here, about which the spine moves in relation to the sacrum, and these hinging movements are prompt and full in a way hardly possible in a normal body. The joint has become adapted to the increased demands, and we must expect to find corresponding anatomical changes in older patients,*" (Peltier, 1998). He describes autopsy findings of the lumbar spine from these patients where "*a very unusual mobility in the lumbo-sacral joint*" and "*the intervertebral substance between the last lumbar vertebra and the sacrum was much thicker than normal,*" (Peltier, 1998).

The Trendelenburg Test is often cited as being a useful clinical test. Tests used clinically should be standardised (Chartered Society of Physiotherapy, 2000; Selfe et al., 2001), with explicit instructions for administration (McDowell, 2006). However Trendelenburg's original description of the test lacked an "operational definition" i.e. a clear method and interpretation (Youdas et al., 2006). This lack of a clear method for administering and interpreting the test may explain Hardcastle and Nades's observation: *"*(they) *found little agreement amongst colleagues about performance or interpretation of the* (Trendelenburg) *Test*" (Hardcastle & Nade, 1985).

Both physiotherapists and chiropractors have been found to have different methods of performing similar Lumbo-Pelvic clinical tests (Billis, Foster, & Wright, 2003; Hestboek & Leboeuf-Yde, 2000). Chiropractors often interpret the response to common, Lumbo-Pelvic clinical tests differently (French, Green, & Forbes, 2000). These studies showed poor intra and inter-tester reliability (Billis et al., 2003; French et al., 2000; Hestboek et al., 2000). These differences may lead to disagreement in interpretation of the examination and the subsequent sub-classification of conditions. This may cause disagreement in the optimal course of treatment. It may be concluded that where clinical tests have different methods of application or interpretation then intra and inter-tester reliability is inevitably poor. Equally to raise intra and inter-tester reliability clinical tests need to be "*precise, reproducible and highly standardized*" (Marcotte, Normand, & Black, 2002).

Due to this confusion over methods and interpretation Hardcastle and Nade (Hardcastle et al., 1985) investigated the Trendelenburg Test. In 1985 Hardcastle and Nade became the first authors since Trendelenburg himself, nearly 100 years before in 1895, to define the method for performing the Trendelenburg Test and how to interpret its response. The paper by Hardcastle and Nade has become the most commonly referenced method and interpretation for performing the Trendelenburg Test (Asayama, Chamnongkich, Simpson, Kinsey, & Mahoney, 2005; Westhoff, Petermann, Hirsch, Willers, & Krauspe, 2005).

Hardcastle and Nade used the latest scientific equipment available; videotape, slides and electromyography. In contrast to Trendelenburg they used a laboratory based study using experimental, same-subject crossover design. Inter and intra-comparative group analyses were made. Trendelenburg used only participants with CDH and progressive muscular atrophy but Hardcastle and Nade used a broader population with participants including; Total Hip Arthroplasty, Leg Calve Perthes disease, Incomplete Paraplegia, Muscular Dystrophy, Nerve Root Entrapment, Cerebral Palsy, Poliomyelitis, Hemiplegia, Scoliosis, Ankylosing Spondylitis, Iliac Crest Disease, CDH, Subluxation, Coxa Vara, Slipped Capital Femoral Epiphysis, Fractured Neck of Femur, Osteoarthritis, Avascular Necrosis and asymptomatic subjects.

Trendelenburg stated two possibilities for a positive test and did not clearly define how to interpret the test. Hardcastle and Nade clarified how to interpret the test giving three well defined possibilities. They also included timing of the test hence creating a more objective test.

3.5.3 Contemporary evidence

Contemporary evidence shows the Trendelenburg Test is now being used internationally within research (Asayama, Naito, Fujisawa, & Kambe, 2002; Chin & Brick, 2000; DeAngelis &

Busconi, 2003; DiMattia, Livengood, Uhl, Mattacola, & Malone, 2005; Downing, Clark, Hutchinson, Colclough, & Howard, 2001; Eskelinen, Helenius, Remes, Ylinen, Tallroth, & Paavilainen, 2006; Pai, 1996; Rozbruch, Paley, Bhave, & Herzenberg, 2005; Smith, Shurnas, Morgan, Agudelo, Luszko, Knox, & Georgopoulos, 2005; Thienpont, Simon, & Fabry, 1999; Westhoff et al., 2005; Youdas et al., 2006). These studies used the Trendelenburg Test to examine the gait of far more than CDH and progressive muscular atrophy. Most subsequent orthopaedic and therapeutic literature has used the Trendelenburg Test when studying structures in and around the hip:

- Downing et al (2001), Asayama et al (2002) and Pai (1996) (Total Hip Replacement)
- Ramesh et al (1996) (Total Hip Replacement – superior gluteal nerve damage)
- Vasudevan et al (1997) (Hip assessment)
- Van Iersel and Mulley (2004) (Literature review - Waddling gait)
- DiMattia et al (2005) (Single leg Dip)
- Inan et al (2005) (Pelvic support osteotomy)
- Rozbuch et al (2005) (Ilazirov Hip – paediatrics)
- Westhoff et al (2005) (Leg Calves Perthes)
- Youdas et al (2006) (Abductor muscle fatigue)

The literature describes different methods for performing the test (Downing et al., 2001; Hardcastle et al., 1985), Table 3.10.

Author and Source of Description of Test	Positive Test Definition
Asayama et al (1985). Taken and referenced from Hardcastle and Nade (1985)	The pelvis on the non-stance side moves more downward below the level of the stance side in proportion to the degree of the abductor weakness < or = -2^0. This also accepts delayed positive response if unable to hold for 30s
DiMattia et al (2005). Taken from Hardcastle and Nade (1985)	The test is considered positive when the pelvis on the non-weight bearing side lowers. Although no quantification was suggested. This does not accept a delayed positive response
Downing et al (2001). Taken from Hardcastle and Nade (1985)	No description in text. Although it accepts delayed positive response if unable to hold for 30s
Hardcastle and Nade (1985)	Accepts delayed positive response if unable to hold for 30s and cites Mitchell 1973
Inan et al (2005). Taken from Hardcastle and Nade (1985)	If the iliac crest was high on the affected side and low on the affected side. No strict interpretation of positive result or delayed Yes if initially negative but, after standing on the leg for a short time, the pelvis gradually began to fall toward the unsupported side
Pai (1996). Taken from Hardcastle and Nade (1985)	Normal. If the pelvis on the non stance side can be elevated high up and is maintained for 30 seconds Elevation of the pelvis is present but not maximal Pelvis is elevated but not maintained for 30 seconds No elevation of the non stance side Drooping of the pelvis Non-valid response: presence of hip pain, uncooperative patient (1-2 were normal, 3-5 were abnormal) Did not formally say delayed but includes it into his own 6 grade scale of responses
Shampo (2001)	Falling rather than elevation of the gluteal fold on the unaffected side when the patient stands on the affected leg and raises the other
Ramesh et al (1996). Taken from Hardcastle and Nade (1985)	Normal. The pelvis on the non-weight bearing side can be elevated high and maintained for 30 seconds Abnormal. Elevation of the pelvis is present but not to the peak value Abnormal. The pelvis is elevated but can not be maintained for 30 seconds Abnormal. There is a dropping of their pelvis on the non-weight-bearing side (Only acknowledges 4 as an abnormal response)
Rozbruch et al (2005)	Photograph in text but no description. Un-described Trendelenburg Test
Van Iersel MB and Mulley (2004) Reference Trendelenburg (1895)	The trunk bends to the side of stance There is falling and rising of the pelvis on the horizontal axis. The pelvis falls to the swinging side (i.e. the side in which the leg is off the ground)
Vasudevan et al (1997) References Apley's	The pelvis drops on the unsupported side – 3 possible mechanisms Supra-pelvic. Costo-pelvic impingement as in scoliosis Pelvic. This is due to loss of the fulcrum as in developmental dysplasia of the Hip, or of the lever mechanism as in non-union of the femoral neck, or of power as in poliomyelitis or muscular dystrophy Infra-pelvic. This is caused by medial deviation of the mechanical axis of the lower limb
Westhoff et al (2005) References Trendelenburg (1895)	Pelvic drop to the swinging limb during single stance phase of more than 4 degrees and / or peak value pelvic drop in the stance phase of more than 8 degrees Trunk lean in relation to the pelvis to the stance limb during single stance phase of more than 5 degrees Hip adduction in single stance phase of more than 9 degrees and / or peak value Hip adduction in the stance phase of more than 11 degrees
Youdas et al (2006) References Hardcastle and Nade (1985)	Uses Hardcastle and Nade however flexes he hip to 45 degrees on the NWB side hence is not accurate – it should be 30 degrees. This also accepts delayed positive response if unable to hold for 30s

Table 3.10 Different authors' definitions of Trendelenburg Test possible outcomes

Within many studies the test is usually described vaguely (van Iersel & Mulley, 2004) however where the method of performing the Trendelenburg Test is stated clearly the authors have used the method proposed by Hardcastle and Nade (1985) (Asayama et al., 2002; DiMattia et al., 2005; Downing et al., 2001; Inan, Alkan, Harma, & Ertem, 2005; Pai, 1996; Youdas et al., 2006). The only authors not to use this method were; van Iersel et al (2004), Vasudevan et al (1997) and Westhoff et al (2005).

Most literature does not define, within the method, how to interpret the test. However recent literature appears in agreement that, when the test is positive, the pelvis drops on the non-weight bearing side (DiMattia et al., 2005; Downing et al., 2001; Hardcastle et al., 1985; Inan et al., 2005; Pai, 1996; Ramesh, O'Byrne, McCarthy, Jarvis, Mahalingham, & Cashman, 1996; Rozbruch et al., 2005; Shampo, 2001; van Iersel et al., 2004; Vasudevan et al., 1997; Westhoff et al., 2005; Youdas et al., 2006). None of this literature defines how far the non-weight bearing pelvis can drop before it is judged as a positive test. It is a subjective decision. This does not help interpretation of the test. Westhoff summarizes this succinctly *"The Trendelenburg (and Duchenne) gaits are well described in the literature. However there are no objective criteria defining abnormal gait changes"* (Westhoff et al., 2005).

Subsequently, only two authors have objectively defined when this pelvic drop becomes positive. Asayama stated that a "*tilt angle*" (pelvic coronal plane minimum) of greater than 2^0 indicated a positive Trendelenburg Test (Asayama et al., 2002). Westhoff stated that "*Pelvic drop (pelvic coronal plane minimum) to the swinging limb during single stance phase of more than 4^0 and / or maximum (peak value) pelvic drop in the stance phase of more than 8^0"* (Westhoff et al., 2005) indicated a positive test. These studies have made the Trendelenburg Test more objective. However many practitioners do not have access to the 3SPACE magnetic sensor system used by Asayama or VICON 512 gait system used by Westhoff. Youdas used a commonly available clinical measurement device; the universal goniometer. However Youdas concluded that the minimal detectable change in hip coronal plane angle using the device was

4^0 (Westhoff et al., 2005). Commonly practitioners visually "eyeball" the Trendelenburg Test. They may find it difficult clinically to identify 2^0 of pelvis movement in the coronal plane.

These studies have established that movement of the hip coronal plane angle can be measured accurately. However the equipment required is not commonly available to practitioners. The equipment that is commonly available is not sensitive enough to detect these small changes in pelvic movement. All of these studies confined themselves, as did Trendelenburg, to coronal plane movement. There are no existing data for sagittal and transverse plane pelvic movement during the Trendelenburg Test.

Recently the Trendelenburg Test has been used to study problems proximal to the hip for the first time (Roussel, Nijs, Truijen, Smeuninx, & Stassijns, 2007). This study investigated the relationship between non-specific low back pain and the Trendelenburg Test (n=36). This author notes that this study adhered strictly to Hardcastle and Nade's method and interpretation of the Trendelenburg Test. This is in contrast to previous studies. It may be one explanation of the study's conclusion that the Trendelenburg Test had good test-retest reliability for the non-specific low back pain population (Roussel et al., 2007). However it did not find any correlation between the Trendelenburg Test, low back pain and disability.

3.5.4 Trendelenburg Test summary

It is clear that further research is required to explore the Lumbo-Pelvic and Hip kinematics of the Trendelenburg Test and their relationship to functional anatomy. To conduct this research optimally the method of Hardcastle et al (1985) with the objective interpretation of the test as proposed by Asayama et al (2002) and Westhoff et al (2005) should be used. Adhering strictly to these methods, as Roussel et al (2007) did, should raise intra and inter tester reliability. The collection of data for sagittal, coronal and transverse plane pelvic movement during the test would fill an evidence gap. Future research should investigate the reliability and validity of the Trendelenburg Test within specific populations. This may in turn help explain the mechanisms and presentations of specific gait types.

3.6 Single Leg Squat

3.6.1 Introduction

The Single Leg Squat is a common clinical test used by clinicians to examine the neuromuscular control of the Lumbo-Pelvic and Hip region. It is a progression of the double leg squat, first reported as part of a closed chain knee rehabilitation program in the 1990s (Fitzgerald, 1997). Double leg squats were progressed into single leg squats as part of exercise progression. The first paper to describe the single leg squat exercise was published by Chris Benn in 1998. Benn used the single leg squat within his study to compare two knee strengthening regimes. He concluded that using single leg squats to strengthen the knee "*could improve muscular performance and enhance a muscle's potential for dynamic stabilization* (of the knee)," (Benn, Forman, Mathewson, Tapply, Tiskus, Whang, & et al, 1998). The Single Leg Squat was subsequently developed from an exercise into a functional clinical test by Liebenson in 2002. It was created to assist practitioners in examining the function of the lower extremity kinetic chain (Liebenson, 2002) and currently forms part of the "dynamic stability tests" commonly used in athletes (Hudson, 2012).

The Single Leg Squat is a clinical test, conducted in the position of single limb stance (Hoefert et al., 2003). This position is seen in many daily functions such as walking and running, or in sports (Hoefert et al., 2003) such as football, rugby, hockey, gymnastics and skiing. Therefore the test appears to have good face validity as single limb stance is a position both healthy and sporting individuals go into repetitively and frequently. The Single Leg Squat is frequently used clinically to provide a simple and convenient assessment of neuromuscular control for the Lumbo-Pelvic region (Alexander, Crossley, & Schache, 2009; Grimaldi, 2011; Perrott, Pizzari, & Cook, 2010). It is assumed that the performance of the Single Leg Squat reflects the movement that is likely to occur during more complex tasks such as gait. However, the potential link between Single Leg Squat performance and gait kinematics has only started to be investigated after 2009 (Alexander et al., 2009).

3.6.2 The Single Leg Squat

Currently the Single Leg Squat is thought to indicate many movement dysfunctions within the kinetic chain including pelvic unlevelling, valgus overstrain at the knee and subtalar hyperpronation (Liebenson, 2002), Table 3.11.

Sign	Dysfunction
Subtalar hyperpronation	Tibial Torsion
Early Heel rise	Tight soleus
Femoral torsion or Valgus overstrain	Hip or Pelvic torsion dysfunction
Trendelenburg Sign or Pelvic unlevelling	Gluteus Medius insufficiency
Poor control of knee when rising up	Gluteus Maximus insufficiency
Excessive Trunk Flexion or control of knee extension on rising up	Gluteus Maximus insufficiency

Table 3.11 Single Leg Squat Dysfunctions – adapted from Liebenson (Liebenson, 2002)

However Livengood was the first author to define a method for performing the Single Leg Squat as a test (Livengood, DiMattia, & Uhl, 2004), Figure 3.13.

A B

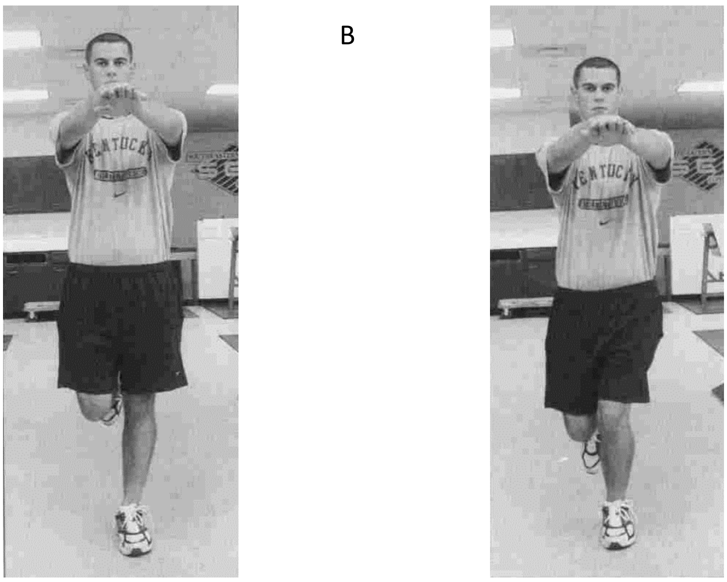


Figure 3.13 Literature review Single Leg Squat method; (A) start / finish position (B) squat position (Livengood et al., 2004)

Previously Liebenson (2002) had interpreted the test in an ordinal manner (positive or negative). Livengood (2004) was the first author to assign the test a scale. This converted it into nominal data, Table 3.12.

Grade	Hip and Knee Criteria
Excellent	Hip flexion greater than 65^0, Hip abduction / adduction less than 10^0, knee valgus / varus less than 10^0
Good	Any of the above 2 criteria are met
Fair	Any 1 of the above criteria are met
Poor	None of the criteria are met or the athlete losses balance or falls

Table 3.12 Single Leg Squat - scoring criteria for movements of closed chain limb

3.6.3 Contemporary evidence

From 2004 most studies of the Single Leg Squat were kinematic studies. Earlier studies (2004-2007) predominantly focusing on patellofemoral pain patients, after 2007 more varied groups have been studied including healthy individuals (Zeller, McCrory, Kibler, & Uhl, 2003), OA knee (McQuade, Coppersmith, & Ashwell, 2007), ACL patients (Madhavan & Shields, 2010), and athletes (Perrott et al., 2010).

Levinger (2004) compared the calcaneal kinematics of patellofemoral pain patients and healthy participants during the Single Leg Squat (n=30). Sagittal and coronal plane data were collected using video tape, at an unstated frequency, of participants performing a Single Leg Squat to 45^0 of knee flexion. The authors concluded that patellofemoral pain patients exhibited a significantly larger peak calcaneal eversion angle (p=0.02) and that this may contribute to altered kinematics proximally in the kinetic chain, at the knee and hip (Levinger, Gilleard, Sprogis, & Coleman, 2004). Levinger (2007) extended this earlier work and was the first author to investigate the femoral kinematics during the Single Leg Squat. This study compared patellofemoral pain patients to healthy participants using a single video camera at 50Hz. The authors concluded that the femoral medial deviation in the coronal plane (hip adduction) was significantly larger for patellofemoral pain patients (p=0.019) (Levinger, Gilleard, & Coleman, 2007). However Levinger did not use Livengood's method for performing the test, Table 3.13.

Method	Livengood	Levinger
Test Posture	Single limb stance	Single limb stance
Pelvic Position	Neutral	Unstated
Upper limb Position	Shoulders flexed to 90 degrees	Shoulders dependent
Duration	6 seconds	Unstated

Table 3.13 Single Leg Squat - Comparison Livengood's with Levinger's method

A potential error was that transverse plane hip and knee movement was not controlled for. Therefore the femoral angle measured in 2 dimensions from the video may have contained crosstalk errors from movement in the transverse plane.

Since 2007 most studies have been kinematic, laboratory based studies. Wilson (2007) also studied the Single Leg Squat, running and single leg jump kinematics in patellofemoral pain patients and healthy participants (n=40). Wilson used a 6 camera optoelectronic movement analysis system at 120Hz. This allowed movement analysis in all three planes of motion. The author concluded that a significantly different hip adduction movement existed between the groups (p=0.019) with a mean of 7.79^0 +/- 4.42^0 for the control group and 11.75^0 +/- 3.61^0 for the patellofemoral pain patients during the three activities. Hip coronal plane range of movement showed no significant differences (p=0.295) with a mean of 2.02^0 +/- 1.11^0 for the control group and 2.54^0 +/- 1.29^0 for the patellofemoral pain patients during the three activities. Mean knee flexion also showed no significant differences (p=0.829) with a mean of 45.3^0 +/- 0.39^0 for the control group and 45.3^0 +/- 0.47^0 for the patellofemoral pain patients during the three activities (Willson et al., 2008). Wilson, in common with Levinger, stated that patellofemoral pain patients demonstrated greater hip adduction however neither author used Livengood's method for performing the test. Levinger's participants were bare foot but Wilson's wore footwear, this may have influenced the kinematic data making comparison between the studies difficult (Jennison, Barton, Crossley, & Pizzari, 2010). McQuade (2007) investigated the effect of knee strength training on performance of a Single Leg Squat knee kinematics (n=6). In contrast to previous work this was the first study using participants with OA. The author's concluded that knee strengthening training increased the quadriceps strength and improved the subject's balance but did not change the knee joint kinematics (McQuade et al., 2007). This is clinically important as this study found that knee strength training generates changes specific to strength but not changes in the neuromuscular control of the knee kinematics.

Two studies in 2009-2010 compared the kinematics of gait to the Single Leg Squat. Alexander (2009) was the first author to investigate the hip and knee kinematics of normal, healthy male and female participants (n=11) using a Vicon motion analysis system. The authors found that poor performers of the Single Leg Squat walked with greater hip abduction during stance when compared to good performers of the test, and concluded that performance of the Single Leg Squat task appears capable of providing a reflection of neuromuscular control during gait (Alexander et al., 2009). Perrot (2010) compared the Single Leg Squat to Dip test in recreational athletes (n = 22). The Dip test is a similar test to the Single Leg Squat but performed with one foot resting on a support that reduces dorsiflexion and balance demands. The authors concluded that participants with poor Lumbo-Pelvic stability exhibited higher hip adduction of the trial leg, hip abduction of the stance leg, pelvic obliquity and trunk rotation ($p<0.01$) (Perrott et al., 2010). Therefore this study agrees with Alexander (2009) that poor performance of the Single Leg Squat is associated with greater hip abduction of the stance hip. However Perrot did not describe the analysis system they used. It is also unclear if the conclusions relate to both the Dip and Single Leg Squat or only to the Dip test.

Jennison (2010) investigated the association between foot orthoses and quality of Single Leg Squat in patellofemoral pain patients (n=23). An assessor rated video footage of five consecutive Single Leg Squats rating the squat as "poor", "fair" or "good". They concluded that individuals at baseline who exhibited fair to good quality of Single Leg Squat using the foot orthoses are more likely to have better outcomes at 12 weeks than individuals with poor quality of Single Leg Squat ($p<0.05$, $r=0.46$) (Jennison et al., 2010). A subsequent study (Madhavan et al., 2010) investigated the differences in neuromuscular response between participants who had an ACL reconstruction and healthy female participants during the Single Leg Squat (n= 24). Data was collected of surface EMG activity, frontal (coronal) and sagittal plane centre of pressure. Madhavan, et al. (2010) found less background EMG activity, increased overshoot error and knee velocity whilst undergoing unexpected perturbations in the ACL reconstruction participants. Of clinical significance is that in the ACL reconstruction participants the long latency response, the reflex which may play a significant role in preventing joint instability, was enhanced. It is suggested that this maybe a protective response that developed in this group due to surgery, rehabilitation or the severity of the injury (Madhavan et al., 2010). Madhavan stated that he used the Single Leg Squat method as described by Livengood. However Madhavan allowed participants to place two fingers onto a load sensor. Whilst loads were low (under 3N) this allowed a degree of fixation of the upper limb, hence closing the kinetic chain (Butler et al., 2003). Livengood's method also has the shoulders forward flexed to 90^0, not dependent as Madhavan. Hence Madhavan's method is different to Livengood's, but could be considered a development of Livengood's method. Madhavan's methodology was different to Levinger's (Levinger et al., 2007), not in strict adherence with Livengood's, and may have influenced the participant's performance of the test. These differences in method limit comparison between the studies.

The Single Leg Squat is a useful clinical test (Alexander et al., 2009). It is frequently used clinically to provide a simple and convenient assessment of neuromuscular control for the Lumbo-Pelvic region (Alexander et al., 2009; Perrott et al., 2010; Stolen et al., 2005). It is assumed performance reflects that which is likely to occur during more complex tasks such as gait (Alexander et al., 2009).

Liebenson used clinical observation to describe the Single Leg Squat. Liebenson (2002) illustrated the Single Leg Squat by drawings (Liebenson, 2002). Livengood and DiMattia used laboratory based studies with both clinical observation and modern equipment such as high resolution video cameras and dynamometers (DiMattia et al., 2005; Livengood et al., 2004).

They conveyed the Single Leg Squat by photographs and description. Both Livengood and DiMattia used experimental, same-subject crossover designs. Inter and intra-comparative group analyses were made. The landmark work of Livengood, et al. (2004) has now become the standard for the test's method and interpretation. However many subsequent studies either fail to describe their method for the tests (Alexander et al., 2009; Jennison et al., 2010; McQuade et al., 2007; Perrott et al., 2010) state that they are using Livengood's method but are not (Madhavan et al., 2010) or use their own method (Levinger et al., 2007; Levinger et al., 2004; Willson et al., 2008). This makes inter-study comparison difficult. None of the studies reviewed have defined exclusion criteria, false negative or positive responses for the Single Leg Squat. Evidence for the Single Leg Squat has been confined to healthy individuals (DiMattia et al., 2005; Livengood et al., 2004), aged 24 (+/- 4) (DiMattia et al., 2005), Patello-femoral (Jennison et al., 2010; Levinger et al., 2007; Levinger et al., 2004), post ACL repair (Madhavan et al., 2010) and athletic individuals (Perrott et al., 2010). There is limited evidence for participants outside of this age group or for the athletic population.

Evidence shows the Single Leg Squat to be a relatively new test. This may explain why the evidence does not come from many sources internationally or from a wide variety of orthopaedic practitioners. Evidence to date comes from American (Jennison et al., 2010; Levinger et al., 2007; Livengood et al., 2004; Madhavan et al., 2010; Willson et al., 2008) or Australian (Alexander et al., 2009; Perrott et al., 2010) based practitioners in Physical Therapy (Benn et al., 1998), Kinesiologists (DiMattia et al., 2005; Livengood et al., 2004) and chiropractic (Liebenson, 2002). Most studies have focused on the knee (Jennison et al., 2010; Levinger et al., 2007; Willson et al., 2008) with few studies including its relationship to pathology or dysfunction proximal or distal within the kinetic chain (Jennison et al., 2010; Willson et al., 2008).

Only one author, Livengood, has objectively defined when the Single Leg Squat becomes positive. Hip flexion greater than 65^0, hip abduction / adduction greater than 10^0, knee valgus /

varus greater than 10^0 (Livengood et al., 2004). This study has made the Single Leg Squat more objective. Presently there is no evidence if a practitioner could "eyeball" a change of hip abduction / adduction less than 10^0, knee valgus / varus less than 10^0. All of these studies confined themselves to coronal plane movement. There is no data for sagittal, coronal and transverse plane pelvic movement during the Single Leg Squat, Table 3.14.

Author	Method	Interpretation	Inclusion / Exclusion criteria	Population / Age	Practitioner
Benn et al., (1998)	Descriptive	N/A	Unstated	Normal / unstated	Physical Therapy - USA
Liebenson (2002)	Figure	Yes – qualitative	Unstated	Normal / unstated	Chiropractic - USA
Livengood et al., (2004)	Defined	Defined - quantitative	Unstated	Normal / unstated	Biomechanist - USA
DiMattia et al., (2005)	Livengood	Livengood	Unstated	Normal / unstated	Athletic Trainer - USA
Levinger et al., (2004)	Unstated	Unstated	Unstated	Patello-femoral pain / unstated	Unstated - USA
Willson et al., (2007)	Unstated	Unstated	Unstated	Patello-femoral pain / unstated	Unstated - USA
Willson et al., (2008)	Own version	Unstated	Unstated	Patello-femoral pain / unstated	Physical Therapy - USA
McQuade et al., (2007)	Limited description	Unstated	Unstated	OA knee / unstated	Unstated - USA
Alexander et al., (2009)	Unstated	Unstated	Unstated	Unstated / Unstated	Unstated - Australia
Perrot et al., (2010)	Unstated	Unstated	Unstated	Athletes / unstated	Unstated - Australia
Jennison et al., (2010)	Unstated	Unstated	Unstated	Patello-femoral pain / unstated	Unstated - Australia
Madhavan et al., (2010)	Own version	Unstated	Unstated	ACL / unstated	Physical Therapy - USA

Table 3.14 Single Leg Squat - summary of current studies

3.6.4 Single Leg Squat summary

The Single Leg Squat has evolved from the double leg squat exercise. It has been given a clear method and interpretation by Livengood. However a limitation of the evidence base is that the data reported is confined to hip sagittal and coronal plane, and knee in the coronal plane.

It is clear that future studies are needed into the kinematics of the Single Leg Squat and its relationship to gait. To conduct this research Livengood's method and interpretation should be used. By adhering strictly to this method it was anticipated that testing would have high intra and inter tester reliability. The collection of Lumbo-Pelvic and Hip kinematic data for sagittal, coronal and transverse plane pelvic motion during the test would fill an evidence vacuum. Future research should investigate the reliability and validity of the Single Leg Squat within specific populations.

3.7 Corkscrew Test

3.7.1 Introduction

The Trendelenburg Test (Bailey, Selfe, & Richards, 2009) and Single Leg Squat (Bailey, Richards, & Selfe, 2011) are commonly used clinical tests in the examination of gait. Both tests are performed in the position of single limb stance. They are thought to examine the neuromuscular control of the pelvis. Movement of the hip in the transverse plane is relatively large during both walking; 15^0 (Richards, 2008; Rose et al., 2006), 40^0 (Kadaba et al., 1989) and running 7^0 (Novacheck, 1998) and 16^0 (Schache et al., 2001). However there are currently no existing tests for neuromuscular control of the pelvis requiring hip internal-external rotation movement in the transverse plane documented in the musculoskeletal literature.

Hence a novel clinical test for the assessment of the Lumbo-Pelvic and Hip region in the transverse plane has been developed within this thesis. This test has been termed the "Corkscrew Test". The method for performing the Corkscrew Test is based upon the Single Leg Squat and its interpretation is based upon the Single Leg Squat criterion in combination with kinematic values found within the walking literature review. As this is a new test there is currently no kinematic data to support the use of the Corkscrew Test in clinical practice. In order to recommend its integration into clinical practice there is a need to establish the normal ranges of kinematic data for the test, this will allow clinicians to interpret the test and identify abnormal responses to it.

3.7.2 The Corkscrew Test

The working definition developed and used within this thesis was;

1. The participant stands on the limb being evaluated, with the contralateral leg lifted off the ground, as though running. The weight bearing limb should be in the anatomical position and the non-weight bearing limb hip is flexed to approximately 45^0 and the knee to approximately 90^0.
2. The participant's upper limbs are held as if running, with shoulder forward on the non-weight bearing side flexed to approximately 20^0, on the weight bearing side extended to approximately 20^0, with the elbows flexed to approximately 20^0 on both sides and the hands normally relaxed, Figure 3.14.
3. The participant is instructed to maintain an erect posture, not to twist the trunk relative to the pelvis, but to rotate the pelvis on the weight bearing hip first to maximal hip internal rotation, then external rotation and return to the start position in less than 6s, Figure 3.14.
4. The participant is instructed to maintain the head looking horizontally and perpendicular to the plane of the pelvis, Figure 3.14.

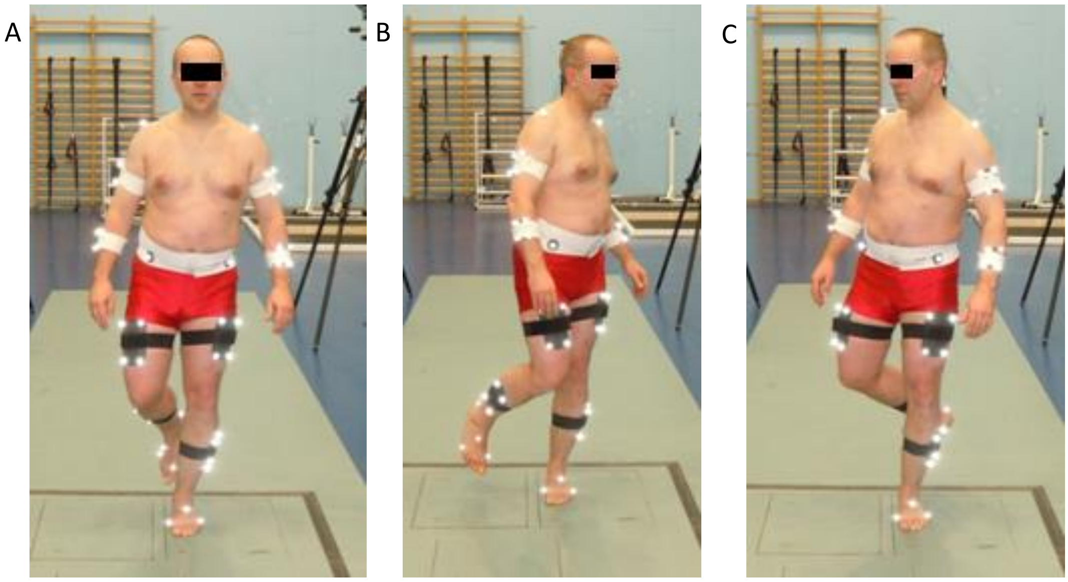


Figure 3.14 Corkscrew Test; (A) Start / finish position (B) rotated left (C) rotated right

False negatives may be particularly evident in neurological disorders and patients with pain in the hip. *False* positives also may occur in patients with severe scoliosis, pain, poor balance, lack of co-operation or understanding, Table 3.15.

Causes of false negatives	Causes of false positives
Use of supra-pelvic muscles	Pain
Use of psoas and rectus femoris	Poor balance
Wide lateral translocation of the trunk to allow balance over the hip as a fulcrum	Lack of co-operation or understanding Costo-pelvic impingement

Table 3.15 False responses to the Corkscrew Test – adapted from Hardcastle and Nade (Hardcastle et al., 1985)

As both the Single Leg Squat and Corkscrew Test are Lumbo-Pelvic and Hip tests performed in single limb stance then, a priori it was assumed, the criteria for interpretation of the Single Leg Squat maybe applied to the Corkscrew Test (Livengood et al., 2004). The normative data established from this study will define the criteria for future interpretation of the test. A positive test will be interpreted as a reduction in control of the hip (pelvis compared to the thigh) in the transverse plane during closed chain, Table 3.16.

Corkscrew Test	
Test Posture	Single limb stance
Pelvis Position	Neutral
Upper limb Position	Held as if running, with shoulder forward on the non-weight bearing side flexed to approximately 20^0, on the weight bearing side extended to approximately 20^0, with the elbows flexed to approximately 20^0 on both sides and the hands normally relaxed
Duration	6 seconds
Joint movement	Hip internal and external rotation
Plane of movement	Transverse
Interpretation	Excellent; Hip internal rotation < 5^0, Hip external rotation < 5^0, Hip abduction/adduction <10^0, Knee valgus/varus<10^0, Good; any 2 of the above criteria met, Fair; any 1 of the above criteria met, Poor; None of the above criteria met or the athlete loses balance and falls
Dysfunction diagnosed	Reduction in control of the hip in the transverse plane in closed chain

Table 3.16 Corkscrew Test – interpretation

3.7.3 Corkscrew Test summary

Within the literature there are currently no clinical tests to examine the neuromuscular control of the pelvis in the transverse plane. The Corkscrew Test is a novel clinical test that has recently started to be used in clinical practice to fulfil this role. However there is currently no normative kinematic data for the test or evidence to support its role in the examination of the components of gait. Further research is therefore required into the normative kinematics for the test and their relationship to walking and running.

3.8 Clinical tests summary

There is a small existing evidence base for the Trendelenburg Test and Single Leg Squat but no evidence base for the Corkscrew Test. For the Trendelenburg Test; the existing studies have been confined to the pelvis coronal plane peak value with no existing evidence for the lumbar or thoracic spine or hip in any of the three cardinal planes. For the Single Leg Squat; the existing studies have been confined to the hip coronal plane peak value with no existing evidence for the pelvis, lumbar or thoracic spine in any of the three cardinal planes. There are currently no existing studies for the Corkscrew Test in any segment or plane of movement. Currently there are no studies to demonstrate if there are any differences between healthy participants and professional football player's Lumbo-Pelvic and Hip kinematics during the clinical tests. Hence, whilst there is existing evidence for clinical tests kinematics there are gaps within it; primarily for the lumbar and thoracic spines and for the transverse plane of movement. These gaps in the evidence base limit clinicians when implementing the existing evidence base fully into their examinations and treatment and comparison between the kinematics of gait and the clinical tests.

To further explore this gap in the literature two papers have been published in the peer reviewed journals "Physical Therapy Reviews," and " Physiotherapy Practice and Research." One paper was a literature review titled "The Role of the Trendelenburg Test in the Examination of Gait" (Bailey et al., 2009). It concludes that despite the Trendelenburg Test being an established test used in the examination of gait it only gained a clear operational method and interpretation in 2007. In addition it also concluded that the existing data for pelvic position during the Trendelenburg Test is inconsistent and there is a gap in the literature as there is no existing data for pelvic control. There was also currently no published literature review of the evidence for the relationship between the Single Leg Squat and gait. However during this study a review paper was published titled "The Single Leg Squat in the Assessment of Musculoskeletal Function: a Review" (Bailey et al., 2011). This concludes that despite human motion occurring in three planes of motion there is no data for combined sagittal, coronal and transverse plane pelvic motion during the Single Leg Squat, Appendix 1.

3.9 Literature review summary

Most of the current evidence base for walking, running and clinical tests has used healthy participants. The evidence base is greatest for the pelvis and hip during walking and running. There is less evidence for the lumbar and thoracic spine during walking. The largest gap in the current evidence is that there is no data for the thoracic spine kinematics during running. There is also currently no evidence for kinematic data exploring sub-groups of the healthy population such as professional football players. Furthermore there is currently no evidence to identify if these kinematic values vary between the sub-groups of a healthy population and professional football players. There is also a lack of evidence to establish if there are identifiable similarities between Lumbo-Pelvic and Hip kinematics during walking, running and the clinical tests for a healthy population and professional football players. These gaps in the current evidence base for the kinematics of the thoracic spine during running, sub-groups of the healthy population and the relationship between the Lumbo-Pelvic and Hip kinematics found during gait and the clinical tests represent gaps in the current evidence. It is clear that further research is required into the kinematics of gait, its relationship to the clinical tests clinicians currently use to examine the components of gait and if different groups of healthy participants move differently during gait and the clinical tests. A greater understanding of these parameters would provide a better understanding of the Lumbo-Pelvic and Hip kinematics during gait and aid comparison of the kinematics observed during walking and running with that during common Lumbo-Pelvic and Hip clinical tests (Hindle et al., 1990). The key messages from the literature review are:

For walking;

- The majority of Lumbo-Pelvic and Hip studies have focused on the pelvis and hip, there are fewer studies on the trunk and virtually none of the lumbar or thoracic spines.
- Most of the existing data has been for the sagittal plane of movement.
- There is little kinematic evidence for the Lumbo-Pelvic and Hip region in the lumbar and thoracic spines and for the transverse and coronal planes of movement.

For running;

- The evidence for running kinematics is more limited than walking.
- Most of the running gait studies related to the Lumbo-Pelvic and Hip region have focused on the hip.
- Most of the existing data has been for the sagittal or transverse plane of movement.
- There are currently no studies for running gait kinematics for the trunk as a two segment spine therefore there is a gap in the existing kinematic values for the lumbar and thoracic spine.

For the Trendelenburg Test;

- The kinematic data that exists for this test is confined to the pelvis coronal plane peak value.
- There is no Lumbo-Pelvic and Hip kinematic data for sagittal or transverse plane pelvic movement, or for the lumbar spine, thoracic spine or hip in any plane.

For the Single Leg Squat;

- The kinematic data that exists is confined to hip sagittal and coronal plane, and knee in the coronal plane.
- There is no kinematic data for sagittal, coronal and transverse plane pelvic motion, the trunk, lumbar or thoracic spine in any plane, or the hip in the transverse plane.

For the Corkscrew Test;

- There is currently no kinematic data for any region, in any plane, to support this test.

4 Methods

4.1 Recruitment

Two groups of participants were recruited. The first group was a sample of convenience from the playing squad of an English premiership professional football team. A priori it was thought that professional football players would exhibit changes in the neuromuscular control pattern of the Lumbo-Pelvic and Hip region. These participants completed the "professional football players" study. This study used a single segment spine model. The second group was a sample of convenience from the male students at the university recruited via posters around the faculty, Appendix 2. These participants completed the "healthy participants" study. This study was a development of the first study using newer cameras, improved camera position, an additional clinical test and a more advanced two segment spinal model. This development from the first study to the second study allowed comparisons to be made between the two groups and additional data to be calculated.

4.2 Study

4.2.1 Design

This was a laboratory based study using an experimental, repeated measures design.

4.2.2 Participants

Following ethical approval from the Faculty of Health Research Ethics Committee at the University of Central Lancashire (UCLan), 18 full time professional football players from an English premier league club and 14 healthy participants from the students of UCLan, gave their written, informed consent to take part in the study, Appendix 3, and provided their demographic data, Table 4.1. Limb dominance was defined by observing which limb participants selected first to kick a static football. Of the professional football players; 16 were right foot dominant and all were out field players. All of the healthy participants were right foot dominant. Prior to testing each participant completed a health screening questionnaire, Appendix 4, to confirm that they were injury free, that they had no diagnosed balance disorder or leg length discrepancy and that they did not have any pre-existing medical condition that would prevent them from participating (Greenhalgh & Selfe, 2003; Maitland et al., 1986; McDonnell, 2000; Perry, 2009; Thomas & Lee, 2000).

Group	Mean		
	Age (Years)	Height (m)	Mass (Kg)
Healthy participants	20.5 +/- 2.0	1.76 +/- 0.13	73.9 +/- 9.0
Professional football players	17.5 +/- 2.5	1.77 +/- 0.09	68.9 +/- 9.0

Table 4.1 Demographic data healthy participants and professional football players

4.2.3 Set up and apparatus

Movement analysis data was captured by using a ten camera ProReflex, three dimensional optoelectronic movement analysis system Qualysis Track Manager (Qualysis Medical AB, Sweden). An L shaped reference structure (750mm) with markers was positioned in the data collection area to orientate the laboratory co-ordinate system. The laboratory co-ordinate system was orientated according to the right hand rule with the positive x-direction orientated forwards, the positive y-direction orientated to the left and the positive z-direction orientated upwards. The system was calibrated prior to testing by moving a wand of the markers of calibrated length (298.1mm) through the image space, Figure 4.1. The peak residual value accepted was 0.7 mm.

Figure 4.1 Laboratory co-ordinate system and calibration of the image space

Retro-reflective markers were placed onto the corners of the four Advanced Mechanical Technology Incorporated (AMTI) force platforms (Model BP400600) and a two second capture recorded. An Automatic Identification of Markers (AIM) model, was then applied to this capture to orientate the force platforms within the laboratory co-ordinate system (McClay & Manal, 1999), Figure 4.2.

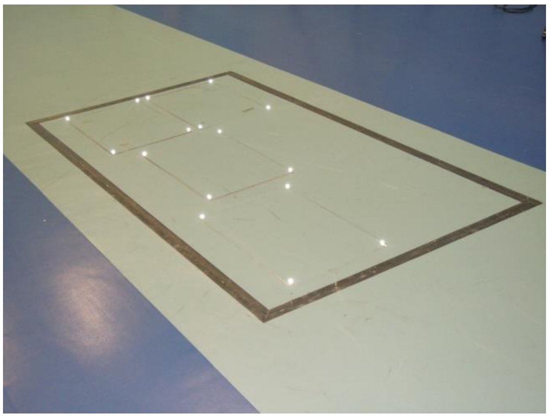


Figure 4.2 Mapping the position of the force plates

The force platforms were calibrated before each data collection session. The thresholds were set to 20N and the direction of gravity was set in the vertical direction (Z). The participant applying in excess of 20N in the vertical would define the gait event of heel strike and therefore the start of weight bearing. 20N was set to avoid any false events, and was considered sensitive enough to identify the start of loading for the different tasks.

Force platform measurement is currently considered the gold standard for the detection of heel strike (Desailly, Daniel, Sardain, & Lacouture, 2009). When considering walking a previous study of healthy participants (n=12) walking barefoot in a laboratory to compare and validate a kinematic-based algorithm used to detect heel strike and toe off with force platform data and visual inspection established that there where were no statistically significant differences between visual inspection and algorithm methods. For defining heel strike, the differences between force platform data, visual inspection and algorithm timings methods were within 1.5 frames sampling at 60Hz. For defining toe off, the differences between the force on one side and the visual and algorithm on the other were higher and more varied (up to 175 ms). The ability to automatically and reliably detect the timings of heel strike and toe off using kinematic data alone is an asset to gait analysis (Ghoussayni, Stevens, Durham, & Ewins, 2004). Another study of walking comparing combined centre of pressure and ankle marker movement with individual force platforms for determining the gait events of heel strike and toe off found that heel strike occurred an average of 1 sample (at a sampling frequency of 120 Hz, 0.00833 s) before the event using the individual force platforms and toe-off events were found an average of 2 samples (0.0167 s) prior to the events (Hansen, Childress, & Meier, 2002). A further study compared a high pass algorithm (HPA) with force platform measurements in 20 Cerebral Palsy (CP) children and on eight healthy adults. True errors in HPA (mean +/- standard deviation) were found to be 1 +/- 23 ms for heel strike and 2 +/- 25 ms for toe off in CP children. The HPA was found to be a simple and robust algorithm, which performs well for adults is therefore recommended as the method of choice for detecting heel strike and toe off (Desailly et al., 2009).

For running a study compared algorithms to predict heel strike and toe off times during normal running at participant self-selected speeds with synchronised force platform data from ten participants performing ten trials each. Using a single 180Hz camera, positioned in the sagittal plane, the average root mean square (RMS) error in predicting heelstrike times is 4.5ms, whereas the average RMS error in predicting toe-off times is 6.9ms. Average true errors (negative for an early prediction) are +2.4ms for heel strike and -2.8ms for toe-off, indicating that systematic errors did not occur. The average RMS error in predicting contact time is 7.5ms, and the average true error in predicting contact time is 0.5ms. Estimations of heel strike and toe off using these simple algorithms compare favourably with other techniques requiring specialised equipment. It is concluded that these algorithms provide an easy and reliable method of determining heel strike and toe off times during normal running at a participant selected pace using only kinematic data (Hreljac & Stergiou, 2000). Hence for both walking and running the use of force platform measurement is able to define heel strike and toe off to less than 0.02s.

Previous studies have used a force platform threshold of; anything over 0N (Hansen et al., 2002), 5N (Desailly et al., 2009), and 10N (Ghoussayni et al., 2004) , to determine heel strike and toe off during walking and 10N for running (Hreljac et al., 2000). Hence the threshold values used in this study are greater than other studies, ensuring that the foot was in contact with the force platform and acting in the stance phase of gait.

4.2.4 Marker placement and modelling

Passive retro-reflective markers were placed on participants to reconstruct the movement of the underlying bone in three dimensional space, Figure 4.3.

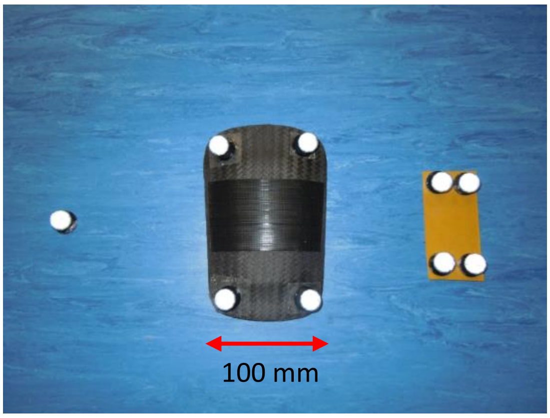
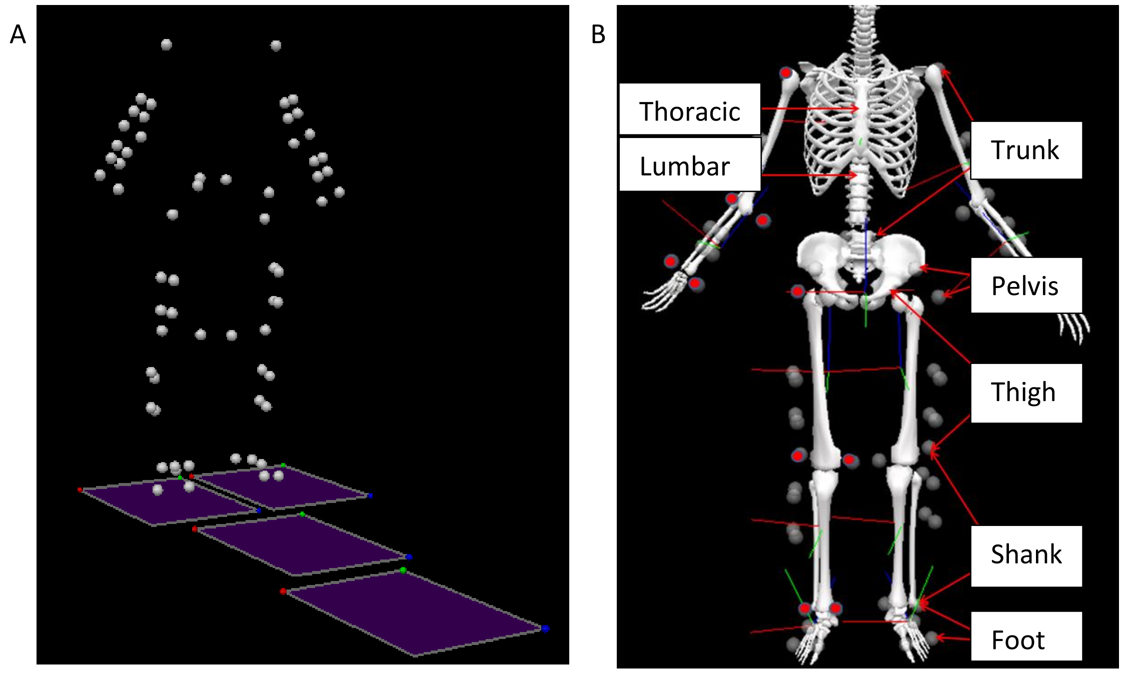


Figure 4.3 Passive retro-reflective markers – single anatomical marker, cluster and two segment spinal cluster

The anatomical markers (size 19mm) were sited to allow a full body model to be generated based upon the Calibrated Anatomical Systems Technique (CAST) (Cappozzo, Catani, la Croce, & Leardini, 1995), whereby a rigid cluster of at least three non-collinear markers is used to track the movement of a body segment. Using three or more markers allows for repeatable femoral anatomical frame orientation (la Croce, Camomilla, Leardini, & Cappozzo, 2003). The passive retro-reflective markers are referenced to the anatomical end-points of a segment by the means of a static calibration, Figure 4.4.

Figure 4.4 Passive retro-reflective markers applied to participant in Calibrated Anatomical Systems Technique (CAST) (Cappozzo et al., 1995)

To generate the static calibration participants stood at the centre of the calibrated area in the anatomical position allowing visualization of all of the markers. A standing calibration was then recorded for one second. This allowed the computer software to introduce a calculated model of the skeleton for visual interpretation, and define the anatomical body segments. Following the static calibration the anatomical markers were removed, Figure 4.5.



Key	
Anatomical markers	
Tracking markers	

Figure 4.5 (A) Passive retro-reflective markers are referenced to the anatomical end-points of a segment by the means of a static calibration (B) calculated model of the skeleton for visual interpretation

For the professional football player's study; the 13-segment model comprised of the pelvis, single segment spine-trunk, bilateral thigh, shank, foot, humerus and forearm segments. Each segment is defined by a pair of single markers (anatomical markers) sited at the proximal and distal ends, with the foot defined proximally by the medial and lateral malleoli of the tibia and fibula respectively by the first and fifth metatarsal heads at the distal end. The shank is defined proximally by the medial and lateral epicondyles of femur and distally by the medial and lateral malleoli of the tibia and fibula respectively. The thigh is defined proximally that the hip joint centre, from a projection from the greater trochanter of the femur and distally by the medial and lateral epicondyles of the femur. The pelvis is defined proximally by left and right anterior superior iliac spines and distally at the greater trochanters. The trunk is also modeled as a single segment defined proximally at the posterior superior iliac spines (PSIS) and distally at the level of the line joining the right and left acromion processes of the scapulae, Figure 4.5.

The pelvis markers were placed onto an elastic cummerbund over tight fitting shorts. This was due to the morphology of this segment. This allowed a three dimensional, six degrees of freedom analysis of the trunk, pelvis and lower limb movement during the functional and clinical tasks.

The healthy participants study used a more advanced model to create a two segment spine and 15-segment model. This required the tracking of a lumbar and thoracic cluster to create the model. Passive retro-reflective markers were placed on participants as previously described based upon the Calibrated Anatomical Systems Technique (CAST) but with additional rigid cluster markers placed over the mid thoracic spine (T6) and mid lumbar spine (L3). These additional clusters acted as both anatomical and tracking markers, Figure 4.6, Figure 4.7.

The hip joint centre is calculated using the ASIS anatomical landmarks (prediction approach) (Bell, Brand, & Pedersen, 1989; Bell, Pedersen, & Brand, 1990). The prediction approach is as follows; "A marker over the greater trochanter projected onto a para-sagittal plane (passing through point located 14% of the inter-ASIS distance medial to the ASIS and 30% of the inter-ASIS distance distal to the ASIS) can predict the antero-posterior hip joint centre location within 0.73 cm of the true location," (Bell et al., 1990).

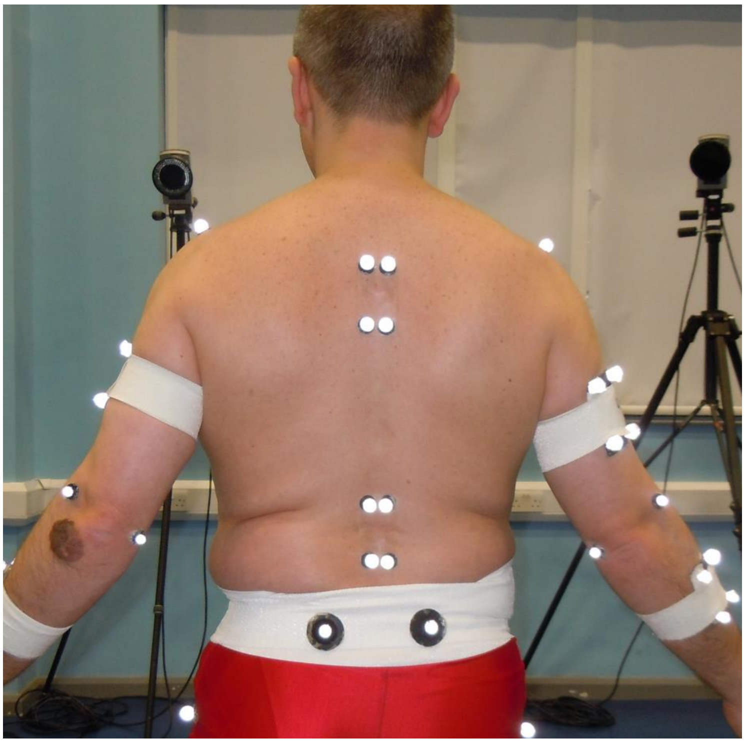


Figure 4.6 Passive retro-reflective markers applied to participant in Calibrated Anatomical Systems Technique (CAST) additional rigid cluster markers placed over the mid thoracic spine (T6) and mid lumbar spine (L3) (Cappozzo et al., 1995)

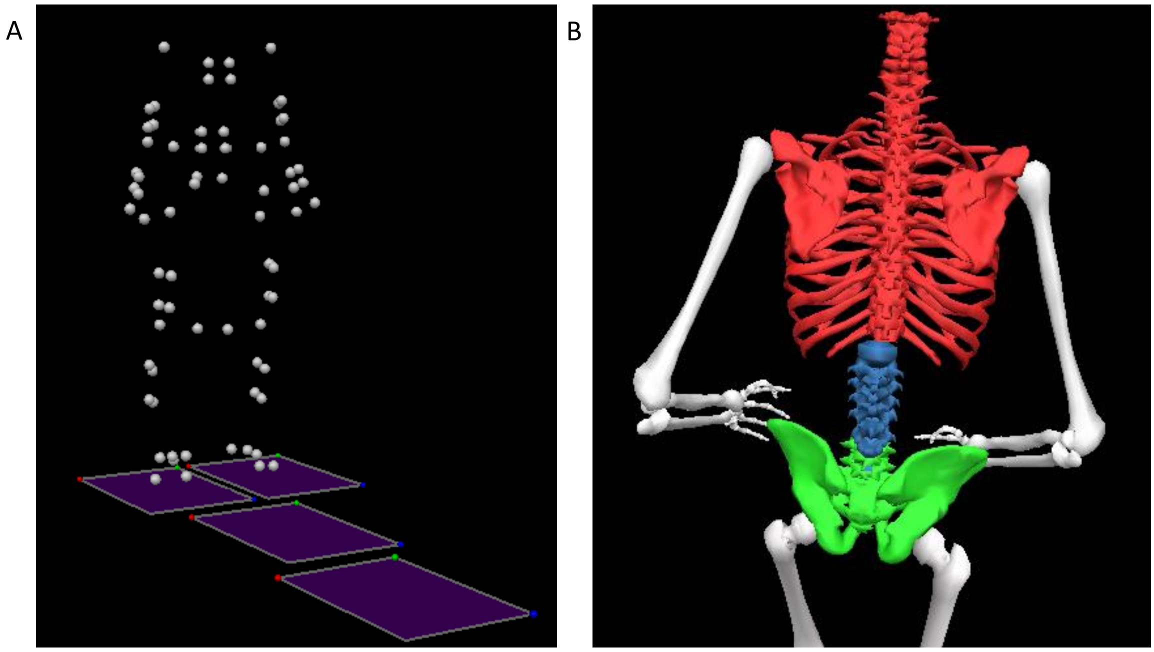


Figure 4.7 (A) Marker placement based on the Calibrated Anatomical Systems Technique (CAST) (Cappozzo et al., 1995) (B) with additional lumbar and thoracic clusters (left) generating a two segment spine (right)

The functional and clinical tests were completed with participants wearing only the tracking markers. The participants then went to a pre-determined start point to commence clinical and functional testing.

4.2.5 Procedure

Testing was divided into two groups of tasks;

1. Functional tests - walking and running.
2. Clinical tests - the Trendelenburg Test, Single Leg Squat and Corkscrew Test.

Clinical tests were always performed before functional tests as experience from pilot testing had established that the markers were more susceptible to falling off during the functional tests. The order of events within the clinical tests and functional tests were randomized using a pseudo-random number generator (Hill & Wichmann, 1982).

Prior to the commencement of testing participants were given the appropriate standardized instruction for the test they were to complete. For the clinical tests the researcher demonstrated the tests and gave the participants an opportunity to practice. This allowed the participants to familiarize themselves with the test, is in common with previous published studies (Levinger et al., 2007; Whatman, Hing, & Hume, 2011) and was felt to reflect how the tests were taught and conducted in routine clinical practice.

Functional tests - walking and running

Participants were asked to stand at a preset position 5m from the data collection area; this formed the start position for the test. The finish position for the test was 10 m from the start position. Participants were not instructed which leg to take the first step with when walking or running. Participants completed the tests by walking or running from the start to the finish position.

For walking the participants were given the following instructions;

"*Stand on the marker and when I say go walk to the other marker at your normal walking speed. When you get there stop. I will tell you when to walk back.* "

For running the participants were given the following instructions;

"Stand on the marker and when I say go jog to the other marker at your normal jogging speed as if you were warming up. When you get there stop. I will tell you when to walk back."

For walking and running data capture was started when the participant was approximately 1m outside of the data collection area and stopped when the participant reached the finish position. This ensured the participants were in a steady state of gait and not accelerating or decelerating. Data was captured at a sampling frequency of 100Hz. This procedure was repeated until three good trials for each test was recorded. The participants were allowed a 1 minute rest between functional tests in order to avoid fatigue. This also provided an opportunity to save the data on to the computer.

Clincial tasks - Trendelenburg Test, Single Leg Squat and Corkscrew Test

Participants were asked to stand on the edge of the laboratory force plates near the centre of the data collection area; this formed the start position for the test. Participants were not instructed which leg to use first during the tasks. Participants completed the tests by stepping onto the laboratory force plates, performing the test on both limbs consecutively and stepping back off the force plates to the start position. It was felt that this reflected how the tests were completed in normal clinical practice.

For the Trendelenburg Test the participants were given the following instructions;

"*Stand facing the force plates with both feet at the edge of it and make yourself comfortable. On my command, step onto the plates and place both feet comfortably apart. Balance onto one leg. You can hold your arms to balance as you like. Hitch your hip up on the non-weight bearing* *side and hold. I will tell you when to swap legs. When I do put your foot back down onto the plate and change straight onto the other leg. Balance, hitch and hold again. I will again tell you when to put the foot down. When I do put both feet back onto the plates and step off*," Figure 4.8

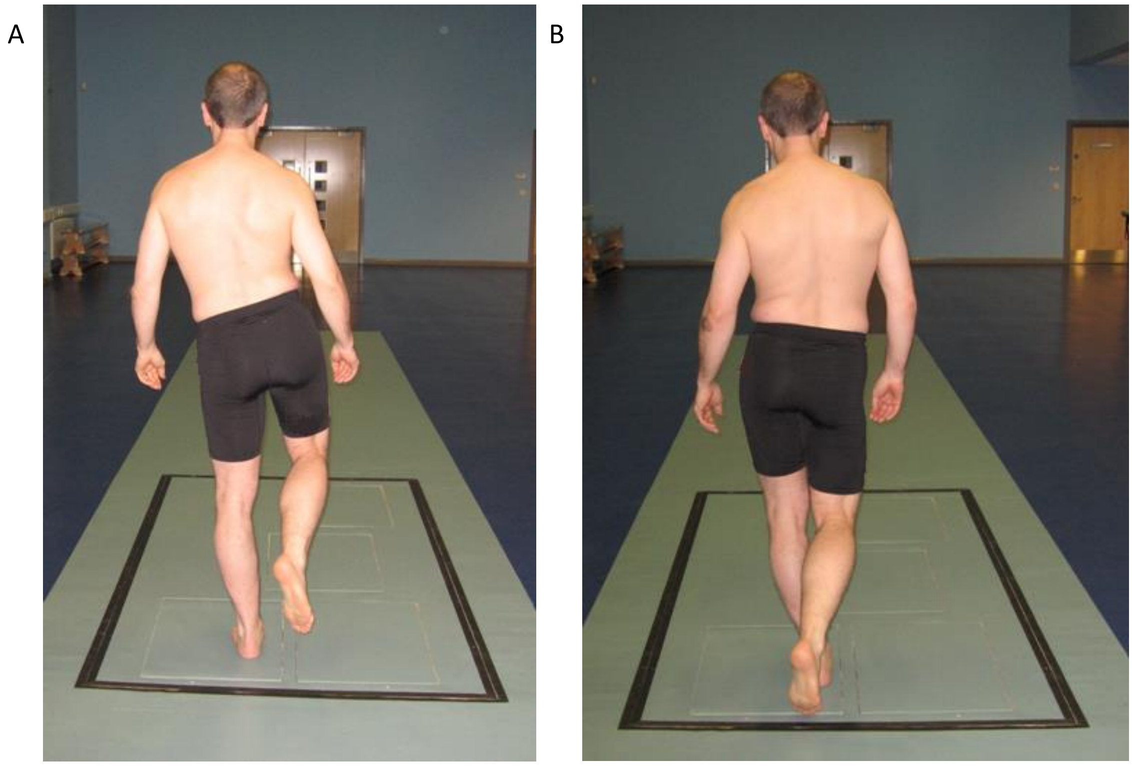


Figure 4.8 Study Trendelenburg Test method; (A) Normal (i.e. the test is "negative") (B) Abnormal (i.e. the test is "positive")

For the Single Leg Squat the participants were given the following instructions;

"*Stand facing the force plates with both feet at the edge of it and make yourself comfortable. On my command, step onto the plates and place both feet comfortably apart. Balance onto one leg. Reach forward as though you are water-skiing. Squat down, to approximately half way and stand back up. Swap straight onto the other leg and repeat. Place both feet back onto the plates and step off. Each leg should take about 6 seconds to go down and up*," Figure 4.9.

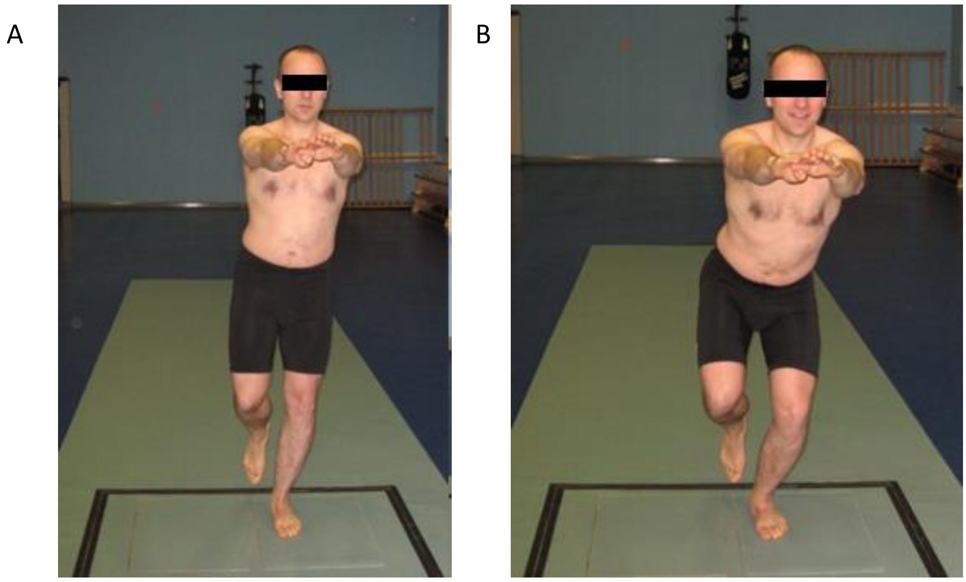


Figure 4.9 Study Single Leg Squat method; (A) start / finish position (B) squat position

For the Corkscrew Test the participants were given the following instructions (healthy participants only);

"*Stand facing the force plates with both feet at the edge of it and make yourself comfortable. On my command, step onto the plates and place both feet comfortably apart. Balance onto one leg. Hold your hands as if you are running. Keep tall and turn your whole body towards the leg that you are standing on, then away, then back to the start. Swap straight onto the other leg and repeat. Place both feet back onto the plates and step off. Each leg should take about 6 seconds to turn on,*" Figure 4.10.

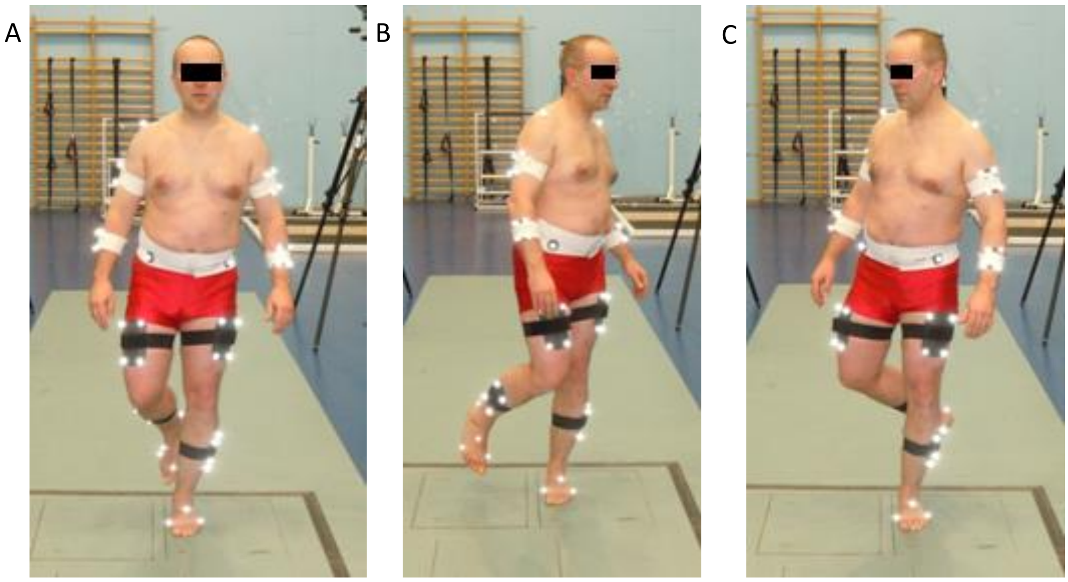


Figure 4.10 Study Corkscrew Test method; (A) Start / finish position (B) rotated left (C) rotated right

The three-dimensional motion caption data was recorded for sufficient duration to complete the test. Data capture was started when the participant started to step onto the force plate for a duration of; 75 seconds for the Trendelenburg Test, 40 seconds for the Single Leg Squat and 15 seconds for the Corkscrew Test. The data was captured at a sampling frequency of 100Hz. This procedure was repeated until three good trials for each test was recorded. The participants were allowed 30 seconds rest between clinical tests in order to avoid fatigue. This also provided an opportunity to save the video data on to the computer. The markers were left in position on the participants between the functional and clinical tasks to minimize any errors in marker placement.

Establishing limb dominance

After the functional and clinical testing was completed participants were also asked to kick a stationary football placed in the centre of the data collection area to a catcher. The dominant limb was identified by limb preference when kicking the stationary football.

4.3 Methods of analysis

The co-ordinate data identified was then exported, using Qualysis Track Manager software (Qualysis AB Medical, Sweden), and imported into Visual 3D (C-Motion, USA). The co-ordinate data was then filtered using a lowpass second order Butterworth Bi-directional filter with a cut-off frequency of 6Hz for walking, 15Hz for running and 6Hz for the clinical tests. Filtering data is performed to remove digitizing and soft tissue artifact errors (Richards, 2008). A full body model was created, with segment coordinate axes; X-Sagittal, Y-Coronal, Z-Transverse. Joint angles were calculated using a Cardan “XYZ” sequence, corresponding to the anatomical axis of motion in the sagittal, coronal and transverse planes (Grood & Suntay, 1983). Movement of the pelvis was defined relative to the global co-ordinate system, movement of the lumbar spine, thoracic spine (healthy participants only), trunk and thigh were defined relative to the next proximal segment using the local co-ordinate system. Hence the movement of the thoracic spine was defined relative to the lumbar spine and the lumbar spine relative to the pelvis (healthy participants only), trunk relative to the pelvis and thigh relative to pelvis. The duration of movement analyzed for walking and running was for the closed chain phase of the gait cycle, defined as heel strike to toe off for the same limb. The Trendelenburg Test started from when the non weight bearing side of the pelvis reached its position of coronal plane peak value and finished 30 seconds later. The Single Leg Squat was from when the weight bearing thigh started to move anteriorly in the sagittal plane and finished when it returned to the starting position. For the Corkscrew Test the movement was analyzed from when the non weight bearing side of the pelvis started to move in the transverse plane and finished when it returned to the starting position. Report templates for the lumbar spine and thoracic spine (healthy participants only), trunk, pelvis and both the left and right lower limbs were created to calculate and display the parameters to be measured. This contained the joint angle data, noting the relative segments and the orientation of the movement. Two script files were produced for both lower limbs, pelvis and trunk. The kinematic data for the relevant parameters in all three planes were collected and exported as ascii files to create a text document for the grouped trials. Kinetic data was collected, for the purposes of this study, only in order to identify the events of toe off and heel strike, therefore allowing the identification of the closed chain single limb stance phase. Each of the tests required a different amount of time to complete. Therefore all data were normalized to 101 points (0 to 100%). The data from the Visual 3D software was exported to Microsoft Excel 2003 to extract peak value and minimum mean values for each participant. All statistical analyses were performed using SPSS version 16.0.

4.4 Statistical analysis

4.4.1 Sample size calculation

A previous kinematic study using the CAST modeling system by Morris (Morris J., 2006) reported a mean difference of 5.6^0 of pelvis to thigh movement in the coronal plane with a standard deviation of 4.6^0. A statistical power calculation yields that with an 80% statistical power and a significance level of 5% requires the sample size to be greater than 11 to produce a result, allowing for Bonferroni adjustment for multiple comparisons. To ensure the sample size was adequate to explore all the parameters measured a sample size of 18 in the professional football players group and 14 in the healthy participants group were recruited. This allowed more parameters previously unreported to be explored and for any data tracking errors.

4.4.2 Statistical methods

The differences between the different tasks were explored using a repeated measures analysis of variance (ANOVA) with pairwise comparisons, and the differences between the two groups were determined using an unpaired t-test with a significance level set to 5% ($p<0.05$) for each parameter using SPSS (V.16.0). A Bonferroni adjustment for multiple comparisons was employed to reduce the risk of type I errors.

There is ongoing debate of the role of Bonferroni's adjustment for multiple comparisons with some statisticians stating that it should not be used when assessing evidence about a specific hypotheses (Perneger, 1998), that it may be used but should be reported alongside unadjusted values (Morgan, 2007), that adjustment for multiple comparison needs to be done but other procedures could be used (Bender & Lange, 1999) and adjustment for multiple comparison should be done but that the results should be considered relative to other published data (Feise, 2002). Currently there does not appear to be a consensus opinion however contemporary studies continue to use the Bonferroni's adjustment for multiple comparisons (Coughlan, McLoughlin, McCarthy Persson, & Caulfield, 2008; Willson et al., 2008).

4.4.3 Methods summary

This study was a laboratory based study using an experimental, repeated measures design of the Lumbo-Pelvic and Hip kinematics of functional and selected clinical tests for a group of professional football players (n=18), and a group of healthy participants (n=14). The "professional football players" study used the CAST modeling system, the "healthy participants" study also used the same model with additional markers placed over the lumbar and thoracic spines. Using the CAST system allowed this study's data to be compared to existing kinematic studies and comparisons to be made between the two groups. The lumbar and thoracic spine markers used in the "healthy participants" study allowed additional data to be collected, including transverse plane data, and the generation of a two segment spine. The application of this two segment spine data during the examination of the Lumbo-Pelvic and Hip region would allow a more detailed examination by the clinician.

5 Results

The following chapter will summarise the results by the segment, plane and event. It is intended that this will enable the clinician to interpret and apply the data clinically. This chapter will contain tables which form a visual representation of the results. They will illustrate the normative values, compare between the functional tests and clinical tests, and the comparison between the professional football players and healthy participants. These tables have the potential to be used in daily clinical practice as reference guides to clinicians.

Appendix 5 contains the results in greater detail and relates the results by segment, plane and event. This may be considered a very biomechanical approach to the results.

5.1 Walking

5.1.1 Normative data

Walking			Healthy Participants		Professional Football Players	
Dependent variable	Event	Plane	Left lower limb weight bearing	Right lower limb weight bearing	Left lower limb weight bearing	Right lower limb weight bearing
Lumbar	Range	Sagittal	4.0^0 (SD=1.52)	3.7^0 (SD=1.47)		
Lumbar	Range	Coronal	4.8^0 (SD=2.16)	4.7^0 (SD=2.07)		
Lumbar	Peak	Coronal	3.9^0 (SD=2.79)	1.3^0 (SD=2.92)		
Lumbar	Range	Transverse	7.9^0 (SD=2.47)	7.8^0 (SD=2.50)		
Thoracic	Range	Sagittal	4.5^0 (SD=1.96)	3.7^0 (SD=1.36)		
Thoracic	Range	Coronal	9.7^0 (SD=2.67)	10.0^0 (SD=3.59)		
Thoracic	Peak	Coronal	5.8^0 (SD=1.60)	5.2^0 (SD=2.80)		
Thoracic	Range	Transverse	9.8^0 (SD=5.06)	9.4^0 (SD=5.42)		
Trunk	Range	Sagittal	2.6^0 (SD=0.97)	2.4^0 (SD=0.86)	2.5^0 (SD=0.95)	2.5^0 (SD=0.81)
Trunk	Range	Coronal	10.5^0 (SD=2.87)	10.8^0 (SD=3.14)	11.9^0 (SD=2.27)	12.1^0 (SD=2.37)
Trunk	Peak	Coronal	6.8^0 (SD=2.15)	5.0^0 (SD=3.04)	6.2^0 (SD=2.91)	7.2^0 (SD=2.77)
Trunk	Range	Transverse	17.0^0 (SD=5.27)	17.1^0 (SD=5.10)	17.8^0 (SD=4.82)	17.6^0 (SD=4.36)
Pelvis	Range	Sagittal	5.4^0 (SD=1.59)	5.2^0 (SD=1.22)	7.2^0 (SD=1.73)	7.5^0 (SD=1.44)
Pelvis	Range	Coronal	2.5^0 (SD=0.70)	2.6^0 (SD=0.95)	2.3^0 (SD=0.92)	2.5^0 (SD=0.70)
Pelvis	Peak	Coronal	8.3^0 (SD=4.82)	8.3^0 (SD=5.14)	8.2^0 (SD=4.07)	8.2^0 (SD=3.91)
Pelvis	Range	Transverse	15.0^0 (SD=5.24)	14.6^0 (SD=5.28)	13.4^0 (SD=4.06)	13.3^0 (SD=3.68)
Hip	Range	Sagittal	38.6^0 (SD=6.89)	37.8^0 (SD=5.11)	39.3^0 (SD=5.17)	37.82^0 (SD=3.63)
Hip	Range	Coronal	9.4^0 (SD=2.31)	9.5^0 (SD=1.92)	10.5^0 (SD=2.23)	11.2^0 (SD=2.60)
Hip	Peak	Coronal	2.4^0 (SD=3.63)	5.4^0 (SD=2.82)	8.7^0 (SD=2.67)	4.1^0 (SD=2.61)
Hip	Range	Transverse	10.5^0 (SD=3.97)	10.8^0 (SD=3.37)	10.2^0 (SD=3.52)	9.9^0 (SD=2.79)

Key	
Peak	Peak value
Range	Range of movement

Table 5.1 The normative Lumbo-Pelvic Hip movement data within healthy participants and professional football players during walking gait

5.1.2 Walking compared to clinical tests

			Left lower limb weight bearing			Right lower limb weight bearing		
Dependent variable	Event	Plane	T Test	SLS	Corkscrew	T Test	SLS	Corkscrew
Lumbar	Range	Sagittal	(green)	(red)	(green)	(green)	(red)	(green)
Lumbar	Range	Coronal	(red)	(green)	(red)	(red)	(green)	(green)
Lumbar	Peak	Coronal	(green)	(green)	(green)	(green)	(green)	(green)
Lumbar	Range	Transverse	(red)	(red)	(red)	(red)	(red)	(red)
Thoracic	Range	Sagittal	(green)	(green)	(green)	(green)	(green)	(red)
Thoracic	Range	Coronal	(red)	(red)	(green)	(red)	(red)	(green)
Thoracic	Peak	Coronal	(red)	(red)	(green)	(green)	(red)	(green)
Thoracic	Range	Transverse	(red)	(green)	(red)	(red)	(green)	(red)
Trunk	Range	Sagittal	(green)	(red)	(green)	(green)	(red)	(green)
Trunk	Range	Coronal	(red)	(red)	(red)	(red)	(red)	(red)
Trunk	Peak	Coronal	(red)	(red)	(red)	(red)	(red)	(red)
Trunk	Range	Transverse	(red)	(red)	(red)	(red)	(red)	(red)
Pelvis	Range	Sagittal	(red)	(red)	(red)	(red)	(green)	(red)
Pelvis	Range	Coronal	(green)	(red)	(red)	(green)	(red)	(green)
Pelvis	Peak	Coronal	(green)	(red)	(green)	(green)	(red)	(red)
Pelvis	Range	Transverse	(red)	(red)	(red)	(red)	(red)	(red)
Hip	Range	Sagittal	(red)	(red)	(red)	(red)	(red)	(red)
Hip	Range	Coronal	(red)	(green)	(red)	(red)	(green)	(red)
Hip	Peak	Coronal	(red)	(green)	(red)	(red)	(green)	(red)
Hip	Range	Transverse	(red)	(red)	(green)	(red)	(red)	(red)

Key	
Significant differences between dependent variables ($p<0.05$) i.e these parameters are not similar to walking	(red)
No significant differences between dependent variables ($p>0.05$) i.e these parameters are similar to walking	(green)

Figure 5.1 Walking compared to clinical tests

5.2 Running

5.2.1 Normative data

Running			Healthy Participants		Professional Football Players	
Dependent variable	Event	Plane	Left lower limb weight bearing	Right lower limb weight bearing	Left lower limb weight bearing	Right lower limb weight bearing
Lumbar	Range	Sagittal	9.0^{0} (SD=3.66)	8.8^{0} (SD=2.70)		
Lumbar	Range	Coronal	6.5^{0} (SD=3.24)	6.3^{0} (SD=2.49)		
Lumbar	Peak	Coronal	6.8^{0} (SD=3.08)	4.1^{0} (SD=3.18)		
Lumbar	Range	Transverse	11.8^{0} (SD=2.15)	12.7^{0} (SD=2.38)		
Thoracic	Range	Sagittal	7.4^{0} (SD=3.21)	7.4^{0} (SD=3.21)		
Thoracic	Range	Coronal	7.5^{0} (SD=2.93)	8.0^{0} (SD=2.65)		
Thoracic	Peak	Coronal	6.4^{0} (SD=2.58)	5.2^{0} (SD=4.05)		
Thoracic	Range	Transverse	9.7^{0} (SD=4.69)	9.0^{0} (SD=3.82)		
Trunk	Range	Sagittal	10.0^{0} (SD=1.97)	8.5^{0} (SD=1.84)	9.7^{0} (SD=2.6)	8.9^{0} (SD=3.13)
Trunk	Range	Coronal	9.9^{0} (SD=3.00)	10.2^{0} (SD=2.54)	11.0^{0} (SD=2.43)	9.4^{0} (SD=2.55)
Trunk	Peak	Coronal	8.6^{0} (SD=2.48)	8.1^{0} (SD=2.27)	4.3^{0} (SD=4.29)	9.0^{0} (SD=3.51)
Trunk	Range	Transverse	20.4^{0} (SD=5.01)	20.3^{0} (SD=3.84)	22.7^{0} (SD=5.60)	21.7^{0} (SD=6.34)
Pelvis	Range	Sagittal	7.5^{0} (SD=1.75)	7.4^{0} (SD=2.18)	7.5^{0} (SD=1.75)	7.4^{0} (SD=2.18)
Pelvis	Range	Coronal	5.5^{0} (SD=1.01)	6.5^{0} (SD=1.50)	6.4^{0} (SD=1.30)	5.9^{0} (SD=1.64)
Pelvis	Peak	Coronal	16.6^{0} (SD=5.26)	17.0^{0} (SD=5.88)	16.5^{0} (SD=3.82)	16.2^{0} (SD=4.25)
Pelvis	Range	Transverse	4.3^{0} (SD=3.05)	5.1^{0} (SD=2.50)	5.6^{0} (SD=3.10)	6.0^{0} (SD=2.96)
Hip	Range	Sagittal	37.4^{0} (SD=5.12)	36.5^{0} (SD=4.23)	34.7^{0} (SD=7.66)	35.5^{0} (SD=6.00)
Hip	Range	Coronal	10.3^{0} (SD=2.51)	10.8^{0} (SD=2.78)	9.1^{0} (SD=2.99)	11.1^{0} (SD=3.75)
Hip	Peak	Coronal	6.5^{0} (SD=2.69)	10.7^{0} (SD=2.18)	12.6^{0} (SD=4.10)	0.5^{0} (SD=5.45)
Hip	Range	Transverse	8.4^{0} (SD=3.22)	9.9^{0} (SD=4.44)	10.5^{0} (SD=4.97)	10.1^{0} (SD=2.76)

Key	
Peak	Peak value
Range	Range of movement

Table 5.2 The normative Lumbo-Pelvic Hip movement data within healthy participants and professional football players during running gait

5.2.2 Running compared to clinical tests

			Left lower limb weight Bearing			Right lower limb weight bearing		
Dependent variable	Event	Plane	T Test	SLS	Corkscrew	T Test	SLS	Corkscrew
Lumbar	Range	Sagittal	Red	Red	Red	Red	Red	Red
Lumbar	Range	Coronal	Red	Red	Red	Red	Green	Red
Lumbar	Peak	Coronal	Green	Red	Red	Green	Green	Red
Lumbar	Range	Transverse	Red	Red	Red	Red	Red	Red
Thoracic	Range	Sagittal	Red	Red	Red	Red	Red	Green
Thoracic	Range	Coronal	Red	Red	Red	Red	Red	Red
Thoracic	Peak	Coronal	Green	Red	Green	Green	Red	Green
Thoracic	Range	Transverse	Red	Green	Red	Red	Green	Red
Trunk	Range	Sagittal	Red	Red	Red	Red	Red	Red
Trunk	Range	Coronal	Red	Red	Red	Red	Red	Red
Trunk	Peak	Coronal	Red	Red	Red	Red	Red	Red
Trunk	Range	Transverse	Red	Red	Red	Red	Red	Red
Pelvis	Range	Sagittal	Red	Green	Red	Red	Green	Red
Pelvis	Range	Coronal	Red	Red	Green	Red	Red	Green
Pelvis	Peak	Coronal	Red	Red	Green	Red	Red	Green
Pelvis	Range	Transverse	Green	Green	Red	Green	Green	Red
Hip	Range	Sagittal	Red	Red	Red	Red	Red	Red
Hip	Range	Coronal	Red	Green	Red	Red	Green	Red
Hip	Peak	Coronal	Red	Red	Red	Red	Green	Red
Hip	Range	Transverse	Red	Red	Green	Red	Red	Red

Key	
Significant differences between dependent variables (p<0.05) i.e these parameters are not similar to running	Red
No significant differences between dependent variables (p>0.05) i.e these parameters are similar to running	Green

Figure 5.2 Running compared to clinical tests

5.3 Trendelenburg Test

5.3.1 Normative data

Trendelenburg Test			Healthy Participants		Professional Football Players	
Dependent variable	Event	Plane	Left lower limb weight bearing	Right lower limb weight bearing	Left lower limb weight bearing	Right lower limb weight bearing
Lumbar	Range	Sagittal	2.1^0 (SD=0.95)	2.2^0 (SD=1.04)		
Lumbar	Range	Coronal	1.8^0 (SD=1.33)	2.3^0 (SD=1.49)		
Lumbar	Peak	Coronal	5.1^0 (SD=3.74)	3.1^0 (SD=4.06)		
Lumbar	Range	Transverse	1.6^0 (SD=0.52)	1.5^0 (SD=0.74)		
Thoracic	Range	Sagittal	3.3^0 (SD=2.12)	4.4^0 (SD=2.52)		
Thoracic	Range	Coronal	3.6^0 (SD=0.78)	3.4^0 (SD=2.03)		
Thoracic	Peak	Coronal	9.1^0 (SD=5.27)	7.9^0 (SD=4.15)		
Thoracic	Range	Transverse	3.0^0 (SD=2.22)	3.3^0 (SD=1.15)		
Trunk	Range	Sagittal	2.3^0 (SD=1.35)	2.5^0 (SD=1.82)	1.9^0 (SD=0.65)	2.4^0 (SD=0.98)
Trunk	Range	Coronal	4.0^0 (SD=1.36)	4.5^0 (SD=1.46)	4.5^0 (SD=1.46)	4.5^0 (SD=1.54)
Trunk	Peak	Coronal	10.2^0 (SD=5.81)	7.5^0 (SD=5.64)	8.4^0 (SD=6.28)	-2.9^0 (SD=5.61)
Trunk	Range	Transverse	2.9^0 (SD=2.60)	3.3^0 (SD=1.40)	3.4^0 (SD=2.42)	2.8^0 (SD=0.93)
Pelvis	Range	Sagittal	3.3^0 (SD=1.75)	4.0^0 (SD=2.32)	3.2^0 (SD=1.14)	3.9^0 (SD=1.42)
Pelvis	Range	Coronal	2.2^0 (SD=0.92)	2.4^0 (SD=1.14)	2.7^0 (SD=1.41)	3.5^0 (SD=1.95)
Pelvis	Peak	Coronal	11.3^0 (SD= 4.81)	10.8^0 (SD=4.96)	10.7^0 (SD=9.91)	12.1^0 (SD=8.53)
Pelvis	Range	Transverse	3.8^0 (SD=1.43)	3.7^0 (SD=2.07)	4.1^0 (SD=1.28)	4.5^0 (SD=1.56)
Hip	Range	Sagittal	2.6^0 (SD=1.60)	2.7^0 (SD=1.98)	3.1^0 (SD=0.95)	2.1^0 (SD=0.75)
Hip	Range	Coronal	4.4^0 (SD=2.61)	3.9^0 (SD=2.19)	3.8^0 (SD=1.46)	3.2^0 (SD=1.06)
Hip	Peak	Coronal	-11.7^0 (SD=4.47)	-7.1^0 (SD=5.12)	-8.2^0 (SD=4.52)	11.6^0 (SD=4.5)
Hip	Range	Transverse	3.1^0 (SD=1.24)	3.6^0 (SD=1.24)	3.2^0 (SD=1.10)	2.7^0 (SD=0.68)

Key	
Peak	Peak value
Range	Range of movement

Table 5.3 The normative Lumbo-Pelvic and Hip movement data within healthy participants and professional football players during the Trendelenburg Test

5.4 Single Leg Squat

5.4.1 Normative data

Single Leg Squat			Healthy Participants		Professional Football Players	
Dependent variable	Event	Plane	Left lower limb weight bearing	Right lower limb weight bearing	Left lower limb weight bearing	Right lower limb weight bearing
Lumbar	Range	Sagittal	11.7^{0} (SD=5.00)	12.6^{0} (SD=5.05)		
Lumbar	Range	Coronal	4.4^{0} (SD=1.88)	4.9^{0} (SD=2.99)		
Lumbar	Peak	Coronal	4.1^{0} (SD=2.78)	2.3^{0} (SD=4.15)		
Lumbar	Range	Transverse	4.8^{0} (SD=2.26)	4.9^{0} (SD=1.76)		
Thoracic	Range	Sagittal	4.8^{0} (SD=2.81)	4.8^{0} (SD=3.00)		
Thoracic	Range	Coronal	3.7^{0} (SD=2.01)	3.3^{0} (SD=2.07)		
Thoracic	Peak	Coronal	1.9^{0} (SD=2.79)	0.2^{0} (SD=3.46)		
Thoracic	Range	Transverse	6.6^{0} (SD=2.91)	7.8^{0} (SD=3.82)		
Trunk	Range	Sagittal	8.5^{0} (SD=5.16)	8.8^{0} (SD=5.25)	18.4^{0} (SD=5.40)	17.1^{0} (SD=6.72)
Trunk	Range	Coronal	5.9^{0} (SD=2.62)	6.0^{0} (SD=2.93)	7.6^{0} (SD=2.89)	7.0^{0} (SD=3.30)
Trunk	Peak	Coronal	4.6^{0} (SD=3.91)	2.2^{0} (SD=4.42)	2.3^{0} (SD=4.6)	4.8^{0} (SD=3.27)
Trunk	Range	Transverse	5.7^{0} (SD=2.58)	5.9^{0} (SD=3.12)	6.1^{0} (SD=2.24)	7.6^{0} (SD=2.94)
Pelvis	Range	Sagittal	6.0^{0} (SD=3.11)	6.9^{0} (SD=4.08)	10.0^{0} (SD=4.28)	7.3^{0} (SD=3.31)
Pelvis	Range	Coronal	10.1^{0} (SD=5.56)	11.4^{0} (SD=7.20)	15.8^{0} (SD=9.11)	15.9^{0} (SD=7.06)
Pelvis	Peak	Coronal	18.9^{0} (SD=9.46)	19.5^{0} (SD=11.04)	23.8^{0} (SD=11.52)	23.9^{0} (SD=8.21)
Pelvis	Range	Transverse	3.8^{0} (SD=1.03)	4.0^{0} (SD=2.19)	5.0^{0} (SD=3.00)	6.6^{0} (SD=3.41)
Hip	Range	Sagittal	44.2^{0} (SD=13.70)	41.7^{0} (SD=10.89)	61.0^{0} (SD=11.58)	55.8^{0} (SD=13.42)
Hip	Range	Coronal	9.1^{0} (SD=5.76)	9.0^{0} (SD=4.55)	8.5^{0} (SD=5.59)	9.7^{0} (SD=4.47)
Hip	Peak	Coronal	4.0^{0} (SD=5.92)	9.3^{0} (SD=5.19)	9.6^{0} (SD=5.45)	-0.3^{0} (SD=5.61)
Hip	Range	Transverse	5.9^{0} (SD=2.41)	5.5^{0} (SD=3.06)	5.8^{0} (SD=2.74)	7.7^{0} (SD=4.33)

Key	
Peak	Peak value
Range	Range of movement

Table 5.4 The normative Lumbo-Pelvic and Hip movement data within healthy participants and professional football players during the Single Leg Squat

5.5 Corkscrew Test

5.5.1 Normative data

Corkscrew Test			Healthy Participants	
Dependent variable	Event	Plane	Left lower limb weight bearing	Right lower limb weight bearing
Trunk	Range	Sagittal	3.6^0 (SD=2.11)	4.0^0 (SD=2.03)
Trunk	Range	Coronal	6.4^0 (SD=3.50)	6.5^0 (SD=5.55)
Trunk	Peak	Coronal	2.7^0 (SD= 3.98)	1.8^0 (SD=3.90)
Trunk	Range	Transverse	26.1^0 (SD=17.40)	28.8^0 (SD=16.00)
Lumbar	Range	Sagittal	4.1^0 (SD=1.95)	3.9^0 (SD=1.49)
Lumbar	Range	Coronal	2.8^0 (SD=1.34)	3.5^0 (SD=1.70)
Lumbar	Peak	Coronal	2.0^0 (SD=2.80)	0.6^0 (SD=2.41)
Lumbar	Range	Transverse	3.6^0 (SD=1.46)	4.3^0 (SD=1.54)
Thoracic	Range	Sagittal	5.3^0 (SD=1.66)	6.1^0 (SD=3.41)
Thoracic	Range	Coronal	11.6^0 (SD=7.56)	13.0^0 (SD=9.97)
Thoracic	Peak	Coronal	5.1^0 (SD=5.75)	5.8^0 (SD=6.37)
Thoracic	Range	Transverse	17.5^0 (SD=11.78)	19.6^0 (SD=13.26)
Pelvis	Range	Sagittal	4.5^0 (SD=2.51)	4.4^0 (SD=2.93)
Pelvis	Range	Coronal	4.4^0 (SD=1.68)	4.8^0 (SD=2.35)
Pelvis	Peak	Coronal	12.6^0 (SD=5.38)	13.7^0 (SD=5.34)
Pelvis	Range	Transverse	53.6^0 (SD=17.48)	61.5^0 (SD=18.82)
Hip	Range	Sagittal	7.8^0 (SD=4.30)	8.2^0 (SD=4.09)
Hip	Range	Coronal	5.7^0 (SD=3.26)	5.7^0 (SD=3.17)
Hip	Peak	Coronal	-4.8^0 (SD=4.40)	-1.0^0 (SD=4.65)
Hip	Range	Transverse	8.3^0 (SD=3.50)	6.4^0 (SD=3.30)

Key	
Peak	Peak value
Range	Range of movement

Table 5.5 The normative Lumbo-Pelvic and Hip movement data within healthy participants and professional football players during the Corkscrew Test

5.6 Professional football players compared to healthy participants

Dependent Variable	Event	Plane	Left	Right
Trunk	Range	Sagittal		
Trunk	Range	Coronal		
Trunk	Peak	Coronal		
Trunk	Range	Transverse		
Pelvis	Range	Sagittal		
Pelvis	Range	Coronal		
Pelvis	Peak	Coronal		
Pelvis	Range	Transverse		
Hip	Range	Sagittal		
Hip	Range	Coronal		
Hip	Peak	Coronal		
Hip	Range	Transverse		

Key	
Significant differences between dependent variables ($p<0.05$) i.e these parameters are not similar when comparing the groups	
No significant differences between dependent variables ($p<0.05$) i.e these parameters are similar when comparing the groups	

Figure 5.3 Professional football players compared to healthy participants

5.7 Results summary

When a clinician observes walking or running they should look to observe movement of all the regions and in all of the three cardinal planes. The only exception is that during walking there should be no observable movement occurring at the lumbar spine; thoracic spine and trunk in the sagittal plane or lumbar spine and pelvis in the coronal plane. Any differences found from this movement pattern maybe interpreted as an abnormal gait pattern and potentially an indication for treatment.

When observing the Trendelenburg Test the pelvis should achieve a position of 10^0 of pelvic obliquity and there should be no observable movement of the participant in the each of the three cardinal planes whilst maintaining this posture. The Single Leg Squat should take 6 seconds to complete. The hip should move through 43^0 in healthy participants, and 58^0 in professional football players in the sagittal plane, whilst allowing a small amount of movement at the trunk and pelvis in all of the other planes. For the Corkscrew Test the hip should move through 6^0 of rotation, and the trunk through 27^0 of rotation. A small amount of movement of the participant is allowable in the each of the three cardinal planes whilst moving through these ranges. The Trendelenburg Test was found to be the most useful test for examining the components of walking. It is an appropriate measure for the sagittal plane range of movement at the lumbar spine, thoracic spine, and trunk. For running the Single Leg Squat was found to be the most useful of the tests studied, however it was an appropriate measure for only 4 of the 20 parameters.

A key finding of this work was that the professional football players exhibited an altered Lumbo-Pelvic and Hip movement pattern when compared to the healthy participants. Their range of movement was greater in the trunk coronal plane during left lower limb weight bearing and transverse plane during right lower limb weight bearing. Also at the pelvis in the sagittal plane during left lower limb weight bearing, coronal plane during left and right lower limb weight bearing, and hip in the sagittal plane during left lower limb weight bearing. The range of movement was less in the trunk sagittal plane and pelvis in the transverse plane during both lower limb weight bearing.

6 Discussion

6.1 Relevance and issues of peak value and range of movement data

The focus of this study was to establish normative kinematic movement data within healthy participants and professional football players for walking, running, the Trendelenburg Test, the Single Leg Squat and the Corkscrew Test in the three cardinal planes of movement. This data was to include the Lumbo-Pelvic and Hip region and trunk with its component regions of the lumbar spine and thoracic spine. Therefore, for each of the participants there are potentially 30 parameters for the minimum values, 30 for the peak value, and 30 for range of movement and this consequently represents a significant volume of data. To aid conciseness of the thesis this needed to be considered.

The minimum value of the tests represents the start point for the test. Many clinical tests, including the Trendelenburg Test, Single Leg Squat and Corkscrew Test, do not include the start position within their interpretation and consequently this is of limited clinical value. The peak value often represents the end of the test; this may be influenced by the starting posture of the participant and the positioning of the anatomical markers. Starting a clinical test which uses a sagittal plane hip movement, such as the Single Leg Squat, with the thigh in a more posterior position may cause a lower hip peak value. Similarly a more anteriorly sited thigh marker may cause a greater minimum and peak value. Hence both the minimum and peak values are of limited clinical value, may be more subject to measurement error and therefore may contain bias. Furthermore, this study found that the standard deviations derived from the peak value data were considerably greater than that of the range of movement data e.g. during the Trendelenburg Test the thoracic coronal plane peak value standard deviation 5.27 degrees, range of movement standard deviation 0.78 degrees, Table 5.3. However the pelvis coronal plane peak value is currently the standard method for interpreting the Trendelenburg Test (Hardcastle et al., 1985), is the primary outcome for contemporary research (Roussel et al., 2007; van Iersel et al., 2004; Westhoff et al., 2005), and is a clinically important parameter when examining neuromuscular control of the pelvis. Therefore within this thesis the discussion of minimum and peak values will be limited to the pelvis coronal plane peak value. The range of movement is highly clinically significant (Sykes, 1975); it is a criteria for interpreting the clinical tests (Livengood et al., 2004), and a commonly quoted parameter in the current evidence base for both walking (Crosbie & Vachalathiti, 1997), and running (Schache et al., 2002b). Hence within this thesis the discussion will also include the range of movement for each of the components forming the Lumbo-Pelvic and Hip region.

6.2 Walking Gait

6.2.1 Normative data and its relationship to current evidence

6.2.1.1 Lumbar movement

The values for the lumbar range of movement during walking from this study were symmetrical and small in the sagittal and coronal plane, but moderate in the transverse plane. However lumbar coronal plane peak value was small and highly asymmetrical. The value for the lumbar sagittal plane range of movement from this study; healthy participants; left 4.0^0 (SD=1.52), right 3.7^0 (SD=1.47), Table 8.1, Table 8.3, and Table 5.1. These values are similar to previously published values; 3.0^0 (Saunders et al., 2005), 3.2^0 (Taylor et al., 1996), 3.5^0 (Crosbie et al., 1997a) (difference between standing and walking), and 4.0^0 (Whittle et al., 1999), Table 3.1. One previous study established a lower value for lumbar sagittal plane range of movement when compared to this study; 2^0 (Rowe et al., 1996). A potential explanation for this is the differences in cohort between Rowe's study and this study. This lower 2^0 value was found in nurse's returning to work following low back pain; hence this may be due to residual pain or guarding. This thesis's study used healthy participants who had been screened for any injuries to ensure that they were asymptomatic. Another study established a greater lumbar sagittal plane range of movement when compared to this study; 10.7^0 (Whittle et al., 1996). A group of studies have consistently found higher values for lumbar sagittal plane range of movement when compared to this study, 21^0 (Schwartz et al., 2007), and 21.5^0 (Rozumalski et al., 2008). A potential explanation of this is that these studies were methodologically different being bone pin studies but this thesis's study used skin markers. Bone pin studies often report larger ranges of movement.

The value for the lumbar coronal plane range of movement from this study; healthy participants; left 4.8^0 (SD=2.16), right 4.7^0 (SD=2.07), Table 8.5, Table 8.7, and Table 5.1. Three previously published studies are agreement with these values; 3^0 (Whittle et al., 1998), 4^0 (Rowe et al., 1996) (LBP), and 6.0^0 (Saunders et al., 2005), Table 3.1. One early study reported a higher value; 7.6^0 (Whittle et al., 1999), and another contemporary study; 9^0 (SD=2) (Zhao et al., 2008). A potential explanation for this may be in the modeling as Whittle used an early spinal model including wands, and Zhao used a "novel marker set" consisting of a sacral cluster and single markers over the spinous processes. In contrast to Whittle and Zhao, this study used the CAST system with an added lumbar cluster, Figure 3.3 and Figure 3.5. Another study reported, 9.0^0 (Crosbie et al., 1997a), but Crosbie's study used a mixed sex cohort of participants aged 20-82 years of age, in contrast this study used an entirely male cohort aged 15-22.5. Other studies have reported 9^0 (SD=unstated) (Fowler et al., 2006) and 12.8^0 (Taylor et al., 1996), but both of these studies were of gait whilst walking on a treadmill, conversely this study was performed walking over ground. Treadmill based studies often generate different kinematics to walking over ground (Chatterley et al., 2007; Schache et al., 2001). Previous evidence has established differences in Lumbo-Pelvic and Hip kinematics during treadmill walking when compared to walking over ground (Schache et al., 2001). Two more recent studies found a far greater lumbar coronal plane range of movement, 17.1^0 (SD= average of 2) (Rozumalski et al., 2008) and 18^0 (Schwartz et al., 2007). A potential explanation of this is that Rozumalski and Schwartz used bone pins but this study used retro reflective markers. These types of study tend to produce ranges of movement in excess of the non-invasive skin markers studies. The value for the lumbar coronal plane peak value from this study; for healthy participants; left 3.9^0 (SD=2.79), right 1.3^0 (SD=2.92), Table 8.9, Table 8.11, and Table 5.1, indicates that during walking the peak value displacement of the lumbar spine is small and asymmetrical with a three times greater displacement occurring during left lower limb weight bearing when compared to right lower limb weight bearing. This study's values are similar to previously published values; 5^0 (Whittle et al., 1999), 5^0 (Zhao et al., 2008), 6^0 (Saunders et al., 2005), and 7^0 (Fowler et al., 2006), Table 3.1. Previous research (Rowe et al., 1996) has also established a lower value of 2^0 (SD=0.26). A potential explanation for this lower value is that the population in Rowe's study was nurses returning to work after low back pain who potentially had residual restriction of lumbar spine movement. That is to say they were different to the asymptomatic, healthy participants with presumably normal lumbar movement participating in this study.

The value for the lumbar transverse plane range of movement from this study; healthy participants; left 7.9^0 (SD=2.47), right 7.8^0 (SD=2.50), Table 8.13, Table 8.15, and Table 5.1. These values are similar to three previously published values; 6^0 (Saunders et al., 2005), 6^0 (Rowe et al., 1996), 6.4^0 (Taylor et al., 1996), and 8.3^0 (Whittle et al., 1999), Table 3.1. Differing lumbar transverse plane range of movement values have been published. The difference between these values and this study's may be explained by differences in modelling and cohort. One lower value of 4^0 (Whittle et al., 1998), and one higher value of 25^0 (Zhao et al., 2008) has been found. Whittle and Zhao's studies were both skin maker studies. In the studies Whittle used wands for markers, as discussed previously, and Zhao used a "novel marker set." The differences in modeling between Whittle, Zhao and this study may explain the differences in values, Figure 3.3, and Figure 3.5. Far higher values of over 20^0 have been established; 22.8^0 (SD= average of 2) (Rozumalski et al., 2008) and 22^0 (Schwartz et al., 2007). A potential explanation of this is that Rozumalski and Schwartz used bone pins but this thesis's study used retro reflective skin markers. The bone pin method appears to generate higher values for range of movement when compared to skin markers. A far lower value for lumbar transverse plane range of movement has been published; 4.5^0 (Crosbie et al., 1997a), but Crosbie used a mixed sex, elder age group when compared to this study. This thesis's study has found values in keeping with existing papers and contributed to the evidence for kinematic studies of the lumbar spine. Lumbar spine kinematic values are of particular importance when examining participants who have lumbar dysfunction when walking such as lumbar disc (Burnett, Khangure, Elliott, Foster, Marshall, & Hardcastle, 1996; Millisdotter, Stromqvist, & Jonsson, 2003; Raty, Battie, Videman, & Sarna, 1997), or zygapophyseal joint pain.

6.2.1.2 Thoracic movement

The values for the thoracic range of movement during walking from this study were symmetrical and small in the sagittal plane, but large in the coronal and transverse planes. The thoracic coronal plane peak value was small and symmetrical. The value for the thoracic sagittal plane range of movement from this study; healthy participants; left 4.5^0 (SD=1.96) right 3.7^0 (SD=1.36), Table 8.17, Table 8.19 and Table 5.1. These values are similar to previously published values; 2.5^0 (Crosbie et al., 1997a), 2.5^0 (Vogt et al., 1999), 4^0 (Stokes et al., 1989) and 4.4^0 (Vogt et al., 2002), Table 3.2. One previous study established a lower value for thoracic sagittal plane range of movement when compared to this study; 1^0 (Fowler et al., 2006). A potential explanation for this is that Fowler's study was a treadmill based study but this thesis's study used walking over ground.

The value for the thoracic coronal plane range of movement from this study; healthy participants; left 9.7^0 (SD=2.67), right 10.0^0 (SD=3.59), Table 8.21, Table 8.23 and Table 5.1. Two previously published studies are agreement with these values; 7.0^0 (Crosbie et al., 1997a), and 8^0 (Fowler et al., 2006), Table 3.2. Some previous studies reported lower values; 2.8^0 (Vogt et al., 1999), and 4.9^0 (Stokes et al., 1989). However both of these were treadmill studies and these types of study have been found to produce different Lumbo-Pelvic and Hip kinematic data to walking on the ground (Schache et al., 2001). A later study by Vogt reported a lower value; 3.9^0 (Vogt et al., 2002). In this study Vogt used a cohort of young males walking on the ground. However a potential explanation for this lower value may be in the modeling. Vogt modelled the thoracic spine differently; as he modelled the thoracic spine relative to the pelvis and movement of the pelvis relative to the "room-based coordinate system" (global co-ordinate). This thesis's study modelled the thoracic spine relative to the lumbar spine and movement of the pelvis relative to the room-based coordinate system. A further study found a lower value; 4^0 (SD=2) (Zhao et al., 2008). However Zhao used a "novel marker set" but this thesis's study used the CAST system with an additional thoracic cluster. The value for the thoracic coronal plane peak value from this study; healthy participants; left 5.8^0 (SD=1.60), right 5.2^0 (SD=2.80), Table 8.25, Table 8.27, and Table 5.1. The values are similar to two previously published study; $3.8\ ^0$ (Lamoth 2006) and 5^0 (Fowler et al., 2006), Table 3.2. One other study found a lower value; 1^0 (Zhao et al., 2008). However Zhao's study was a single case study and hence this lower value may merely reflect individual variation within this participant.

The value for the thoracic transverse plane range of movement from this study; healthy participants; left 9.8^0 (SD=5.06), right 9.4^0 (SD=5.42), Table 8.29, Table 8.31, and Table 5.1. These values are similar to a previously published study; 4.0^0 (Crosbie et al., 1997a), 5^0 (Stokes et al., 1989), 6.8^0 (Vogt et al., 1999), 7^0 (Zhao et al., 2008), 8.2^0 (Vogt et al., 2002), 11^0-15^0 (Wu et al., 2011) (pregnant and speed dependent), 11^0-13^0 (Wu et al., 2011) (speed dependent), Table 3.2. There are fewer existing papers for the kinematics of the thoracic spine when compared to the number of papers for the lumbar spine. Of note is that many clinicians currently presume that the thoracic spine is a region where a large amount of transverse plane movement occurs and very little other movement. However this study has found that the range of thoracic transverse and coronal plane movement during walking are almost equal, challenging this common clinical assumption. Thoracic spine kinematic values are of particular importance when examining participants who have thoracic dysfunction when walking such as costo-vertebral joint pain.

6.2.1.3 Trunk movement

The values for the trunk range of movement during walking from this study were symmetrical and small in the sagittal plane, moderate in the coronal plane and large in the transverse planes. However trunk coronal plane peak values were small and symmetrical. The values for the trunk sagittal plane range of movement from this study; healthy participants; left 2.6^0 (SD=0.97), right 2.4^0 (SD=0.86), professional football players; left 2.5^0 (SD=0.95), right 2.5^0 (SD=0.81), Table 8.33, Table 8.36, and Table 5.1. These values are in agreement with four previously published studies; 1^0 (Fowler et al., 2006), 2^0 (Bianchi et al., 1998), 2^0 (Sartor et al., 1999) and 4^0 (Krebs et al., 1992), Table 3.3.

The value for the trunk coronal plane range of movement from this study; healthy participants; left 10.5^0 (SD=2.87), right 10.8^0 (SD=3.14), professional football players; left 11.9^0 (SD=2.27), right 12.1^0 (SD=2.37), Table 8.39, Table 8.42 and Table 5.1. These values are similar to previously published studies; 6^0 (Krebs et al., 1992), 8^0 (Veneman et al., 2008), and 12^0 (Sartor et al., 1999), Table 3.3. One previously published study (Fowler et al., 2006) found a lower trunk coronal plane range of movement value of 4^0. A potential explanation for this discrepancy in values may be the methodological differences between Fowler's study and this study as this thesis's study used walking over ground but Fowler's study was a treadmill based study. The values for the trunk coronal plane peak value from this study; healthy participants were; left 6.8^0 (SD= 2.15), right 5.0^0 (SD=3.04), professional football players; left 6.2^0 (SD= 2.91), right 7.2^0 (SD=2.77), Table 8.45, Table 8.48 and Table 5.1. There are a limited number of previously published values for this variable but those that are published are in agreement with this study; 3^0 (Krebs et al., 1992) and 6^0 (Sartor et al., 1999), Table 3.3. More recently a study (Fowler et al., 2006) established a lower value of 1^0. A potential explanation for this difference is that Fowler's study used a treadmill, but this thesis's study used walking in a laboratory. A previous study has established lower ranges of movement in the thoracic spine and pelvis in the coronal and sagittal planes during walking on a treadmill when compared to the ground (Vogt et al., 2002).

The value for the trunk transverse plane range of movement from this study were; healthy participants; left 17.0^0 (SD=5.27), right 17.1^0 (SD=5.10), professional football players; left 17.8^0 (SD=4.82), right 17.6^0 (SD=4.36), Table 8.51, Table 8.54 and Table 5.1; indicate that during walking the trunk transverse plane range of movement is large and symmetrical. These values are similar to previously published studies, 10^0 (Krebs et al., 1992), 8^0-22^0 (Wu et al., 2011) (pregnant and speed dependent), 8^0-17^0 (Wu et al., 2011) (speed dependent), and 14^0 (Sartor et al., 1999), Table 3.3. There are more existing papers for the kinematics of the trunk when compared to the number of papers for the lumbar or thoracic spine. Trunk kinematics are of particular clinical utility at the start of the clinical examination of gait. Many clinical paradigms start their examination with a view of the trunk as a single segment. Once this preliminary examination has been completed they then progress to examining the lumbar and thoracic spine (Cyriax, 1944; Cyriax, 2001; Maitland et al., 1986).

6.2.1.4 Pelvis movement

The values for the pelvis range of movement during walking from this study were symmetrical and moderate in the sagittal plane, small in the coronal plane and large in the transverse plane. Pelvis coronal plane peak values were moderate and symmetrical. The values for the pelvis sagittal plane range of movement from this study were; healthy participants; left 5.4^0 (SD=1.59), right 5.2^0 (SD=1.22), professional football players; left 7.2^0 (SD=1.73), right 7.5^0 (SD=1.44), Table 8.57, Table 8.60, and Table 5.1. These values are in agreement with previously published studies; 4.3^0 (Taylor et al., 1996), 4.9^0 (Vogt et al., 2002), 5.0^0 (Franz et al., 2009), 7.6^0 (Stokes et al., 1989), and 8^0 (Bianchi et al., 1998) (difference between standing and walking), Table 3.4. Some authors have published values that differ from this study, all of which have been lower than this study. A value of 1^0 (Rose et al., 2006) has been found.

However; Rose's value was extrapolated from the graphs within the book "Human Walking." Rose's cohort was not defined and the model not described. Another study established a lower pelvis sagittal plane range of movement when compared to this study; 2^0 (Kadaba et al., 1989). Potential explanations are that Kadaba used posterior sacral and lateral pelvic wands to model the pelvis and calculated the hip joint centre by using regression equations. In contrast this study modeled the pelvis by using the CAST system and calculated the hip joint centre by the prediction approach (Bell et al., 1989; Bell et al., 1990). One established author has published two papers with lower values for pelvis sagittal plane range of movement when compared to this study, 2.87^0 (SD=0.95) (Whittle et al., 1996), and 2.8^0 (SD=0.76) (Whittle et al., 1999). A potential explanation for this is that the 1996 study reported the difference between standing and walking posture. The value therefore would not represent the full range of pelvic movement. During Whittle's later 1999 study he used wands for markers, in contrast this study which used the CAST system of retro reflective markers attached to the skin. Current opinion is that wands are considered to be susceptible to excessive movement and hence may generate errors within the data and consequently skin markers should be used in preference (Wren et al., 2008). Another lower value has been found; 3.5^0 (Crosbie et al., 1997a). But Crosbie's study used a mixed sex, not single sex, and different age group to this study. Another lower value was found; 3.8^0 (Vogt et al., 1999). A potential explanation for this is that Vogt's study used a treadmill whereas this study used walking on the ground.

The value for the pelvis coronal plane range of movement from this study from this study; healthy participants; left 2.5^0 (SD=0.70), right 2.6^0 (SD=0.95), professional football players; left 2.3^0 (SD=0.92), right 2.5^0 (SD=0.70), Table 8.63, Table 8.66, and Table 5.1. These values are similar to one previously published study; 3^0 (Kadaba et al., 1989), Table 3.4. In contrast some authors have published values that differ for the pelvis coronal plane range of movement from this study, all of which have reported higher values than this study's. A value of 5^0 (Zhao et al., 2008) has been found. However Zhao used a different marker set when compared to this study. Another author found the value of 5^0 (Kennedy et al., 2009). However Kennedy's study used a modified Helen-Hayes marker set but this study used the CAST system. The Helen-Hayes marker set was developed for low resolution imaging systems and therefore has few markers, as far apart as possible. This results in joint motion being constrained with only three degrees of freedom (Collins, Ghoussayni, Ewins, & Kent, 2009). It is also unclear if Kennedy encouraged targeting of the footplates as "each participant performed a few practice walking trials until they could land with their foot on a force plate… without altering their gait". Whilst Kennedy states "without altering their gait" this methodology infers that targeting may have occurred and hence the data would not be representative of normal gait. Another higher value has been found; 6.0^0 (Crosbie et al., 1997a). But Crosbie's study used a mixed sex, and different age group to this study. One author has published two higher values, 7.8^0 (Vogt et al., 1999), and 6.2^0 (Vogt et al., 2002). A potential explanation for this is that Vogt's 1999 study used a treadmill whereas this study used walking on the ground. Vogt's 2002 study used a different data capture system (ZEBRIS ultrasound) and model when compared to this study. Some authors have found pelvis coronal plane range of movement values far in excess of this studies values ; 7.7^0 (Whittle et al., 1999). A potential explanation for this may be in the modeling as Whittle used an early spinal model including wands but this study used the CAST system. Previous values have been found as high as; 11.7^0 (Taylor et al., 1996), and 9^0 (Stokes et al., 1989). A potential explanation of these values is that both of these studies used a treadmill, but this study used walking over the ground. A similar value was previously found; 10° (Rose et al., 2006) but the value has been extrapolated from the text book and Rose's methodology is unstated within the text. The value for the pelvis coronal plane peak value in this study of; healthy participants; left 8.3^0 (SD=4.82), 8.3^0 (SD=5.14), professional football players; left 8.2^0 (SD=4.07), right 8.2^0 (SD=3.91), Table 8.69, Table 8.72 and Table 5.1. One previously published studies was reviewed but it was found to be in agreement with these values; 7.0^0 (Crosbie, Vachalathiti, & Smith, 1997b), Table 3.4.

The value for the pelvis transverse plane range of movement from this study; healthy participants; left 15.0^0 (SD=5.24), right 14.6^0 (SD=5.28), professional football players; left 13.4^0 (SD=4.06), right 13.3^0 (SD=3.68), Table 8.75, Table 8.78, Table 5.1. These values are in agreement with; 9^0 (Stokes et al., 1989), 9^0-14^0 (Wu et al., 2011) (speed dependent), 9^0-17^0 (Wu et al., 2011) (pregnant and speed dependent) and 10.4^0 (Whittle et al., 1999), Table 3.4. Six previous studies have found lower values of pelvis transverse plane range of movement when compared to this study. The first found a range of; 4.0^0 (Crosbie et al., 1997a). However Crosbie's study used a mixed sex, not single sex, and different age group to this study. Another study found; 5^0 (Kadaba et al., 1989). Potential explanations are that Kadaba used posterior sacral and lateral pelvic wands to model the pelvis and calculated the hip joint centre by using regression equations. A further study found; 7.7^0 (Vogt et al., 2002). A potential explanation for this is that Vogt's study used a treadmill whereas this study used walking on the ground. A popular publication reported; 8^0 (Rose et al., 2006). But, as previously stated, this value has been extrapolated from the text book and Rose's methodology is unstated within the text. Two studies found; 6.4^0 (Vogt et al., 1999), and 8.5^0 (Taylor et al., 1996). In common with other previous studies (Fowler et al., 2006; Vogt et al., 2002) these were treadmill studies and hence would generate different Lumbo-Pelvic and Hip kinematics (Schache et al., 2001). One previous study has found a higher transverse plane pelvis range of movement value when compared to this study; 22^0 (SD=2) (Zhao et al., 2008). This may be explained by the differences in models used where Zhao's study used a "novel marker set" but this study used the CAST system. The kinematics of the pelvis have been extensively investigated and this study's values are in agreement with many of these previously published papers. The kinematics of the pelvis are currently thought to be important during gait for load transfer (Lee, 2007) and the generation of an efficient gait by the "spinal engine" (Gracovetsky

& Iacono, 1987). Increasing clinical understanding therefore of pelvic kinematics is of clinical utility for participants who present with sub-optimal load transfer and inefficient gait.

6.2.1.5 Hip movement

The values for the hip range of movement during walking from this study were symmetrical and very large in the sagittal plane, and large in the coronal and transverse planes. However hip coronal plane peak value was moderate and asymmetrical. The values for the hip sagittal plane range of movement from this study; healthy participants were; left 38.6^{0} (SD=6.89), right 37.8^{0} (SD=5.11), professional football players; left 39.3^{0} (SD=5.17), right 37.8^{0} (SD=3.63), Table 8.81, Table 8.84, and Table 5.1. These values are similar to previously published studies; 27.6^{0} (Lelas et al., 2003), 36^{0} (Ostrosky et al., 1994) (young), 40^{0} (Franz et al., 2009), 40^{0} (Whittle, 1996), 40^{0} (Kadaba et al., 1989), 40^{0} (Kennedy et al., 2009), 45^{0} (Rose et al., 2006), 45^{0} (Richards, 2008), and 45^{0} (Levine et al., 2012), Table 3.5. One considerably lower hip sagittal plane range of movement has been found 21^{0} (Ostrosky et al., 1994). A potential explanation for this maybe differences in cohort as Ostrosky's study used elderly participants (60-80 years old) but this study used participants who were younger (16-21 years old). The study by Ostrosky found that that elderly participants had reduced hip extension, a sagittal plane movement, when compared to younger participants (Ostrosky et al., 1994).

The value for the hip coronal plane range of movement from this study from this study; healthy participants; left 9.4^{0} (SD=2.31), right 9.5^{0} (SD=1.92), professional football players; left 10.5^{0} (SD=2.23), right 11.2^{0} (SD=2.60), Table 8.87, Table 8.90, and Table 5.1. These values are similar to previously published studies; 7^{0} (Kadaba et al., 1989), 10^{0} (Kennedy et al., 2009), and 12^{0} (Rose et al., 2006), Table 3.5. One considerably higher hip coronal plane range of movement has been published; 15^{0} (Richards, 2008). But this value has been extrapolated from the text book and Richards' data source, in common with other text books, is unstated within the text. The value for the hip coronal plane peak value in this study of were; healthy participants; left 2.4^{0} (SD=3.63), right 5.4^{0} (SD=2.82), professional football players; left 8.7^{0}

(SD=2.67), right 5.4^0 (SD=2.82), Table 8.93, Table 8.96 and Table 5.1. Three previously published studies are in agreement with these values; 5^0 (Kadaba et al., 1989), 5^0 (Kennedy et al., 2009), and 6^0 (Rose et al., 2006), Table 3.5.

The value for the hip transverse plane range of movement from this study; healthy participants; left 10.5^0 (SD=3.97), right 10.8^0 (SD=3.37), professional football players; left 10.2^0 (SD=3.52), right 9.9^0 (SD=2.79), Table 8.99, Table 8.102, and Table 5.1. These values are slightly lower than previously published studies; 15^0 (Kadaba et al., 1989), 15^0 (Richards, 2008) and 15^0 (Rose et al., 2006), Table 3.5. Potential explanations are that Kadaba used posterior sacral and lateral pelvic wands to model the pelvis and calculated the hip joint centre by using regression equations. Richards and Rose were textbooks where the values were extrapolated from the graphs and their methodologies were unstated. However, despite this, these previously published values are only 0.5^0 in excess of 1 standard deviation apart. The movement of the hip and pelvis during walking are currently thought to be synchronous (Richards, 2008). When participants present with hip dysfunction, such as hip joint OA or hip acetabular tears, the clinician needs to evaluate if the hip or pelvis is generating the problem (Richards, 2008; Sahrmann, 1988; Van Dillen, Maluf, & Sahrmann, 2009). Hence increasing the evidence base and clinical understanding of the hip kinematics during walking may aid this evaluation process. In order to help clinician's implement this study's Lumbo-Pelvic and Hip kinematic values into clinical practice a summary figure is presented, Appendix 6.

6.2.1.6 Clinical relevance – observation of walking in clinical practice

It has been previously discussed that movement below 5^0 is not perceivable by the human eye in the clinical environment. This has been termed the "level of observability." From this study's range of movement data; lumbar spine; thoracic spine and trunk sagittal plane values and lumbar spine and pelvis coronal plane values lie below this 5^0 threshold, but none of the hip movements. The peak value data established that only the lumbar spine coronal plane peak value lies below the 5^0 threshold. Hence when observing a patient walking there should be no observable movement of the lumbar spine, thoracic spine and trunk in the sagittal plane and lumbar spine or pelvis in the coronal plane. Conversely; when a clinician observes a patient walking they are able to see any movement of these regions in these planes they should interpret this as an abnormal gait pattern. This may indicate, pain, pathology or the need for treatment, Figure 6.1.

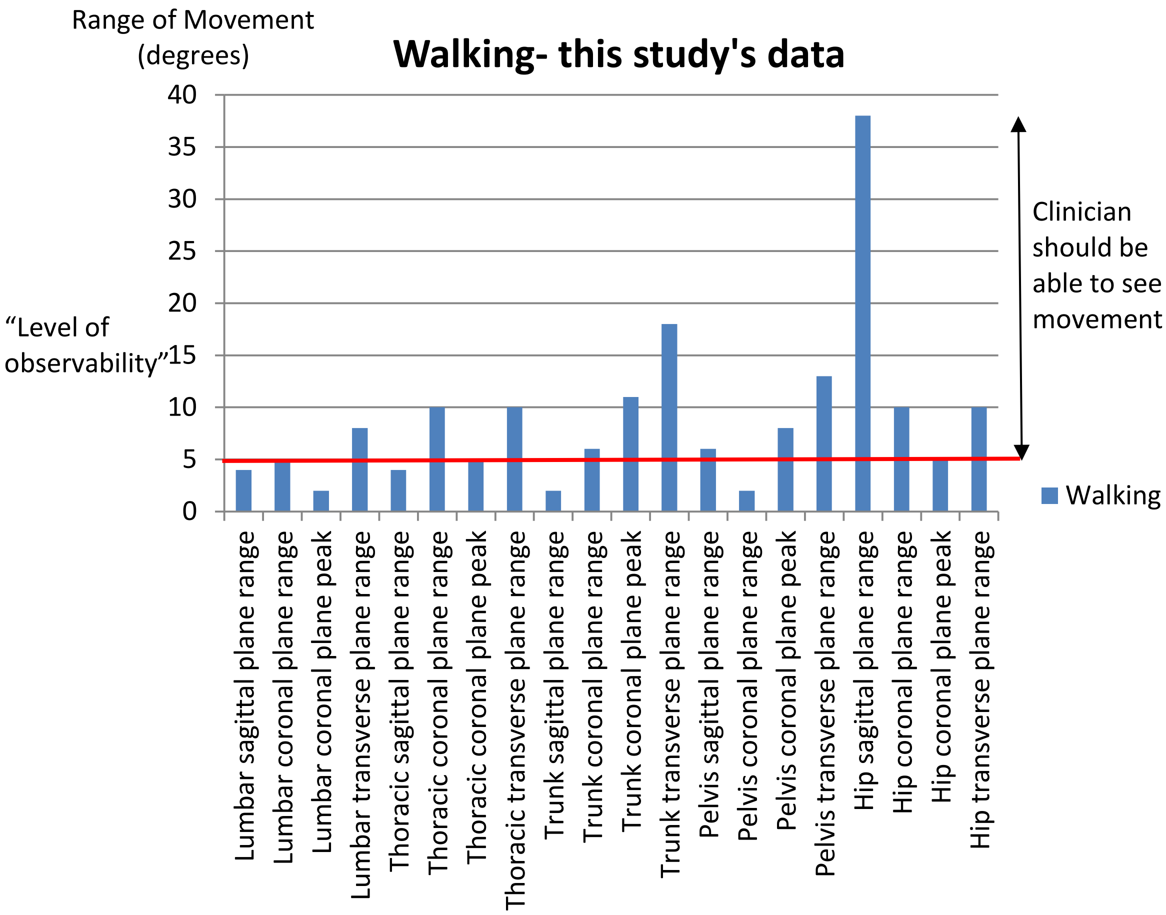


Figure 6.1 Clinically perceivable in unperceivable components of walking gait

6.2.1.7 Walking compared to clinical tests

When comparing the lumbar spine range of movement values of walking to those of the clinical tests there were no statistically significant differences for both lower limbs in the sagittal plane for the Trendelenburg and Corkscrew Tests, and in the coronal plane for the Trendelenburg Test, but in the transverse plane there were statistically significant differences between walking and all of the tests, Figure 5.1. When comparing the thoracic spine range of movement values of walking to those of the clinical tests there were no statistically significant differences for both lower limbs in the sagittal plane for the Trendelenburg test and Single Leg Squat, in the coronal plane for the Corkscrew Test, and in the transverse plane for the Single Leg Squat, Figure 5.1. When comparing the trunk range of movement values of walking to those of the clinical tests there were no statistically significant differences for both lower limbs in the sagittal plane for the Trendelenburg Test and Corkscrew Test, but in the coronal and transverse plane there were statistically significant differences between walking and all of the tests, Figure 5.1. When comparing the pelvis range of movement values of walking to those of the clinical tests there were no statistically significant differences for both lower limbs in the coronal plane for the Trendelenburg Test and Corkscrew Test. However there were statistically significant differences between walking and all of the tests and in the sagittal and transverse plane for all of the tests, Figure 5.1. When comparing the hip range of movement values of walking to those of the clinical tests there were statistically significant differences for both lower limbs in the sagittal and transverse planes for all of the tests. In the coronal plane there were no statistically significant differences between walking and the Single Leg Squat, Figure 5.1.

The clinical importance of these inter-comparisons is that when examining the components of walking gait in the clinical environment the Trendelenburg Test was found to be the most useful test. It is an appropriate measure for the sagittal plane range of movement at the lumbar spine, thoracic spine, trunk and pelvis. In the coronal plane the range of movement was represented by different tests in different regions. The transverse plane was the worst represented by the tests as only the Single Leg Squat was found to be an appropriate measure of thoracic range of movement. Many clinicians feel that the transverse plane is an important plane in the treatment of movement disorders as it commonly exhibits dysfunction (Ellison et al., 1990). It is therefore suggested that if a clinician wishes to examine the transverse plane range of movement of walking an alternative test should be used. A summary figure is presented in order to help clinician's implement this study's comparison of walking to the clinical tests, Appendix 7.

6.3 Running Gait

6.3.1 Normative data and its relationship to current evidence

6.3.1.1 Lumbar movement

The values for the lumbar range of movement during running from this study were symmetrical and large in the sagittal and transverse plane, but moderate in the coronal plane. However lumbar coronal plane peak value was moderate and highly asymmetrical. The value for the lumbar sagittal plane range of movement from this study; healthy participants; left 9.0^0 (SD=3.66), right 8.8^0 (SD=2.70), Table 8.1, Table 8.3, and Table 5.2. These values are similar to previously published values; 7^0 (Schache et al., 2001), and 10^0 (Saunders et al., 2005), Table 3.6. Two studies by Schache have found higher values; 13.3^0 (Schache et al., 2002a), and 14.5^0 (Schache et al., 2002b). A potential explanation for this is that all of these studies used a combination of wands and markers to model the lumbar spine but this thesis's study used the CAST system of individual markers and clusters.

The value for the lumbar coronal plane range of movement from this study; healthy participants; left 6.5^0(SD=3.24), right 6.3^0 (SD=2.49), Table 8.5, Table 8.7 and Table 5.2. These values are similar to one previously published value; 6^0 (Saunders et al., 2005), Table 3.6.

Higher values for coronal plane lumbar range of movement have been found; 18.5^0 (Schache et al., 2002a), 22^0 (Schache et al., 2001) and 22.5^0(Schache et al., 2002b). A potential explanation for this is that all of these studies by Schache used a combination of wands and markers to model the lumbar spine but this study used the CAST system. The value for the lumbar coronal plane peak value from this study was; for healthy participants; left 6.8^0 (SD=3.08), right 4.1^0 (SD=3.18), Table 8.9, Table 8.11, and Table 5.2; indicate that during running the lumbar spine peak value is moderate and asymmetrical with a 50% greater displacement occurring during left lower limb weight bearing when compared to right lower limb weight bearing. An asymmetry of lumbar coronal plane peak value is also seen during walking, suggesting that the movement pattern observed during walking manifests during running also. This asymmetry is 300% greater during walking and it is clinically more difficult to observe during running, clinicians may therefore wish to use walking as a surrogate measure of running kinematics for this parameter. This asymmetry of lumbar coronal plane peak value may cause healthy participants to have sub-optimal load transfer or predispose them to pathologies such as quadratus lumborum pain (Dananberg, 2007). There are a limited number of previously published values for this variable but one is in agreement with this study; 5.8^0 (Saunders et al., 2005), Table 3.6. Two studies by Schache have found a higher value, 10^0 (Schache et al., 2001), and 10^0 (Schache et al., 2002a). A potential explanation for this is that Schache's studies were of gait whilst running on a treadmill but this study was performed running on the laboratory ground floor. The Lumbo-Pelvic and Hip kinematics during treadmill running when compared to running on the ground are different (Schache et al., 2001).

The value for the lumbar transverse plane range of movement from this study; healthy participants; left 11.8^0 (SD=2.15), right 12.7^0 (SD=2.38), Table 8.13 and Table 8.15. These values are similar to previously published values; 10^0 (Saunders et al., 2005). Higher values for the lumbar transverse plane range of movement have been found 20^0 (Schache et al., 2001), 23.0^0 (Schache et al., 2002a), and 24.3^0 (Schache et al., 2002b), Table 3.6. The use of wands and markers by Schache offers a potential explanation for this difference in values. This thesis's study has found values in keeping with existing papers and contributed to the evidence for kinematic studies of the lumbar spine. Interestingly, whilst the lumbar spine kinematic values for running are greater than those found during walking they remain relatively small ranges of movement. In contrast, patients with lumbar spine pain, such as disc pathology, are often able to walk a long time before they are able to run (O'Sullivan, 2000). A potential explanation of this is that it is the patient's inability to transmit compressive load through the lumbar spine rather than range of movement that prevents them from running.

6.3.1.2 Thoracic movement

The values for the thoracic range of movement during running from this study were symmetrical and moderate in the sagittal and coronal plane, but large in the transverse plane. The thoracic coronal plane peak value was moderate and asymmetrical. There have been no previous studies that have reported the thoracic movements occurring during running. The value for the sagittal plane thoracic range of movement from this study; healthy participants; left 7.4^0 (SD=3.21), right 7.7^0 (SD=3.11), Table 8.17, Table 8.19, and Table 5.2. The value for the coronal plane thoracic range of movement from this study were; healthy participants; left 7.5^0 (SD=2.93), right 8.0^0 (SD=2.65), Table 8.21, Table 8.23, and Table 5.2. The value for the coronal plane thoracic movement peak value in this study; healthy participants; left 6.4^0 (SD=2.58), right 5.2^0 (SD=4.05), Table 8.25, Table 8.27 and Table 5.2. The greater coronal plane thoracic movement peak value found during left lower limb weight bearing may cause healthy participants to have sub-optimal load transfer (Lee, 2007) or predispose them to pathologies such as costo-vertebral joint pain. A small asymmetry of thoracic coronal plane peak value is also seen during walking, suggesting that the movement pattern observed during walking manifests during running also. As the coronal plane movement pattern is similar during both functions but technically more difficult to observe during running clinicians may wish observe this parameter during walking rather than running. The value for the transverse plane thoracic range of movement from this study were; healthy participants; left 9.7^0 (SD=4.69), right 9.0^0 (SD=3.82), Table 8.29, Table 8.31, and Table 5.2. Of note is that many clinicians currently presume that the thoracic spine is a region where a large amount of transverse plane movement occurs and very little other movement. However this study's data has found that the range of thoracic transverse and coronal plane movement during running is similar.

6.3.1.3 Trunk movement

The values for the trunk range of movement during running from this study were symmetrical and moderate in all of the three cardinal planes. The trunk coronal plane peak value was also moderate and symmetrical in healthy participants but asymmetrical in professional football players. The values for the trunk sagittal plane range of movement from this study; healthy participants; left 10.0^0 (SD=1.97), right 8.5^0 (SD=1.84), professional football players; left 9.7^0 (SD=2.6), right 8.9^0 (SD=3.13), Table 8.33, Table 8.36, and Table 5.2. There are fewer previously published running studies for kinematics when compared to walking. A previously published study by Schache was in agreement with this study and found; 9.6^0 (Schache et al., 2002b), Table 3.7.

The value for the trunk coronal plane range of movement from this study; healthy participants; left 9.9^0 (SD=3.00), right 10.2^0 (SD=2.54), professional football players; left 11.0^0 (SD=2.43), right 9.4^0 (SD=2.55), Table 8.39, Table 8.42 and Table 5.2. These values are similar to previously a published study; 9.1^0 (Schache et al., 2002b), Table 3.7. The values for the trunk coronal plane peak value from this study; healthy participants; left 8.6^0 (SD=2.48), right 8.1^0 (SD=2.27), professional football players; left 4.3^0 (SD=4.29), right 9.0^0 (SD=3.51), Table 8.45, Table 8.48, and Table 5.2; indicate that during running the peak value of the trunk is moderate and relatively symmetrical in healthy participants but asymmetrical in professional football players where a 50% lower value was found during left lower limb weight bearing.

The value for the trunk transverse plane range of movement from this study; healthy participants; left 20.4^0 (SD=5.01), right 20.3^0 (SD=3.84), professional football players; left 22.7^0 (SD=5.60), right 21.7^0 (SD=6.34), Table 8.51, Table 8.54, and Table 5.2. These values are similar to previously a published study, 23.8^0 (Schache et al., 2002b), Table 3.7. There was only one previously published paper for the trunk kinematics of running, and the values reported were limited to the sagittal and transverse planes (Schache et al., 2002b). Hence there are no previously published values for the trunk coronal plane movement during running. The lower trunk coronal plane peak value found during left lower limb weight bearing in professional football players illustrates a neuromuscular control difference between the groups, may cause professional football players to have sub-optimal load transfer (Lee, 2007) and be a potential explanation of the professional football player's increased incidence of spinal related injuries (Merron et al., 2006).

6.3.1.4 Pelvis movement

The values for the pelvis range of movement during walking from this study were symmetrical and moderate in all of the three cardinal planes. However pelvis coronal plane peak value was large and symmetrical. The values for the sagittal plane pelvis range of movement from this study; healthy participants; left 7.5^0 (SD=1.75), right 7.4^0 (SD=2.18), professional football players; left 8.1^0 (SD=1.96), right 6.7^0 (SD=1.82), Table 8.57, Table 8.60, and Table 5.2. These values are in agreement with previously published studies; 5^0 (Novacheck, 1998), 7^0 (Schache et al., 2001), 7.4^0 (Franz et al., 2009), 7.6^0 (Schache et al., 2002a), and 8.6^0 (Schache et al., 2002b), Table 3.8.

The value for the pelvis coronal plane range of movement from this study; healthy participants; left 5.5^0 (SD=1.01), right 6.5^0 (SD=1.50), professional football players; left 6.4^0 (SD=1.30), right 5.9^0 (SD=1.64), Table 8.63, Table 8.66, and Table 5.2. These values are similar to one previously published study; 6^0 (Novacheck, 1998), Table 3.8. Two higher values for the pelvis coronal plane range of movement have been found; 10.6^0 (Schache et al., 2002a), and

14^0 (Schache et al., 2001). The use of wands and markers in these studies offers a potential explanation for this difference between values (Wren et al., 2008). The value for the pelvis coronal plane peak value in this study of; healthy participants; left 16.6^0 (SD=5.26), right 17.0^0 (SD=5.88), professional football players; left 16.5^0 (SD=3.82), right 16.2^0 (SD=4.25), Table 8.69, Table 8.72, and Table 5.2. A symmetrical pelvis coronal plane peak value is also seen during walking, suggesting that the movement pattern observed during walking manifests during running also. There are few previously published studies for this parameter, but one that is available is in agreement with these values; 13.6^0 (Schache et al., 2001), Table 3.8. Another paper by Schache found a lower value; 10.6^0 (Schache et al., 2002a). Lumbo-Pelvic and Hip kinematics during treadmill running when compared to running on the ground have been found to be different (Schache et al., 2001). Another previous literature review (Novacheck, 1998) had also stated a lower value, 5^0 (Novacheck, 1998), but both the source and methodology of the data is not stated within the paper.

The value for the pelvis transverse plane range of movement from this study; healthy participants; left 4.3^0 (SD=3.05), right 5.1^0 (SD=2.50), professional football players; left 5.6^0 (SD=3.10), right 6.0^0 (SD=2.96), Table 8.75, Table 8.78, and Table 5.2. These values are divergent with previous studies; a potential explanation is due to methodological differences between the studies. Two higher values have been found; 13.9^0 (SD=5.2) (Schache et al., 2002a), and 14^0 (Schache et al., 2001), Table 3.8. A potential explanation for this is that these studies used a combination of wands and markers but this study used skin markers (Wren et al., 2008). Another study found; 10^0 (Novacheck, 1998). But this study was a literature review and both the source and methodology of the data collection is not stated.

There are fewer papers for the kinematics of the pelvis during running when compared to the number of papers for walking. Those papers that exist are in agreement with this study's values for the sagittal plane but in the coronal and transverse planes the values are divergent. These discrepancies maybe explained by differences in methods between the studies, usually how the markers were applied. The closed chain event of running, where load transfer occurs, is shorter than during walking. The kinematics of the pelvis are currently thought to be important during load transfer (Lee, 2007) hence it maybe suggested that optimal pelvic movement is more important during running than walking. Hence by increasing clinical understanding of pelvic kinematics clinicians may implement evidence based examinations for participants who present with sub-optimal load transfer during running.

6.3.1.5 Hip movement

The values for the hip range of movement during running from this study were symmetrical and very large in all of the three cardinal planes. However hip coronal plane peak value was large and asymmetrical. The values for the hip sagittal plane range of movement from this study; healthy participants; left 37.4^0 (SD=5.12), right 36.5^0 (SD=4.23), professional football players; left 34.7^0 (SD=7.66), right 35.5^0 (SD=6.00), Table 8.81, Table 8.84, and Table 5.2. All of the previous studies found higher values for hip sagittal plane range of movement; 50^0 (Franz et al., 2009), 55^0 and 68.2^0 (Schache et al., 2001), Table 3.9. The participants in this thesis's study were asked to "jog as if warming up". The hip sagittal plane range of movement has been found to increase consistently with faster running (Novacheck, 1998; Schache et al., 1999). Therefore this increased range of movement may simply be due to faster running speeds in these other studies.

The value for the hip coronal plane range of movement from this study from this study; healthy participants; left 10.3^0 (SD=2.51), right 10.8^0 (SD=2.78), professional football players; left 9.1^0 (SD=2.99), right 11.1^0 (SD=3.75), Table 8.87, Table 8.90, and Table 5.2. These values are similar to a previously published study; 14^0 (Novacheck, 1998), Table 3.9. A previously published study found a greater hip coronal plane range of movement value; 26^0 (Schache et al., 2001). A potential explanation for this is that this study used a combination of wands and markers but this thesis's study used skin markers. The value for the hip coronal plane peak value in this study of; healthy participants; left 6.5^0 (SD=2.69), right 10.7^0 (SD=2.18), professional football players; left 12.6^0 (SD=4.10), right 0.5^0 (SD=5.45), Table 8.93, Table 8.96, and Table 5.2; indicate that during running the coronal plane peak value of the hip is large and very asymmetrical for both of the groups, particularly the professional football players. An asymmetry of hip coronal plane peak value is also seen during walking, suggesting that the movement pattern observed during walking manifests during running also. These values are in agreement with three previously published studies; 7^0 (Novacheck, 1998), 9.07^0 (males) (whilst cutting) (Pollard et al., 2004), and 13^0 (Schache et al., 2001), Table 3.9.

The value for the hip transverse plane range of movement from this study; healthy participants; left 8.4^0 (SD=3.22), right 9.9^0 (SD=4.44), professional football players; left 10.5^0 (SD=4.97), right 10.1^0 (SD=2.76), Table 8.99, Table 8.102, and Table 5.2. These values are in agreement with a previously published study; 7^0 (Novacheck, 1998), Table 3.9. A higher value for the hip transverse plane range of movement has been found; 31.1^0 (SD=5.2) (Schache et al., 2001). A potential explanation for this is that this study used a combination of wands and markers but this thesis's study used skin markers. The movement of the hip and pelvis during running are currently thought to be synchronous (Richards, 2008). When participants present with hip dysfunction, the clinician needs to evaluate if the hip or pelvis is generating the problem (Richards, 2008; Sahrmann, 1988; Van Dillen et al., 2009). Hence increasing the evidence base and clinical understanding of the hip kinematics during running may aid this evaluation process. In order to help clinician's implement this study's Lumbo-Pelvic and Hip kinematic values into clinical practice a summary figure is presented, Appendix 8.

6.3.1.6 Clinical relevance – observation of running in clinical practice

It has been previously discussed that movement below 5^0 is not perceivable by the human eye in the clinical environment. This has been termed the "level of observability." From this study's range of movement data; all of the values lie above this 5^0 threshold. The peak value data established that all of the regions coronal plane peak value also lay above the 5^0 threshold. Hence when observing a patient running there should be observable movement of all of these regions in all of the planes. Conversely; when a clinician observes a patient running if they are not able to see any movement of these regions in any of these planes they should interpret this as an abnormal gait pattern. This may indicate, pain, pathology or the need for treatment, Figure 6.2.

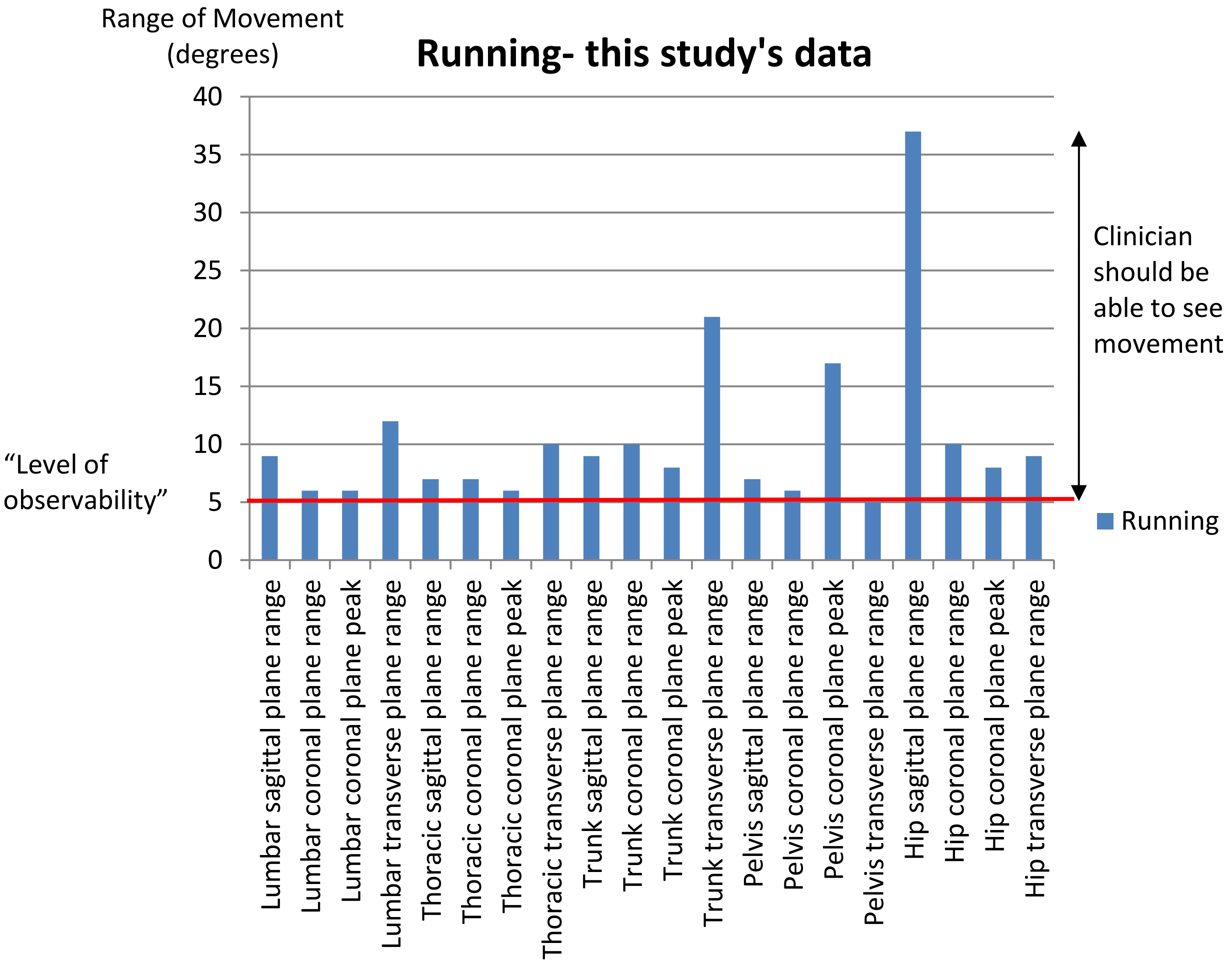


Figure 6.2 Clinically perceivable in unperceivable components of running gait

6.3.1.7 Assessment of walking and running summary

The speeds required during running are greater than walking and therefore make the clinical examination of running more difficult. However the data from this study has found that the Lumbo-Pelvic and Hip kinematics of walking are not significantly different when compared to running in the lumbar spine, trunk and pelvis. Significant differences were seen though at the thoracic spine in the coronal and transverse planes and at the hip in all three planes, Table 6.1.

Therefore to make the examination process easier, clinicians may wish to use the ranges of movement observed during walking at the lumbar spine, trunk and pelvis as surrogate measures of running. Clinicians will still need to observe the thoracic spine and hip during running, however these are amongst the larger movements found during gait and hence are relatively easy to observe. Alternatively clinicians could use a clinical test to examine the thoracic spine and hip components of running. This study found that the Single Leg Squat was an appropriate measure for both the thoracic spine transverse plane movement and for the hip coronal plane movement during running, Figure 5.2. Hence clinicians may wish to use the Single Leg Squat as a surrogate measure of the thoracic spine and hip movement during running and not attempt to observe these regions during the running cycle. A limitation of using the Single Leg Squat is that it is not an appropriate test for examining the thoracic spine in the sagittal or coronal planes or for the hip in the sagittal or transverse planes. Interestingly none of the other clinical tests studied were appropriate tests for these components of running, Figure 5.2.

Walking compared to running range of movement			Sig.[a]
Lumbar	Left	Sagittal	0.000
Lumbar	Right	Sagittal	0.000
Lumbar	Left	Coronal	0.040
Lumbar	Right	Coronal	0.062
Lumbar	Left	Transverse	0.000
Lumbar	Right	Transverse	0.000
Thoracic	Left	Sagittal	0.002
Thoracic	Right	Sagittal	0.000
Thoracic	Left	Coronal	0.135
Thoracic	Right	Coronal	0.290
Thoracic	Left	Transverse	0.945
Thoracic	Right	Transverse	0.876
Trunk	Left	Sagittal	0.000
Trunk	Right	Sagittal	0.000
Trunk	Left	Coronal	0.249
Trunk	Right	Coronal	0.044
Trunk	Left	Transverse	0.019
Trunk	Right	Transverse	0.029
Pelvis	Left	Sagittal	0.015
Pelvis	Right	Sagittal	0.268
Pelvis	Left	Coronal	0.000
Pelvis	Right	Coronal	0.000
Pelvis	Left	Transverse	0.000
Pelvis	Right	Transverse	0.000
Hip	Left	Sagittal	0.131
Hip	Right	Sagittal	0.320
Hip	Left	Coronal	0.799
Hip	Right	Coronal	0.517
Hip	Left	Transverse	0.295
Hip	Right	Transverse	0.696

Key	
Significant differences between dependent variables ($p<0.05$) i.e these parameters are not similar to running	(red)
No significant differences between dependent variables ($p>0.05$) i.e these parameters are similar to running	(green)

Table 6.1 Walking compared to running Lumbo-Pelvic and Hip range of movement

6.3.1.8 Running compared to clinical tests

When comparing the sagittal, coronal and transverse plane range of movement values of the lumbar spine and trunk for running to those of the clinical tests there were statistically significant differences for both lower limbs for all of the clinical tests, Figure 5.2. When comparing the thoracic spine range of movement values of running to those of the clinical tests there were statistically significant differences for both lower limbs in the sagittal and coronal planes, but no statistically significant differences for both lower limbs in the transverse plane for the Single Leg Squat, Figure 5.2. When comparing the sagittal plane pelvis range of movement values of running to those of the clinical tests there were statistically significant differences for both lower limbs for the Trendelenburg Test and Corkscrew Test, in the coronal plane for the Trendelenburg Test and Single Leg Squat, and in the transverse plane for the Corkscrew Test, Figure 5.2. When comparing the hip sagittal plane, and transverse plane, range of movement values of running to those of the clinical tests there were statistically significant differences for both lower limbs for all of the clinical tests. However when comparing the coronal plane hip range of movement values of running to those of the clinical tests there were statistically significant differences for both lower limbs for the Trendelenburg Test and Corkscrew Test, Figure 5.2.

The clinical importance of these inter-comparisons is that when examining the components of running gait in the clinical environment the Single Leg Squat was found to be the most useful of the tests studied. However it was an appropriate measure for only 4 of the 20 parameters. The sagittal plane range of movement was the worst represented by the tests as only the Single Leg Squat was found to be an appropriate measure of pelvis range of movement. The coronal plane was represented by the Single Leg Squat at the pelvis and Corkscrew Test at the hip. The transverse plane was the best represented but even here only by the Single Leg Squat at the thoracic spine, and Trendelenburg Test or Single Leg Squat in the pelvis. Of note is that none of the tests were an appropriate measure of trunk or lumbar range of movement in any of the planes during running. It is therefore suggested that if a clinician wishes to examine trunk or lumbar range of movement of running an alternative test should be used. In order to help clinician's implement this study's comparison of running to the clinical tests a summary figure is presented, Appendix 9.

6.4 Differences between healthy participants and professional football players

Inter-comparison between the two groups for the trunk range of movement demonstrated a statistically significant difference between the groups during both left and right lower limb weight bearing in the sagittal plane, left (mean difference = -2.7^0, p=0.000), right (mean difference = -2.4^0, p=0.000), in the coronal plane; left lower limb weight bearing; (mean difference = -1.4^0, p=0.002), and in the transverse plane during right lower limb weight bearing (mean difference= 2.6^0, p=0.021), Table 8.56. Inter-comparison between the two groups for the pelvis range of movement demonstrated a statistically significant difference between the groups in the sagittal plane during left lower limb weight bearing, (mean difference = -1.8^0, p=0.000), and in the coronal during both lower limb weight bearing, left (mean difference = -1.8^0, p=0.006), and right (mean difference= -1.4^0, p=0.026), and in the transverse plane, during left lower limb weight bearing (mean difference= 9.1^0, p= 0.000), and right lower limb weight bearing; (mean difference= 10.2^0, p= 0.000), Table 8.80. Inter-comparison between the two groups for the hip range of movement demonstrated a statistically significant difference between the groups during both left lower limb weight bearing in the sagittal plane, left lower limb weight bearing (mean difference = -8.4^0, p=0.000), and right lower limb weight bearing (mean difference= -7.5^0, p= 0.000), Table 8.86. Conversely there were no statistically significant differences in the coronal, and transverse planes, Figure 6.3

Trunk			
Side	Sagittal	Coronal	Transverse
Left	Different	Different	Similar
Right	Different	Similar	Different
Pelvis			
Left	Different	Different	Different
Right	Similar	Different	Different
Hip			
Left	Different	Similar	Similar
Right	Different	Similar	Similar

Key	
Significant differences between dependent variables (p<0.05) i.e these parameters are different when comparing the groups	
No significant differences between dependent variables (p>0.05) i.e these parameters are similar when comparing the groups	

Figure 6.3 Differences in kinematics between healthy participants and professional football players

6.5 Clinical relevance – rehabilitation

This inter-comparison illustrates that the healthy participants exhibit a different neuromuscular control pattern when compared to the professional football players. These differences were most frequently found in the pelvis, where 5 of the 6 parameters were found to be significantly different, but differences were also found in the left hip and trunk. Pelvic movements, particularly in the transverse and coronal planes, are thought to be important determinants of gait where they help to flatten the trajectory of the body centre of mass during stance phase, reducing the vertical translation of the body during walking (Rose et al., 2006). Hence, it maybe suggested that the pelvis is acting to try to optimize the professional football player’s movement pattern by a neuromuscular compensation at the pelvis for changes in the left hip and trunk. If these differences in the neuromuscular control pattern existed before starting their careers as professional football players, or is an effect of training whilst being one, is beyond the scope of this thesis, but maybe the subject of a longitudinal study of this population. Another potential explanation may be that this difference in pattern represents an inefficient muscular contraction, namely a structural cause rather than functional cause, within the oblique sling (Liebenson, 2004; Myers, 1997). However the path of the difference in control pattern is not strictly oblique and it is improbable that all of the professional football players had a similar structural dysfunction.

The concept of abnormal neuromuscular control in one part of the Lumbo-Pelvic and Hip region causing symptoms in another is well established (Scheets, Sahrmann, & Norton, 2007). Abnormal hip sagittal plane movement has been associated with anterior hip pain (Lewis et al., 2010), and abnormal hip transverse plane movement with both low back pain (Ellison et al., 1990; Gombatto, Collins, Sahrmann, Engsberg, & Van Dillen, 2006), and pelvic pain (Zierenberg, Sahrmann, & Prather, 2010). Therefore the difference found in the neuromuscular control pattern in professional football players may help explain the incidence of lumbar spine (Ekstrand, Hagglund, & Walden, 2011; Hagglund et al., 2006; Hawkins et al., 2001; Merron et al., 2006), pelvis (Cunningham et al., 2007; Fon et al., 2000; Merron et al., 2006) and hip injuries (Drawer et al., 2001) within this population.

Prehab, therapeutic intervention before an injury starts, is common within professional football. In view of the abnormal neuromuscular pattern that was found in this study for the professional football players it maybe suggested that neuromuscular exercises to reverse this pattern could be useful within this population. In the professional football players the range of movement was greater in the trunk coronal plane during left lower limb weight bearing and transverse plane during right lower limb weight bearing. At the pelvis in the sagittal plane during left lower limb weight bearing, coronal plane during left and right lower limb weight bearing, and hip in the sagittal plane during left lower limb weight bearing. The range of movement was less in the trunk sagittal plane and pelvis in the transverse plane during both lower limb weight bearing. A suggested neuromuscular exercise regime may be;

Balance stabilizing exercises on lower limb;

- Trunk coronal plane theraband (left)
- Trunk transverse plane theraband (right)
- Pelvis sagittal plane (left)
- Pelvis coronal plane (left and right)
- Hip sagittal plane (left)

Mobilising exercises on lower limb;

- Trunk sagittal plane toe touches and leaning backwards (left and right)
- Pelvis transverse plane “salsa style” twists (left and right)

6.6 Trendelenburg Test

6.6.1 Normative data and its relationship to current evidence

The Trendelenburg Test is currently interpreted by the orientation of the pelvis compared to the laboratory (pelvic obliquity) (Hardcastle et al., 1985), therefore the pelvis coronal plane peak value is currently a value normally quoted within research (Asayama et al., 2002; Westhoff et al., 2005) and a clinically important parameter (Hardcastle et al., 1985). The pelvis coronal plane peak values found in this study were large and symmetrical for the Trendelenburg Test; healthy participants; left 11.3^0 (SD= 4.81), right 10.8^0 (SD= 4.96), professional football players; left 10.7^0 (SD= 9.91), right 12.1^0 (SD= 8.53), Table 5.3. The healthy participants exhibited a slightly greater displacement during left lower limb weight bearing when compared to right lower limb weight bearing, but the professional football players had a lesser displacement occurring during left lower limb weight bearing when compared to right lower limb weight bearing. The current evidence states that the Trendelenburg Test is positive if the pelvis coronal plane peak value is between 2^0 (Asayama et al., 2002) and 4^0 (Westhoff et al., 2005), hence current evidence advocates lower values for the interpretation of the test. This disagreement may be explained by the population studied; Asayama's participants were post Total Hip Arthroplasty, Weshoff's study used participants with Legg Calve Perthe's disease, but this thesis's study was of healthy participants and professional football players. It could therefore be suggested that the Trendelenburg Test should interpreted as positive if the participant is unable to achieve a value of 10^0 or more for the pelvis coronal plane peak value (pelvic obliquity) in a healthy participant or professional football player. However if the angle that needs to be achieved is amended to fit within 1 standard deviation then the pelvis coronal plane peak value would become 6^0 for healthy participants and 4^0 for professional football players and hence would be in keeping with the previous studies.

6.6.2 Clinical relevance – potential expansion of interpretation criteria and observability of the Trendelenburg Test in clinical practice

The Hardcastle and Nade method for performing the Trendelenburg Test does not describe the required position or movements of the other regions during the test. There have been no previous studies that have reported the trunk, lumbar, thoracic, pelvis or hip range of movement in the sagittal, coronal or transverse planes during the Trendelenburg Test. However it is a common clinical assumption that the participant should maintain an upright posture and minimal movement in all planes during the test. This study found the trunk, lumbar, thoracic, pelvis and hip ranges of movement to be small and symmetrical in the three cardinal planes of movement during the Trendelenburg Test, Table 5.3. All of the ranges of movement found in this study were below the "level of observability" but the pelvis coronal plane peak values were above it, hence when performing the Trendelenburg Test there should be no observable movement of the participant except at the pelvis in the coronal plane. Consequently during the Trendelenburg Test the participant should appear to be in a position of pelvic obliquity but not moving, Figure 6.4.

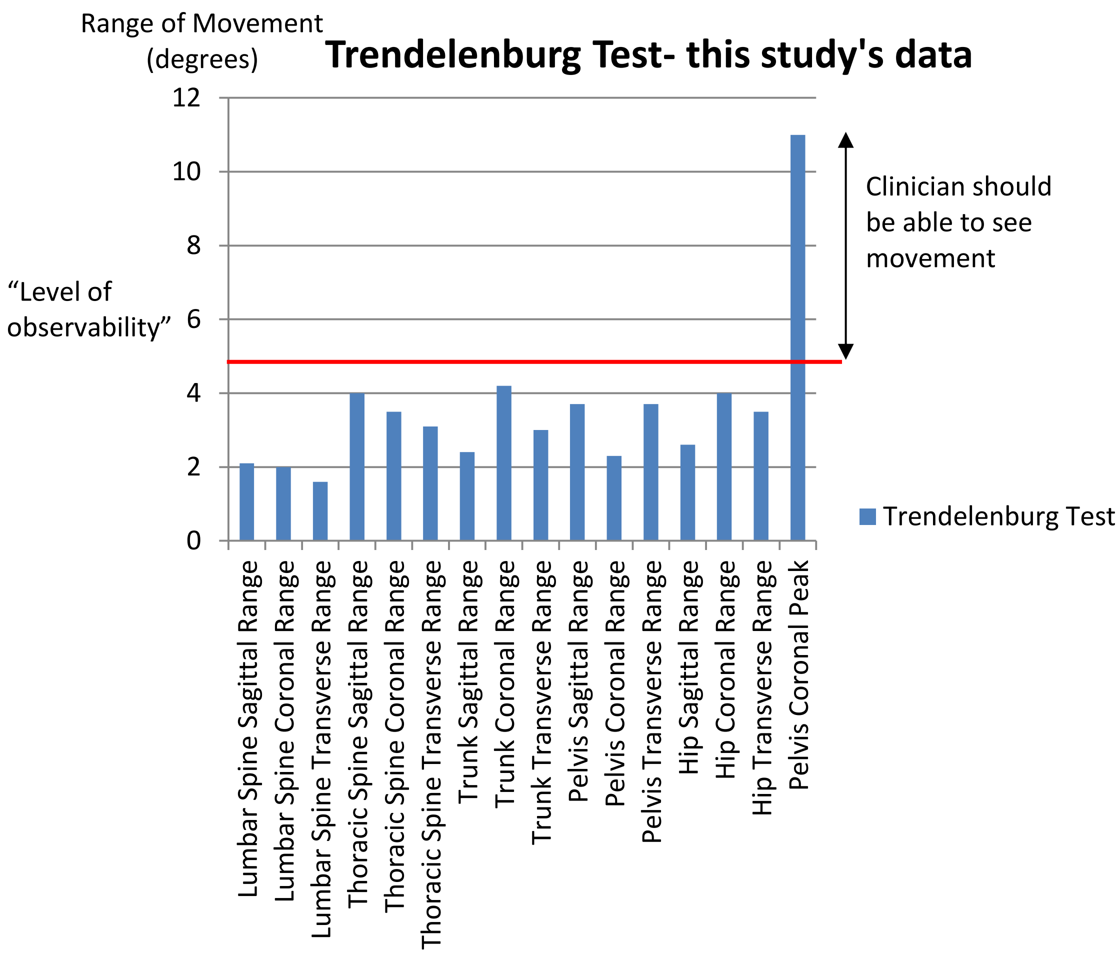


Figure 6.4 Clinically perceivable in unperceivable parameters of Trendelenburg Test

6.6.3 The relationship between walking, running and the Trendelenburg Test

When considering examining walking the Trendelenburg Test was found to be an appropriate test for examining the trunk, lumbar and thoracic sagittal plane ranges of movement, the pelvis coronal plane range of movement and both the lumbar and pelvis coronal plane peak value components, Figure 5.1. For running the Trendelenburg Test was also found to be an appropriate test for examining the pelvis transverse plane range of movement, and both the lumbar and thoracic coronal plane peak value components, but of note it was not an appropriate test for examining pelvis coronal plane peak value, Figure 5.2.Trendelenburg originally developed his test to examine the pelvis coronal plane peak value during walking, however in clinical practice it is currently used to also examine the pelvis during running. Of clinical importance is that this thesis's study has found that the Trendelenburg Test is appropriate for examining the walking pelvis coronal plane peak value, as it was intended for, but not running as clinicians have subsequently used it for.

Previous studies have established an increased incidence of trunk injuries amongst young professional football players when compared with the senior squad (Merron et al., 2006) and highlighted a consequent need to develop diagnostic algorithms for this particular group of players (Mayer et al., 2012). This study has found that the Trendelenburg Test is an appropriate test to examine the trunk sagittal plane range of movement component of walking in professional football players and hence the Trendelenburg Test is an appropriate test for both clinical use and development of a diagnostic algorithm for the trunk component of walking in the sagittal plane for this group.

Professional football players exhibit a low rate of injuries to the pelvis (Merron et al., 2006). However, when present, pelvic injuries are thought to be difficult to treat, create an economic and personal burden to the player and result in chronic disability and early retirement (Cunningham et al., 2007; Fon et al., 2000). This study has found that the Trendelenburg Test is an appropriate test to examine the pelvis coronal plane peak value components of walking in professional football players. Therefore using the Trendelenburg Test as part of the examination and treatment of the pelvis in the coronal plane may increase treatment efficacy and reduce chronic disability within professional football players.

6.6.4 Implications for clinical practice

Subsequent to this study's data; for the Trendelenburg Test to be normal the pelvis should achieve a position of 10^0 of pelvic obliquity and there should be no observable movement of the participant in the each of the three cardinal planes whilst maintaining this position. The Trendelenburg Test is appropriate for examining some specific components of walking and running. For walking these components are; trunk, lumbar and thoracic sagittal plane ranges of movement, and both the lumbar and pelvis coronal plane peak values. For running; the pelvis transverse plane range of movement, and both the lumbar and thoracic coronal plane peak values.

6.7 Single Leg Squat

6.7.1 Normative data and its relationship to current evidence

The Single Leg Squat is currently interpreted by criteria including movement at the hip. Participants exhibiting a hip sagittal range of movement greater than 65^0 and coronal plane range of movement of less than 10^0 are given a score of excellent (Livengood et al., 2004). Therefore the hip sagittal and coronal plane ranges of movement value are currently values that are quoted within the literature and clinically important for interpretation of the test (DiMattia et al., 2005). The hip sagittal plane ranges of movement found in this study were large and symmetrical for the Single Leg Squat; healthy participants were; left 44.2^0 (SD=13.70), right 41.7^0 (SD=10.89), professional football players; left 61.0^0 (SD=11.58), right 55.8^0 (SD=13.42), Table 5.4. Hence the limited number of previously published papers available have advocated higher values for hip sagittal range of movement for the interpretation of the test than found in this thesis's study. However there are no previously published kinematic studies for the Single Leg Squat. The values published by DiMattia and Livengood have been suggested values from clinical experience. It could therefore be recommended that the Single Leg Squat should interpreted as positive if a healthy participant is unable to achieve a hip sagittal plane ranges of movement value of 43^0 and professional football player of 58^0. However if the angle that needs to be achieved is amended to fit within 1 standard deviation then the hip sagittal plane ranges of movement would become 56^0 for healthy participants and 69^0 for professional football players and hence would be in keeping with the previous studies for the professional football players. For the hip coronal plane range of movement found in this study were large and symmetrical for the Single Leg Squat; healthy participants; left 9.1^0 (SD=5.76), right 9.0^0 (SD=4.55), professional football players; left 8.5^0 (SD=5.59), right 9.7^0 (SD=4.47) and in keeping with Dimattia and Livengood's suggested value of 10^0.

6.7.2 Clinical relevance – potential expansion of interpretation criteria and observability of the Single Leg Squat in clinical practice

The Livengood method for performing the Single Leg Squat does not describe the required position or movements of the other regions during the test. There have been no previous studies that have reported the trunk, lumbar, thoracic, or pelvis range of movement in the sagittal, coronal or transverse planes during the Single Leg Squat. However it is a common clinical assumption that all of the participant should maintain an upright posture and exhibit minimal movement in the three cardinal planes. This study found the trunk, lumbar, thoracic, and pelvis ranges of movement to be moderate and symmetrical in the three cardinal planes of movement during the Single Leg Squat, Table 5.4.

The ranges of movement found in this study were near or above the "level of observability" for all the regions with very large ranges of movement occurring at the hip in the sagittal plane, hence when using the Single Leg Squat there should be observable movement of the participant in all of the regions particularly at the hip in the sagittal plane, Figure 6.5.

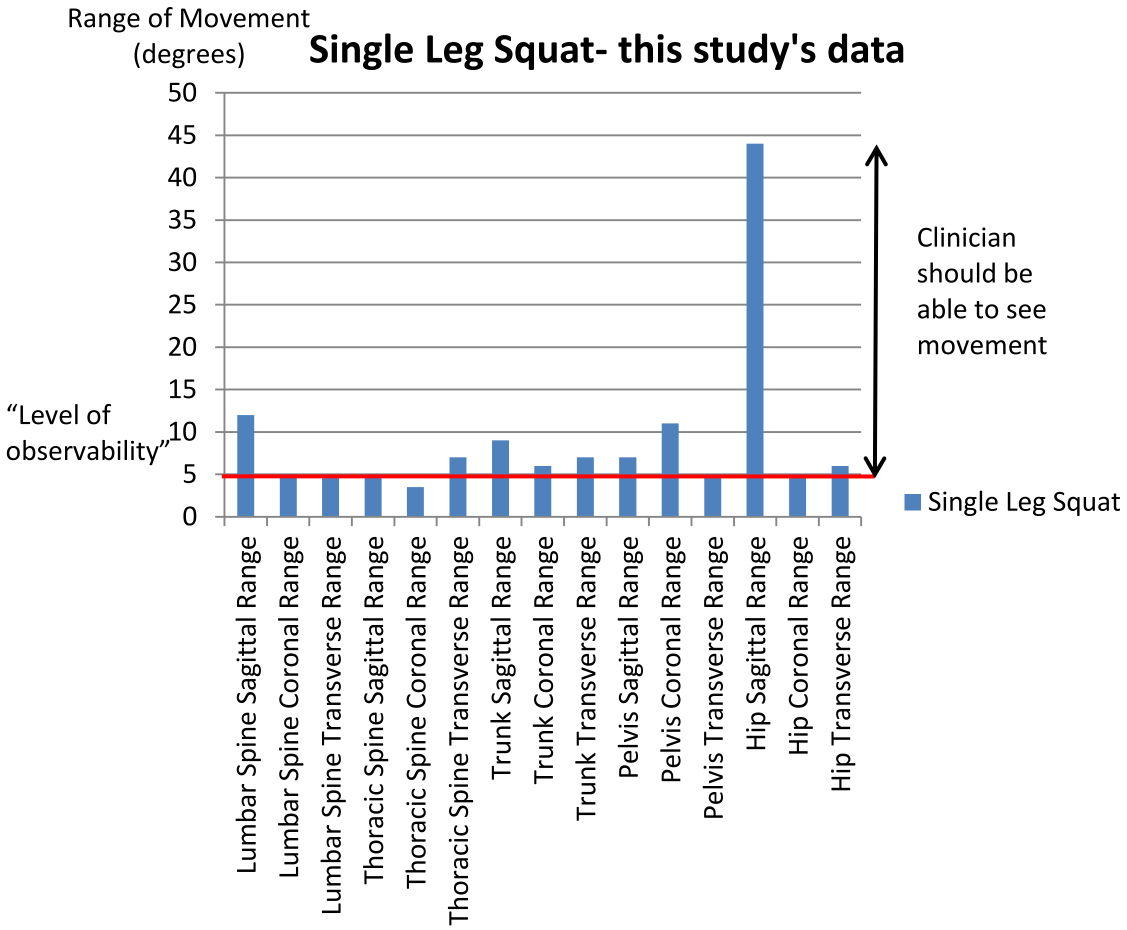


Figure 6.5 Clinically perceivable in unperceivable parameters of Single Leg Squat

6.7.3 The relationship between walking, running and the Single Leg Squat

When considering examining walking the Single Leg Squat was found to be an appropriate test for examining the, lumbar coronal plane, thoracic sagittal and transverse plane, and hip coronal plane ranges of movement, also both the lumbar and hip coronal plane peak value components. For running the Single Leg Squat was also found to be an appropriate test for examining the thoracic transverse plane, pelvis sagittal and transverse, and hip coronal range of movement, Figure 5.1. Therefore this study has found that the Single Leg Squat is an appropriate test to examine the hip, for coronal plane range and peak value of walking and peak value of running. This is clinically useful as hip joint symptoms are a substantial problem for professional football players. The hip exhibits the highest rate of arthritis per 10000 hours and joint pain score (static activities, 0.06, dynamic activities 0.09) (Drawer et al., 2001).

Consequently the Single Leg Squat is an appropriate test for both clinical use and development of a diagnostic algorithm for the hip component of walking and running in the coronal plane for professional football players. This may help reduce the high rates of hip arthritis and joint pain found within this population. However its utility is limited to the coronal plane as it was not found to be a good representation of walking or running for the hip in the sagittal or transverse planes.

6.7.4 Implications for clinical practice

Subsequent to this study's data; for the Single Leg Squat to be normal the hip should move through 43^0 (healthy participants), and 58^0 (professional football players) in the sagittal plane, whilst allowing a small amount of movement in the trunk and pelvis in all the other planes, during a 6 second test movement. The Single Leg Squat is appropriate for examining some specific components of walking and running. For walking these components are; lumbar coronal plane, thoracic sagittal and transverse plane, and hip coronal plane ranges of movement, also both the lumbar and hip coronal plane peak value components. For running; the thoracic transverse plane, pelvis sagittal and transverse, and hip coronal range of movement.

6.8 Corkscrew Test

6.8.1 Normative data and its relationship to current evidence

The Trendelenburg Test and Single Leg Squat are both commonly used clinical tests in the examination of gait (Bailey et al., 2011; Bailey et al., 2009). Both tests are performed in the position of single limb stance. They are thought to examine the neuromuscular control of the pelvis. The Trendelenburg Test requires movement of the pelvis in the coronal plane; the Single Leg Squat requires movement of the hip in the sagittal plane. Despite the movement of the hip in the transverse plane being relatively large; walking 15^0 (Richards, 2008; Rose et al., 2006) and 40^0 (Kadaba et al., 1989), running 7^0 (Novacheck, 1998) and 16^0 (Schache et al.,

2001) there is currently no existing test for neuromuscular control of the hip in the transverse plane. Based on these data it was presumed a priori that during the Corkscrew Test the hip would rotate through 40^0 in the transverse plane whilst maintaining a similar 10^0 hip coronal plane range of movement to that required during the Single Leg Squat (Livengood et al., 2004).

The hip transverse plane range of movement values found in this study were large and symmetrical for the Corkscrew Test; healthy participants; left 8.3^0 (SD=3.50), right 6.4^0 (SD=3.30), Table 8.99, Table 8.102, and Table 5.5. However the values found in this thesis study were smaller than those predicted a priori. Most of the transverse plane movement occurred in the trunk; left 26.1^0 (SD=17.40), right 28.8^0 (SD=16.00), Table 5.5, and therefore the Corkscrew Test appears to be a greater challenge of trunk rather than hip transverse plane movement. In contrast the hip coronal plane range of movement values found in this study were moderate and symmetrical for the Corkscrew Test; healthy participants; left 5.7^0 (SD=3.26), right 5.7^0 (SD=3.17), Table 8.87, Table 8.90, and Table 5.5, and smaller than those predicted a priori.

It could therefore be suggested that the Corkscrew Test should interpreted as positive if the participant is unable to achieve a value of 6^0 for the hip transverse plane range of movement in a healthy participant. However if the angle that needs to be achieved is amended to fit within 1 standard deviation then the hip transverse plane range of movement would become 9^0 for healthy participants and hence would be in keeping with the values predicted a priori.

6.8.2 Clinical relevance – potential expansion of interpretation criteria and observability of the Corkscrew Test in clinical practice

The current method for performing the Corkscrew Test does not describe the required position or movements of the other regions during the test. There have been no previous studies that have reported the trunk, lumbar, thoracic, pelvis or hip range of movement in the sagittal, coronal or transverse planes during the Corkscrew Test. However, as the test is becoming more commonly used in clinical practice it is being assumed by clinicians that participants should maintain an upright posture during the test. This study found the sagittal and coronal plane ranges of movement to be symmetrical and either moderate or small for all of the regions during the Corkscrew Test, Table 5.5. The ranges of movement found in this study were close the "level of observability" but the trunk and thoracic spine transverse plane range of movement values were above it, hence when using the Corkscrew Test there should be some observable movement of the participant in each of the regions and cardinal planes with a large amount of movement being observed in the trunk and thoracic spine in the transverse plane, Figure 6.6.

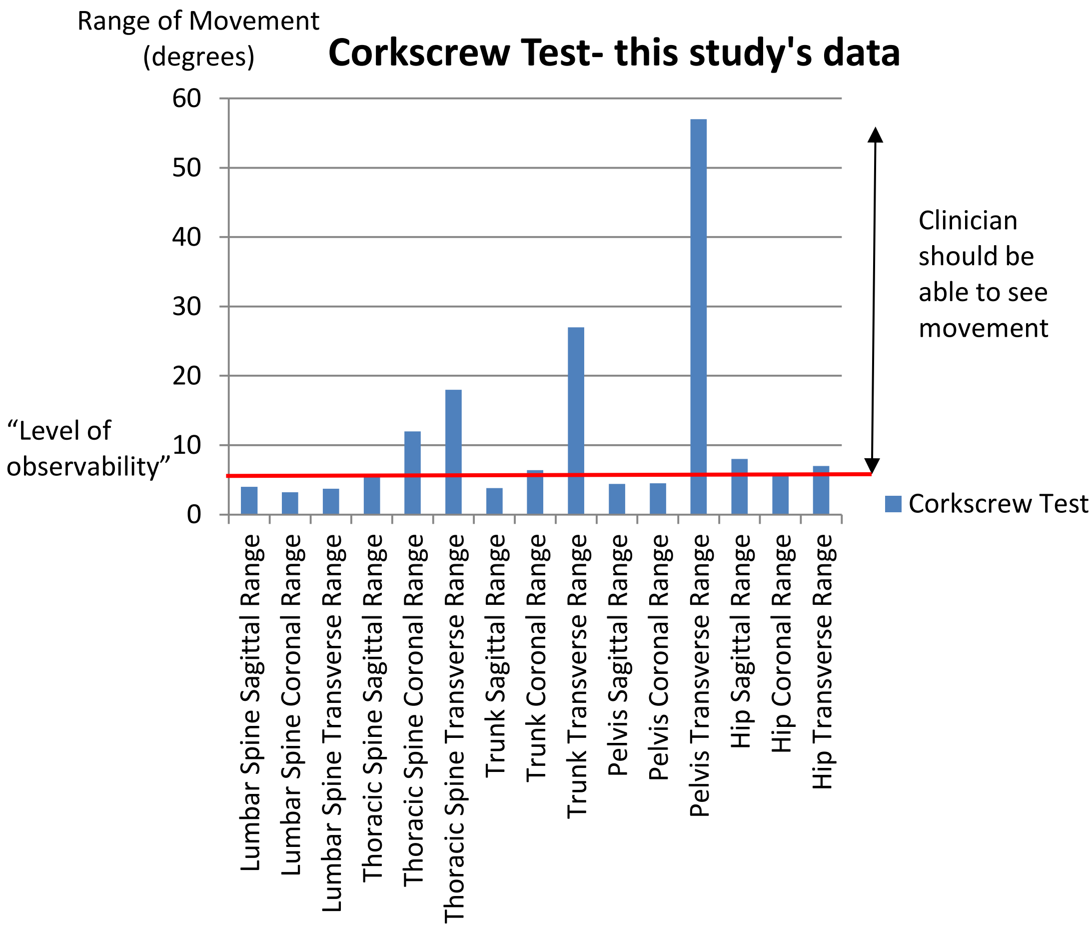


Figure 6.6 Clinically perceivable in unperceivable parameters of Corkscrew Test

6.8.3 The relationship between walking, running and the Corkscrew Test

When considering examining walking the Corkscrew Test was found to be an appropriate test for examining the trunk and lumbar sagittal plane ranges of movement, and the lumbar and thoracic coronal plane peak values. For running the Corkscrew Test was also found to be an appropriate test for examining the pelvis coronal plane range of movement, and both the thoracic and pelvis coronal plane peak value components, Figure 5.1.

The clinical utility of this is that if a clinician uses both the Corkscrew Test and the Single Leg Squat in the examination then both the sagittal and coronal plane range of movement for the thoracic and lumbar spine have been completed relevant to walking, Figure 5.1. This will enable the clinician to more fully understand the movements of the lumbar and thoracic spine during walking. Therefore the Corkscrew Test expands clinicians' understanding of the lumbar and thoracic spines during walking gained from the Single Leg Squat and may therefore lead to greater examination and treatment efficacy.

6.8.4 Implications for clinical practice

Subsequent to this study's data; for the Corkscrew Test to be normal the hip should move through 6^0 of rotation, and the trunk through 27^0 of rotation. There should be some observable movement of the participant in the each of the three cardinal planes whilst maintaining this position. The Corkscrew Test is appropriate for examining specific components of walking and running. For walking the Corkscrew Test was found to be an appropriate test for examining the trunk and lumbar sagittal plane ranges of movement, and the lumbar and thoracic coronal plane peak values. For running the Corkscrew Test was also found to be an appropriate test for examining the pelvis coronal plane range of movement, and both the thoracic and pelvis coronal plane peak value components. When the Corkscrew and Single Leg Squat Tests are used in combination the sagittal and coronal plane components of the lumbar and thoracic spine maybe more comprehensively examined relevant to walking.

6.8.5 Discussion summary

This study established Lumbo-Pelvic and Hip data that was similar to previous marker based studies. There is currently little evidence for the lumbar and thoracic spine movement occurring during walking and no data for the thoracic spine kinematics during running. The two segment spine model used in this thesis's study generated range of movement data for the lumbar and thoracic spine movements of walking and running. The movements occurring in the lumbar spine during walking were found to be similar to running but the thoracic spine movements were greater. The professional football player's movement patterns were significantly different to the healthy participants at the trunk, pelvis and hip. There were identifiable similarities between Lumbo-Pelvic and Hip kinematics during walking, running and the clinical tests for the groups. However these similarities were found to be task, region and plane specific. The Trendelenburg Test and Single Leg Squat were the most useful of the tests when examining gait.

6.9 Study strengths and limitations

A strength of this study is that it has been a kinematic study using the most up to date equipment in an advanced movement analysis laboratory. This has enabled it to be completed using techniques and technology that are currently considered to be the gold standard for research into movement analysis. The participants in this study were felt to be typical of their particular sub-group of the general population; however this also limits the results to these specific populations. The study was completed in a laboratory and not wearing shoes. Therefore this study has generated data that maybe applied within the clinic, but when considering the professional football players, the data may not be generalized to the playing field where individuals are usually standing on grass and wearing boots. This study used a methodology that was similar to other studies therefore the data generated was able to be compared to the current evidence base. The CAST model used within the study is a popular model with an existing current evidence base of its efficacy. The two additional clusters used in the healthy participants study however have not currently been validated. The data that has been generated within this thesis's study has underpinned areas of the existing evidence base and filled gaps for the kinematics of the Lumbo-Pelvic and Hip region where none previously existed.

7 Conclusion

It is acknowledged that the medical paradigm for the examination and classification of pain syndromes within the Lumbo-Pelvic and Hip region often fails to identify the dysfunctional structure and does not clearly identify appropriate non-surgical treatment. The clinical shift has therefore moved away from the medical diagnosis and towards a therapy based diagnostic system. A large amount of clinical time and research effort is being put into sub-grouping Lumbo-Pelvic and Hip dysfunction to create this system. The mechanism for sub-grouping participants is by completing a clinical examination using common clinical tests. However how these tests should be interpreted and if they yield information that assists in predicting function has not been established. The underpinning philosophy of this study was to determine if the clinical tests currently being used provide clinicians with the necessary information when considering problems associated with gait. In establishing this, better examination, sub-grouping, and selection of treatment may be implemented into clinical practice leading to improved clinical outcomes. The aim of this study was to investigate the validity of the Trendelenburg Test, Single Leg Squat and Corkscrew Test as measures of dynamic stability in healthy participants and professional football players during gait.

7.1 Examination of Lumbo-Pelvic Hip movement

When examining walking the clinician should be able to see movement in all of the regions and in each the three cardinal planes except at the lumbar spine; thoracic spine and trunk in the sagittal plane or lumbar spine and pelvis in the coronal plane. During running there should be observable movement in all the regions and planes. The faster speeds required during running make it difficult for clinicians to examine it. It is of clinical interest that the data from this study found that the Lumbo-Pelvic and Hip kinematics of walking are not significantly different to running in the lumbar spine, trunk and pelvis. Significant differences were only found at the thoracic spine in the coronal and transverse planes and at the hip in all three planes. Clinicians therefore may wish to use the ranges of movement observed during walking at the lumbar spine, trunk and pelvis as surrogate measures of running. Clinicians will still need to observe the thoracic spine and hip during the running cycle. Alternatively clinicians could use the Single Leg Squat to examine these regions.

For the Trendelenburg Test to be normal the pelvis should achieve 10^0 of pelvic obliquity and there should be no observable movement of the participant in the each of the three cardinal planes whilst maintaining this position. The Single Leg Squat should take 6 seconds to complete. During the test the hip should move 43^0 in the sagittal plane in healthy participants, and 58^0 in professional football players. A small amount of movement in the trunk and pelvis in all the other planes is normal. When examining the Corkscrew Test the hip should rotate through 6^0, and the trunk through 27^0. Some observable movement of the participant in each of the three cardinal planes whilst maintaining this position is normal.

7.2 Similarities between functional and clinical tests

When considering which clinical test to use to examine a patient's walking this study found the Trendelenburg Test to be the most useful test. It is an appropriate measure for the sagittal plane range of movement at the lumbar spine, thoracic spine, and trunk. Similarly when selecting a test to examine running the Single Leg Squat was found to be the most useful of the tests studied, however it was an appropriate measure for only 4 of the 20 parameters.

Two planes of movement were particularly poorly represented by the tests; the transverse plane range of movement during walking and sagittal during running. Interestingly the Single Leg Squat was found to be an appropriate measure of thoracic transverse plane range of movement during walking and pelvic sagittal plane range of movement during running. However the clinical tests were not appropriate for the other regions. Consequently if a clinician wishes to examine the transverse plane range of movement of walking or the sagittal plane range of movement for running it is suggested that an alternative test to those studied in this thesis should be used. Furthermore, it is of note that none of the tests were an appropriate measure of trunk or lumbar range of movement during running. It is therefore suggested that if a clinician wishes to examine the range of movement of either of these regions an alternative test should be used.

The clinical tests are appropriate measures of gait for specific regions and planes of movement. The Trendelenburg Test is appropriate for walking; trunk, lumbar and thoracic sagittal plane ranges of movement, pelvis coronal plane range of movement and both the lumbar and pelvis coronal plane peak values. For running; the pelvis transverse plane range of movement, and both the lumbar and thoracic coronal plane peak values. The Single Leg Squat is appropriate for examining walking; lumbar coronal plane, thoracic sagittal and transverse plane, and hip coronal plane ranges of movement, also both the lumbar and hip coronal plane peak value components. For running; the thoracic transverse plane, pelvis sagittal and transverse, and hip coronal range of movement. The Corkscrew Test is appropriate for examining walking; trunk and lumbar sagittal plane ranges of movement, and the lumbar and thoracic coronal plane peak values. For running the Corkscrew Test was also found to be an appropriate test for examining the pelvis coronal plane range of movement, and both the thoracic and pelvis coronal plane peak value components.

7.3 Differences between healthy participants and professional football players

This study found that the professional football player’s range of movement was greater in the trunk coronal plane during left lower limb weight bearing and transverse plane during right lower limb weight bearing. It was also greater at the pelvis in the sagittal plane during left lower limb weight bearing, coronal plane during left and right lower limb weight bearing, and hip in the sagittal plane during left lower limb weight bearing. The range of movement was less in the trunk sagittal plane and pelvis in the transverse plane during both lower limb weight bearing.

7.4 Clinical relevance of the tests when examining walking and running gait

The Trendelenburg Test was originally developed to examine pelvic obliquity during walking. However clinicians commonly use it to examine both walking and running. This study found it to be an appropriate test for examining the pelvic obliquity of walking, but not of running. Hence clinicians should not use it to examine this component of running. The results of this study suggest that when using the test to examine walking a higher level of pelvic obliquity is used. This study's recommendations for the interpretation of the Trendelenburg Test is as follows: The response is NORMAL (i.e. the test is "negative") if the pelvis on the non-stance can be elevated to 10^0, whilst maintaining a static posture of the trunk, pelvis and hip in all the other planes, for 30 seconds. The response is ABNORMAL (i.e. the test is "positive") if this cannot be done. Implementing this study's Trendelenburg Test data into clinical practice may help to improve evidence based examinations and consequently reduce chronic disability within professional football players.

The results of this study would suggest that the current method for interpreting the Single Leg Squat is developed further by reducing the hip sagittal plane range of movement required in healthy participants and increasing it for professional football players. This study's recommendations for the interpretation of the Single Leg Squat is as follows: The response is NORMAL (i.e. the test is "negative") if the hip on the stance side can be flexed in the sagittal plane to 43^0 in healthy participants and 58^0 in professional football players, whilst allowing a small amount of movement in the trunk and pelvis in all the other planes, during a 6 second test movement. The response is ABNORMAL (i.e. the test is "positive") if this cannot be done. The Single Leg Squat was found to be an appropriate test for both clinical use and the development of a diagnostic algorithm for the hip component of walking and running in the coronal plane for professional football players. This may help reduce the high rates of hip arthritis and joint pain found within this population. However its utility is limited to the coronal plane as it was not found to be a good representation of walking or running for the hip in the sagittal or transverse planes.

The Corkscrew test data from this study suggests that the test's method should include criteria for both trunk and hip transverse plane movement. This study's recommendations for the interpretation of the Corkscrew Test are as follows: Excellent; Hip rotation = 6^0, trunk rotation = 27^0, Good; any 2 of the above criteria met, Fair; any 1 of the above criteria met, Poor; None of the above criteria met or the athlete loses balance and falls. Some observable movement of the participant in the each of the three cardinal planes whilst maintaining this position is acceptable.

This study's results demonstrated that often one test in isolation will not fully examine a region or plane of gait. However by using the Corkscrew and Single Leg Squat Test in combination then the lumbar and thoracic spine, sagittal and coronal plane ranges of movement are fully examined for walking. Hence whilst one test in isolation is insufficient to fully examine gait, in combination the tests are able to comprehensively examine specific components of gait. This use of tests in combination may lead to greater examination and treatment efficacy of the lumbar injuries which have been found to be a considerable problem for professional football players. Consequently the clinical tests were found to be task, region and plane specific and clinically useful particularly when used in combination.

7.5 Key Clinical Message

Key Points	
	Normative Lumbo-Pelvic Hip movement data
•	For walking there should be observable movement of all the regions and in all of the three cardinal planes except at the lumbar spine; thoracic spine and trunk in the sagittal plane or lumbar spine and pelvis in the coronal plane. For running there should be observable movement of all the regions and in all of the three cardinal planes.
•	Observe the ranges of movement used during walking gait and use them as a surrogate measure of running except at the thoracic spine and hip. For these regions use the Single Leg Squat.
•	Trendelenburg Test = 10^0 of pelvic obliquity and no observable movement of the other regions in the three cardinal planes.
•	Single Leg Squat = hip moves 43^0 (healthy participants), and 58^0 (professional football players) in the sagittal plane, and a small movement of the other regions in the three cardinal planes.
•	Corkscrew Test = hip moves 6^0 of rotation, trunk 27^0 of rotation, and some observable movement of the other regions in the three cardinal planes.
	Similarities between functional and clinical tests
•	For walking the Trendelenburg Test was found to be the most useful test. For running the Single Leg Squat was found to be the most useful of the tests studied.
•	For walking the transverse plane was the worst represented by the tests and for running the sagittal plane. Clinicians should use alternative tests to examine these planes during walking and running.
•	None of the tests were appropriate measures of trunk or lumbar range of movement during running. Clinicians should use alternative tests to examine these regions during running.
	Differences between healthy participants and professional football players
•	In the professional football players the range of movement was greater in the trunk coronal plane during left lower limb weight bearing and transverse plane during right lower limb weight bearing.
•	At the pelvis in the sagittal plane during left lower limb weight bearing, coronal plane during left and right lower limb weight bearing, and hip in the sagittal plane during left lower limb weight bearing.
•	The range of movement was less in the trunk sagittal plane and pelvis in the transverse plane during both lower limb weight bearing.
	Clinical relevance of the tests when examining walking and running gait
•	Trendelenburg Test is appropriate for examining the pelvis coronal plane peak value of walking but not during running.
•	Using the Trendelenburg Test as part of the examination and treatment of the pelvis in the coronal plane may increase treatment efficacy and reduce chronic disability within professional football players.
•	Single Leg Squat is appropriate for clinical use and developing a diagnostic algorithm for the hip component of walking and running in the coronal plane. This may help reduce the high rates of hip arthritis and joint pain found within this population.
•	Using the Corkscrew and Single Leg Squat Tests in combination allows clinicians to comprehensively examine the sagittal and coronal plane range of movement of the lumbar and thoracic spine relevant to walking. This may reduce the lumbar injuries which have been found to be a considerable problem for professional football players.

7.6 Further Work

Few studies have examined the relationship between the clinical tests and gait. This study found that the tests were appropriate measures of walking and running but only in specific regions and planes. The corkscrew test was found to be the least useful test. The study also found that the professional football players' movement pattern was different to healthy participants. There are limited previous studies to establish if the movement pattern found in low back pain patients is different to healthy participants and none investigating if the movement patterns during the clinical tests differ. This would increase clinicians understanding of the relationship between low back pain and movement, help to sub-classify low back pain patients and implement evidence based examination and treatments. It is evident that future study should aim to investigate the validity of the Trendelenburg Test and Single Leg Squat as measures of dynamic stability of the Lumbo-Pelvic and Hip region in healthy participants and a specific low back pain population. The objectives of the study will be to establish normative Lumbo-Pelvic and Hip movement data for these functional and clinical tests, to identify similarities between these tests, to investigate if there is an identifiable difference between the groups, and to consider the clinical relevance of these relationships.

This thesis's study found that the clinical tests studied were not appropriate tests for the examination of the thoracic spine and hip movements during running. This represents a large gap in the evidence based examination of running. Hence the development a new clinical test for the examination of these regions during running is appropriate. The "Step Through Test "is a clinical test which is starting to be used in musculoskeletal practice however there is currently no evidence base to support its use. It is currently thought to replicate the thoracic spine and hip movements occurring during the stance phase of running. In order to recommend its integration into clinical practice there is a need to establish the normal kinematic data for the test. This will allow clinicians to interpret the test, identify abnormal responses, sub-classify patients and implement evidence based examination and treatments. Future study should aim to investigate the validity of the Step Through Test as a measure of dynamic stability of the thoracic spine and hip in healthy participants and professional football players. The objectives of the study will be to establish normative thoracic spine and hip movement data for these functional and clinical tests, to identify similarities between these tests, to investigate if there is an identifiable difference between the groups, and to consider the clinical relevance of these relationships.

8 Appendices

8.1 Appendix 1

The role of the Trendelenburg Test in the examination of gait

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Background: The Trendelenburg Test was developed by Friedrich Trendelenburg, an orthopaedic surgeon, in 1895. Contemporary evidence shows the Trendelenburg Test is now being used internationally by a wide variety of practitioners.
Method: This review describes the evolution of the Trendelenburg Test and its role within the examination of gait and examines the evidence relating clinical assessment using the Trendelenburg Test to the mechanics of walking. Literature was reviewed from electronic databases CINAHL, Medline, ScienceDirect, Ovid. Papers written in English were reviewed.
Results: The possible outcomes of the Trendelenburg Test and its interpretation are defined. The outcomes and interpretation for the future use of the Trendelenburg Test are discussed.
Conclusion: Further research is required into the biomechanics of the Trendelenburg Test and its relationship to functional anatomy and to investigate its reliability and validity within specific populations.

Keywords: Trendelenburg Test, orthopaedic clinical test, gait

Introduction

The Trendelenburg Test was developed by Friedrich Trendelenburg, an orthopaedic surgeon, in Bonn, Germany in 1895.[1–5] It was a progression of previous work by Dupytren on '- glissement vertical'.[1] The Trendelenburg Test was created to assist doctors in examining the gait of patients with congenital dislocation of the hip (CDH) and progressive muscular atrophy.[1,5] The test is conducted in the position of single leg stance.[6] This position is seen in many daily functions such as walking and running, or in sports such as football, rugby, hockey, gymnastics and skiing. An individual walks over 10 000 steps per day on average[7–9] and a professional football player runs over 10 km per game.[10,11] Therefore, single leg stance is a position both normal and sporting individuals go into repetitively and frequently.

During single leg stance, the weight bearing limb forms a closed kinetic chain with the floor and the non weight bearing limb forms an open kinetic chain.[12] If the two limbs and pelvis are considered as a whole then at the point of single leg stance, they are in 'controlled open kinetic chain'[13] (Figure 1).

Loss of control at any point in this chain may cause uncontrolled movement at that particular link in the chain, or at a link proximal or distal to it,[6,13] where uncontrolled movement may be termed dysfunction and dysfunction may cause symptoms or disability.[14] Symptoms or disability may therefore manifest at the site of dysfunction, or a joint proximal or distal to it (Figure 2). Therefore, by examining single limb stance, the Trendelenburg Test is a functional test for this kinetic chain of joints and their ability to transduce force across them.

The Trendelenburg Test

Originally, Trendelenburg described his test as "standing on the treated (affected) leg and raising the buttock of the other side up to or above the horizontal line" [1,5] (Figure 3). He stated that the test was positive if the patient was unable to stand on the treated (affected) leg and raise the buttock of the other side up to or above the horizontal line[1,5] (Figure 4). Trendelenburg felt that this indicated "… that the abductors of the standing leg cannot keep the pelvis horizontal".[1,5]

DOI 10.1179/174328809X452836

Appendix 1.1 Published article, published in peer reviewed journals, Bailey, R., Selfe, J., & Richards, J. 2009, "The role of the Trendelenburg Test in the examination of gait", Physical Therapy Reviews, vol. 14, pp. 190-197.

Physiotherapy Ireland. 2011;32(2)

The Single Leg Squat Test in the Assessment of Musculoskeletal Function: a Review

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Abstract

Contemporary evidence shows the Single leg squat has evolved into a functional test and is now being used clinically by some practitioners. This review describes the evolution of the Single leg squat test and its role within the examination of musculoskeletal function. It examines the evidence relating clinical assessment using the Single leg squat test to the mechanics of walking and discusses the possible outcomes of the Single leg squat test and its interpretation. Papers were obtained through a search of electronic databases cinahl, medline, science direct, sport discus and ovid from inception, with various combinations of the terms "Single leg," "Squat," "Dip," "Pelvis," "Stability" and "Test." An additional manual search was made of relevant bibliographies without limitation for year of publication.

Keywords: Single leg squat test, clinical test, gait.

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INTRODUCTION

Squatting using both legs, the double leg squat, was first reported as part of closed chain knee rehabilitation in the 1990s.[1] Double leg squats were progressed into single leg squats as part of exercise progression. The first paper to describe the Single leg squat was published by Chris Benn, a student physical therapist, at the University of Rhode Island, United States of America in 1998(1). Benn used the single leg squat within his study to compare two knee strengthening regimes. He concluded that using Single leg squats to strengthen the knee "could improve muscular performance and enhance a muscle's potential for dynamic stabilisation (of the knee)." [2]

The Single leg squat was subsequently developed from an exercise into a functional clinical test by Liebenson, a chiropractor in Los Angeles, United states of America in 2002. It was created to assist practitioners in examining the function of the lower extremity kinetic chain.[3]

The Single leg squat test is a clinical test, conducted in the position of single limb stance.[4] This position is seen in many daily functions such as walking and running, or in sports[5] such as football, rugby, hockey, gymnastics and skiing. An individual walks over 10,000 steps per day on average[6-7] and a professional football player runs over 10km per game.[8,9] Therefore the test appears to have good face validity as single leg stance is a position both healthy and sporting individuals go into repetitively and frequently. The Single leg squat test is frequently used clinically to provide a simple and convenient assessment of neuromuscular control for the Lumbo-Pelvic region.[10-12] It is assumed performance of the single leg squat reflects the movement that is likely to occur during more complex tasks such as gait. However, the potential link between Single leg squat performance and gait kinematics has only started to be investigated after 2009.[13]

The Single Leg Squat Test

Benn and colleagues' work focused on the effect of a single leg squat as a strengthening exercise for the knee.[2] Liebenson developed the single leg squat exercise into a test. He stated that when the Single leg squat is considered as a test then it may indicate many movement dysfunctions within the kinetic chain including pelvic unleveling, valgus overstrain at the knee and subtalar hyperpronation.

However Livengood was the first author to define a method for performing the Single leg squat as a test.[13]

Previously Liebenson had interpreted the test in an ordinal manner (positive or negative). Livengood was the first author to assign the test a scale. This converted it into nominal data. Table 2.

Appendix 1.2 Published article, published in peer reviewed journals, Bailey, R., Richards, J., & Selfe, J. 2011, "The Single Leg Squat Test in the Assessment of Musculoskeletal Function: a Review", Physiotherapy Practice and Research, vol. 32, no. 2, pp. 18-23.

8.2 Appendix 2

Title of study:

An investigation of the reliability and validity of the Trendelenburg Test as a measure of dynamic pelvic stability in normal healthy adults.

Aim of study:

This study aims to compare how people balance (the "Trendelenburg Test") with how they walk. The Trendelenburg Test is a standard Orthopaedic Test which involves balancing on one leg.

What we will ask you to do

In the movement analysis laboratory small reflective balls will be attached to your feet and legs with double sided sticky tape

Figure 1. Data will be collected using a motion analysis system, this consists ten cameras

Figure 2. These cameras will display as an animated skeleton

Figure 3. You will be asked to kick a ball into a goal, walk, run, balancing on one leg and balancing on one leg whilst squatting

Figure 1: Lower limb reflective markers

Figure 2: Movement Analysis Laboratory

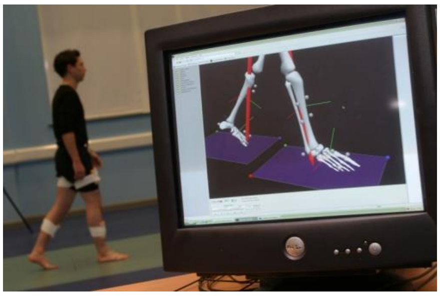

Figure 3: Generation of an animated skeleton

You will be videoed whilst performing the balancing on one leg task. We will require your age, weight and height. The testing will take **no more than one hour** to complete. It is up to you to decide whether or not to take part. You are still free to withdraw at any time and without giving a reason.

If you wish to contact the lead researcher or project supervisor about this work you are more than welcome to do so.

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Appendix 2, Recruitment poster

8.3 Appendix 3

Title of study:
An investigation of the reliability and validity of the Trendelenburg Test as a measure of dynamic pelvic stability in normal healthy adults.

Aim of study:
This study aims to compare how people balance (the "Trendelenburg Test") with how they walk. The Trendelenburg Test is a standard Orthopaedic Test which involves balancing on one leg.

What we will ask you to do
Small reflective balls will be attached to your feet and legs with double sided sticky tape, Figure 1. Data will be collected using a motion analysis system, this consists ten cameras, Figure 2. These cameras will not record any video footage which could be used to determine your identity and will only be displayed as an animated skeleton, Figure 3. You will be asked to kick a ball into a goal. This is to see which your dominant leg is. You will then be asked to carry out four tests; walking, running, balancing on one leg and balancing on one leg whilst squatting. The testing will take **no more than one hour** to complete. All tests will not exceed either the range of movement or forces on the lower limb experienced in normal daily life.

Figure 1: Lower limb reflective markers Figure 2: Movement Analysis Laboratory

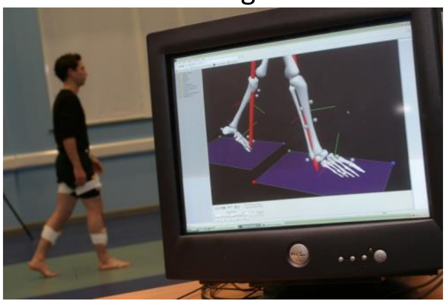

Figure 3: Generation of an animated skeleton

You will be videoed whilst performing the balancing on one leg task, but the camera will be set up to exclude your face and only those directly involved with the project will be given access to this information.

Appendix 3, Consent form, page 1

All data will be coded and no names will be able to be associated with any data recorded. Personal information and consent forms will be kept separate from study data. All data will be anonymised using a unique study number before entry onto computer; only aggregated data will be reported in study reports and publications. Data will be kept for 5 years after which time it will be destroyed.

An investigation of the reliability and validity of the Trendelenburg Test as a measure of dynamic pelvic stability in normal healthy adults.

We will require your age, weight and height. These will be coded and stored independently from any other records which could be used to determine your identity. All data will be coded and no names will be able to be associated with any data recorded.

It is up to you to decide whether or not to take part. If you do, you will be given this information sheet to keep and be asked to sign a consent form. You are still free to withdraw at any time and without giving a reason. A decision to withdraw at any time, or a decision not to take part, will not affect your statutory legal rights.

Please answer the questions below if you answer yes to any of these questions you will not be able to participate but we thank you for your involvement.

1. Do you presently, or have you previously suffered from any major medical problems that may affect your movement? Yes/No
2. Do you have any pain or problems with your muscles and joints? Yes/No
3. Do you have any know leg length difference? Yes/No
4. If the answer to 3 was yes do you know how much? Yes/No
5. Have you read the above information and do you understand it? Yes/No

6) Do you agree to take part in this study Yes/No

You may withdraw at any time if you do not wish to take part in the study.

Signed ………………………. **Date ……** Print name …………………..

Witnessed ……………………. **Date ……** Print name …………………..

If you wish to contact the lead researcher or project supervisor about this work you are more than welcome to do so.

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Appendix 3, Consent form, page 2

8.4 Appendix 4

Title of study:

An investigation of the reliability and validity of the Trendelenburg Test as a measure of dynamic pelvic stability in normal healthy adults.

Name	Date of Birth	Date

Inclusion Criteria

	Yes	No
Are you aged 17-21?	☐	☐
Are you male	☐	☐
Are you a professional football player?	☐	☐

Exclusion Criteria

	Yes	No
Have you previously been declined physiotherapy treatment?	☐	☐
Are you under the care of a doctor / surgeon?	☐	☐
Do you have a diagnosed balance condition?	☐	☐
Do you have a diagnosed leg length discrepancy?	☐	☐
Do you have previous or present injuries of the back or legs?	☐	☐
Are you being treated for a significant medical problem?	☐	☐

Appendix 4, Health screening questionnaire

8.5 Appendix 5

8.5.1 Lumbar movement

8.5.1.1 Lumbar sagittal plane range of movement (left)

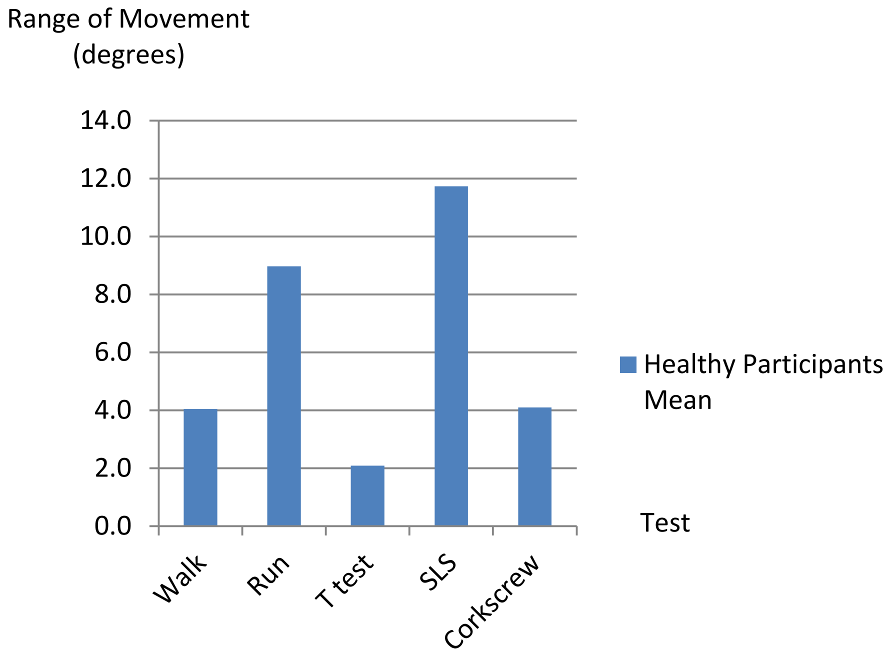


Figure 8.1 Lumbar sagittal plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	4.0	1.52
Run	9.0	3.66
T test	2.1	0.95
SLS	11.7	5.00
Corkscrew	4.1	1.95

Table 8.1 Lumbar sagittal plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	2.0	1.14	65	0.090	-0.3	4.2
Walk	SLS	-7.7	1.14	65	0.000	-10.0	-5.4
Walk	Run	-4.9	1.14	65	0.000	-7.2	-2.7
Walk	Cork	-0.1	1.14	65	0.963	-2.3	2.2
T Test	SLS	-9.6	1.14	65	0.000	-11.9	-7.4
T Test	Run	-6.9	1.14	65	0.000	-9.2	-4.6
T Test	Cork	-2.0	1.14	65	0.082	-4.3	0.3
SLS	Run	2.8	1.14	65	0.018	0.5	5.0
SLS	Cork	7.6	1.14	65	0.000	5.4	9.9
Run	Cork	4.9	1.14	65	0.000	2.6	7.2

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.2 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the pelvis in the sagittal plane; there was no statistically significant difference when comparing Walking to the Trendelenburg Test (p=0.090), or when comparing Walking to the Corkscrew Test (p=0.963). There was a statistically significant difference when comparing Walking to Running (mean difference=-4.9^0, p=0.000), and when comparing Walking to the Single Leg Squat (mean difference=-7.7^0, p=0.000), Table 8.2.

There was a statistically significant difference when comparing Running to the Trendelenburg Test (mean difference=-6.9^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference=2.7^0, p=0.018), or when comparing Running to the Corkscrew Test (mean difference=4.9^0, p=0.000), Table 8.2.

8.5.1.2 Lumbar sagittal plane range of movement (right)

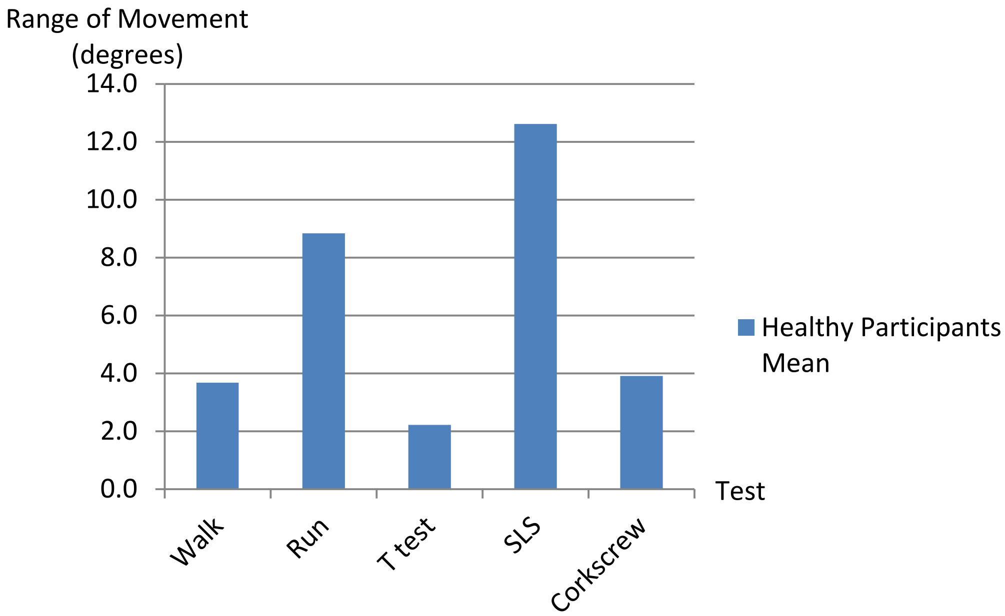


Figure 8.2 Lumbar sagittal plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	3.7	1.47
Run	8.8	2.70
T test	2.2	1.04
SLS	12.6	5.05
Corkscrew	3.9	1.49

Table 8.3 Lumbar sagittal plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	1.5	1.05	65	0.167	-0.6	3.5
Walk	SLS	-8.9	1.05	65	0.000	-11.0	-6.9
Walk	Run	-5.2	1.05	65	0.000	-7.2	-3.1
Walk	Cork	-0.2	1.05	65	0.829	-2.3	1.9
T Test	SLS	-10.4	1.05	65	0.000	-12.5	-8.3
T Test	Run	-6.6	1.05	65	0.000	-8.7	-4.5
T Test	Cork	-1.7	1.05	65	0.111	-3.8	0.4
SLS	Run	3.8	1.05	65	0.001	1.7	5.9
SLS	Cork	8.7	1.05	65	0.000	6.6	10.8
Run	Cork	4.9	1.05	65	0.000	2.8	7.0

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.4 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the pelvis in the sagittal plane; there were no statistically significant differences when comparing Walking to the Trendelenburg Test (p=0.167), or when comparing Walking to the Corkscrew Test (p=0.829). There were statistically significant differences when comparing Walking to Running (mean difference=-5.2^0, p=0.000), and when comparing Walking to the Single Leg Squat (mean difference=-8.9^0, p=0.000), Table 8.4.

There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference=-6.6^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference=3.8^0, p=0.001), and when comparing Running to the Corkscrew Test (mean difference=4.9^0, p=0.000), Table 8.4.

8.5.1.3 Lumbar coronal plane range of movement (left)

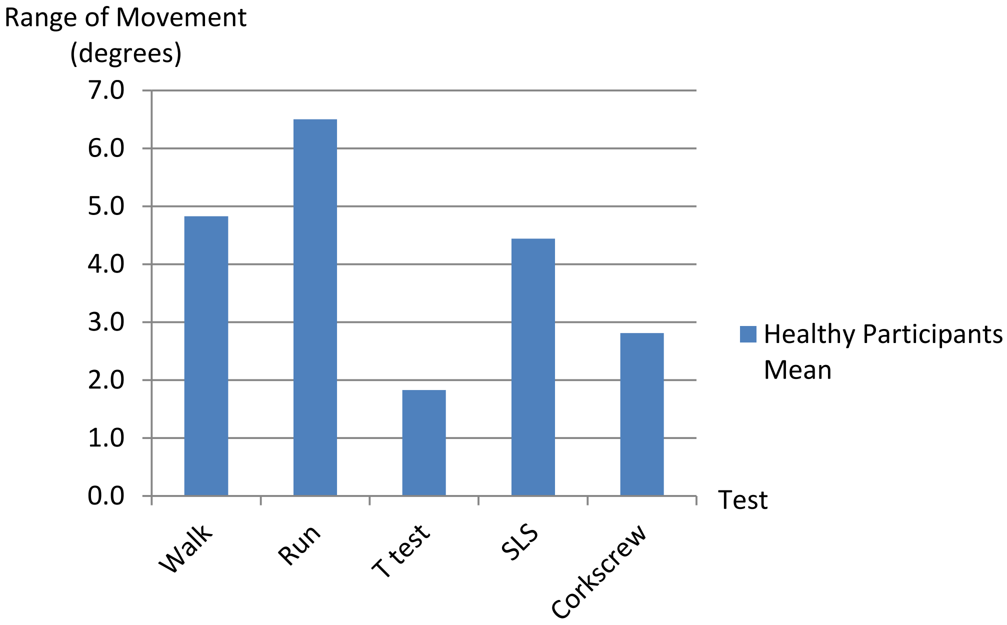


Figure 8.3 Lumbar coronal plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	4.8	2.16
Run	6.5	3.24
T test	1.8	1.33
SLS	4.4	1.88
Corkscrew	2.8	1.34

Table 8.5 Lumbar coronal plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	3.0	0.80	65	0.000	1.4	4.6
Walk	SLS	0.4	0. 80	65	0.631	-1.2	2.0
Walk	Run	-1.7	0.80	65	0.040	-3.3	-0.1
Walk	Cork	2.0	0.80	65	0.014	0.4	3.6
T Test	SLS	-2.6	0.80	65	0.002	-4.2	-1.0
T Test	Run	-4.7	0.80	65	0.000	-6.3	-3.1
T Test	Cork	-1.0	0.80	65	0.222	-2.6	0.6
SLS	Run	-2.1	0.80	65	0.012	-3.7	-0.5
SLS	Cork	1.6	0.80	65	0.045	0.0	3.2
Run	Cork	3.7	0.80	65	0.000	2.1	5.3

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.6 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the pelvis in the coronal plane; there was no statistically significant difference when comparing Walking to the Single Leg Squat (p=0.631). There was a statistically significant difference when comparing Walking to Running (mean difference=-1.7^0, p=0.040), when comparing Walking to the Trendelenburg Test (mean difference=3.0^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference=2.0^0, p=0.014), Table 8.6.

There was a statistically significant difference when comparing Running to the Trendelenburg Test (mean difference=-4.7^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference=-2.1^0, p=0.012), and when comparing Running to the Corkscrew Test (mean difference=3.7^0, p=0.000), Table 8.6.

8.5.1.4 Lumbar coronal plane range of movement (right)

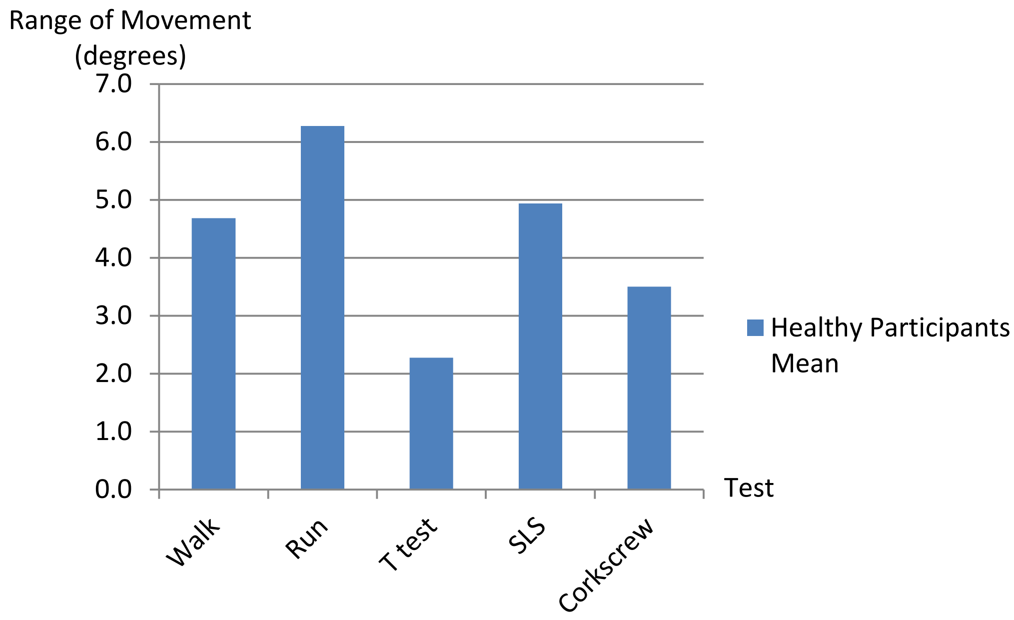


Figure 8.4 Lumbar coronal plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	4.7	2.07
Run	6.3	2.49
T test	2.3	1.49
SLS	4.9	2.99
Corkscrew	3.5	1.70

Table 8.7 Lumbar coronal plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	2.4	0.84	65	0.005	0.7	4.1
Walk	SLS	-0.3	0.84	65	0.764	-1.9	1.4
Walk	Run	-1.6	0.84	65	0.062	-3.3	0.1
Walk	Cork	1.2	0.84	65	0.162	-0.5	2.9
T Test	SLS	-2.7	0.84	65	0.002	-4.3	-1.0
T Test	Run	-4.0	0.84	65	0.000	-5.7	-2.3
T Test	Cork	-1.2	0.84	65	0.149	-2.9	0.5
SLS	Run	-1.3	0.84	65	0.115	-3.0	0.3
SLS	Cork	1.4	0.84	65	0.091	-0.2	3.1
Run	Cork	2.8	0.84	65	0.002	1.1	4.4

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.8 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the pelvis in the coronal plane; there were no statistically significant differences when comparing Walking to Running (p=0.062), when comparing Walking to the Single Leg Squat (p=0.764), or when comparing Walking to the Corkscrew Test (p=0.162). There was a statistically significant difference when comparing Walking to the Trendelenburg Test (mean difference=2.4^0, p=0.005), Table 8.8.

There was no statistically significant difference when comparing Running to the Single Leg Squat (p=0.115). There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference=-4.0^0, p=0.000), and when comparing Running to the Corkscrew Test (mean difference=2.8^0, p=0.002), Table 8.8.

8.5.1.5 Lumbar coronal plane peak value (left)

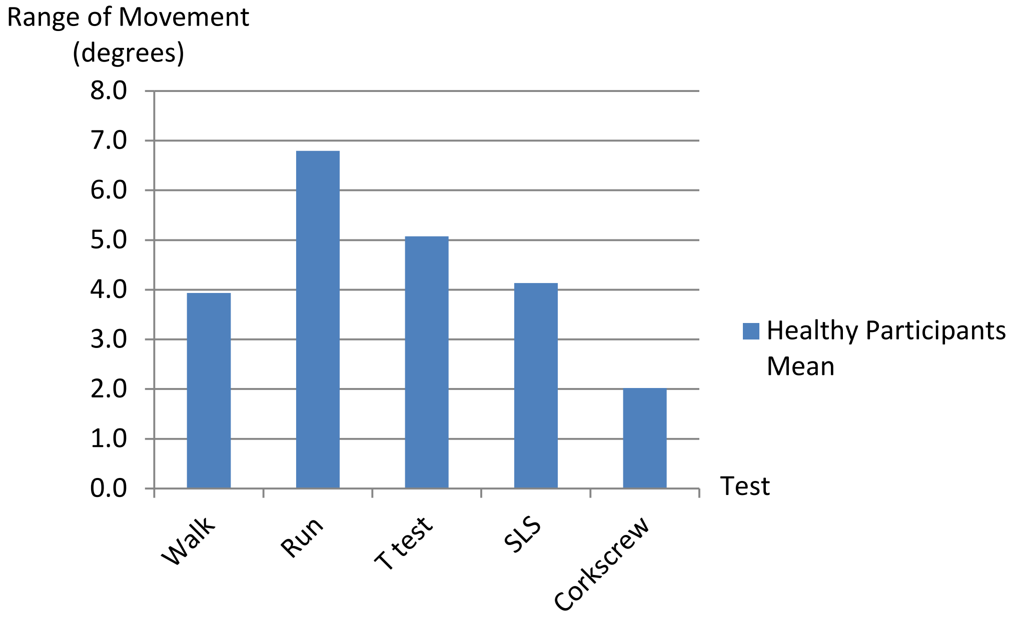


Figure 8.5 Lumbar coronal plane peak value normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	3.9	2.79
Run	6.8	3.08
T test	5.1	3.74
SLS	4.1	2.78
Corkscrew	2.0	2.80

Table 8.9 Lumbar coronal plane peak value normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	-1.1	1.16	65	0.327	-3.5	1.2
Walk	SLS	-0.2	1.16	65	0.864	-2.5	2.1
Walk	Run	-2.9	1.16	65	0.016	-5.2	-0.6
Walk	Cork	1.9	1.16	65	0.104	-0.4	4.2
T Test	SLS	0.9	1.16	65	0.418	-1.4	3.3
T Test	Run	-1.7	1.16	65	0.142	-4.0	0.6
T Test	Cork	3.1	1.16	65	0.010	0.7	5.4
SLS	Run	-2.7	1.16	65	0.025	-5.0	-0.4
SLS	Cork	2.1	1.16	65	0.073	-0.2	4.4
Run	Cork	4.8	1.16	65	0.000	2.5	7.1

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.10 Comparison between functional tests and clinical tests

For the peak value of the lumbar spine relative to the pelvis in the coronal plane; there were no statistically significant difference when comparing Walking to the Trendelenburg Test (p=0.327), when comparing Walking to the Single Leg Squat (p=0.864), or when comparing Walking to the Corkscrew Test (p=0.104). There was a statistically significant difference when comparing Walking to Running (mean difference=-2.9^0, p=0.016), Table 8.10.

There was no statistically significant difference when comparing Running to the Trendelenburg Test (p=0.142). There were statistically significant differences when comparing Running to the Single Leg Squat (mean difference=-2.7^0, p=0.025), or when comparing Running to the Corkscrew Test (mean difference=4.8^0, p=0.000), Table 8.10.

8.5.1.6 Lumbar coronal plane peak value (right)

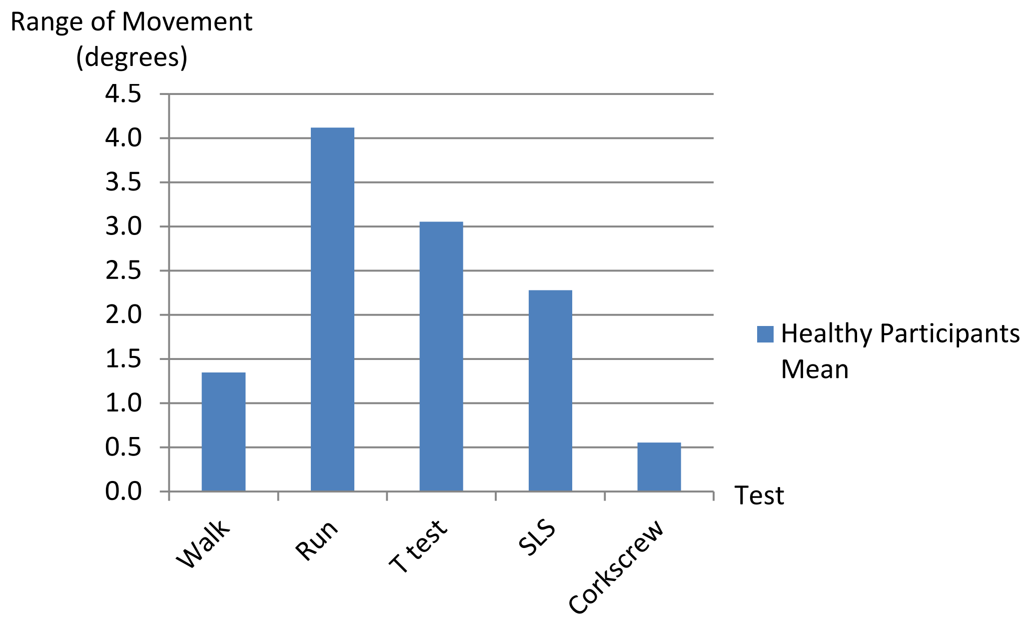


Figure 8.6 Lumbar coronal plane peak value normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	1.3	2.92
Run	4.1	3.18
T test	3.1	4.06
SLS	2.3	4.15
Corkscrew	0.6	2.41

Table 8.11 Lumbar coronal plane peak value normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	-1.7	1.29	65	0.190	-4.3	0.9
Walk	SLS	-0.9	1.29	65	0.472	-3.5	1.6
Walk	Run	-2.8	1.29	65	0.035	-5.3	-0.2
Walk	Cork	0.8	1.29	65	0.541	-1.8	3.4
T Test	SLS	0.8	1.29	65	0.551	-1.8	3.3
T Test	Run	-1.1	1.29	65	0.412	-3.6	1.5
T Test	Cork	2.5	1.29	65	0.057	-0.1	5.1
SLS	Run	-1.8	1.29	65	0.159	-4.4	0.7
SLS	Cork	1.7	1.29	65	0.185	-0.8	4.3
Run	Cork	3.6	1.29	65	0.007	1.0	6.1

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.12 Comparison between functional tests and clinical tests

For the peak value of the lumbar spine relative to the pelvis in the coronal plane; there were no statistically significant differences when comparing Walking to the Trendelenburg Test (p=0.190), when comparing Walking to the Single Leg Squat (p=0.472), or when comparing Walking to the Corkscrew Test (p=0.541). There was a statistically significant difference when comparing Walking to Running (mean difference=-2.8^0, p=0.035), Table 8.12.

There were no statistically significant differences when comparing Running to the Trendelenburg Test (p=0.412), or when comparing Running to the Single Leg Squat (p=0.159). There was a statistically significant difference when comparing Running to the Corkscrew Test (mean difference=3.6^0, p=0.007), Table 8.12.

However of interest is that for lumbar coronal plane peak value all of the functional and clinical tests exhibited lower values for right lower limb weight bearing than for left lower limb weight bearing suggesting that for this parameter asymmetry was normal, Table 8.11.

8.5.1.7 Lumbar transverse plane range of movement (left)

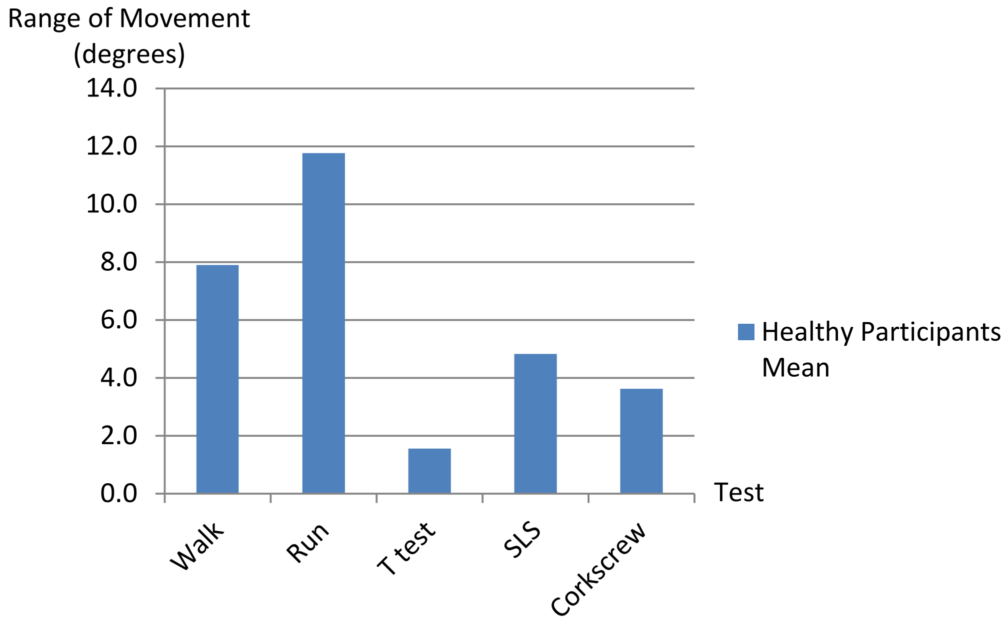


Figure 8.7 Lumbar transverse plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	7.9	2.47
Run	11.8	2.15
T test	1.6	0.52
SLS	4.8	2.26
Corkscrew	3.6	1.46

Table 8.13 Lumbar transverse plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	6.3	0.72	65	0.000	4.9	7.8
Walk	SLS	3.1	0.72	65	0.000	1.6	4.5
Walk	Run	-3.9	0.72	65	0.000	-5.3	-2.4
Walk	Cork	4.2	0.72	65	0.000	2.8	5.7
T Test	SLS	-3.3	0.72	65	0.000	-4.7	-1.8
T Test	Run	-10.2	0.72	65	0.000	-11.7	-8.8
T Test	Cork	-2.1	0.72	65	0.005	-3.5	-0.6
SLS	Run	-6.9	0.72	65	0.000	-8.4	-5.5
SLS	Cork	1.2	0.72	65	0.101	-0.2	2.6
Run	Cork	8.1	0.72	65	0.000	6.7	9.6

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.14 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the pelvis in the transverse plane; there were statistically significant difference when comparing Walking to Running (mean difference=-3.9^0, p=0.000), when comparing Walking to the Trendelenburg Test (mean difference=6.3^0,p=0.000), when comparing Walking to the Single Leg Squat (mean difference=3.1^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference=4.3^0, p=0.000), Table 8.14.

There were statistically significant difference when comparing Running to the Trendelenburg Test (mean difference=-10.2^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference=-6.9^0, p=0.000), and when comparing Running to the Corkscrew Test (mean difference=8.1^0, p=0.000), Table 8.14.

8.5.1.8 Lumbar transverse plane range of movement (right)

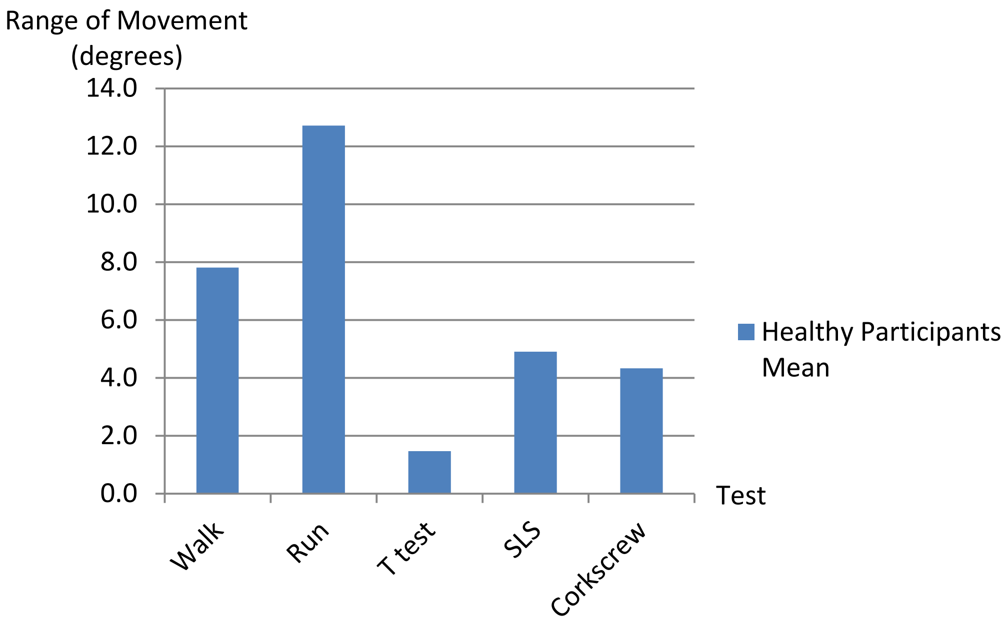


Figure 8.8 Lumbar transverse plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	7.8	2.50
Run	12.7	2.38
T test	1.5	0.74
SLS	4.9	1.76
Corkscrew	4.3	1.54

Table 8.15 Lumbar transverse plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	6.3	0.72	65	0.000	4.9	7.8
Walk	SLS	2.9	0.72	65	0.000	1.5	4.3
Walk	Run	-4.9	0.72	65	0.000	-6.3	-3.5
Walk	Cork	3.5	0.72	65	0.000	2.0	4.9
T Test	SLS	-3.4	0.72	65	0.000	-4.9	-2.0
T Test	Run	-11.2	0.72	65	0.000	-12.7	-9.8
T Test	Cork	-2.9	0.72	65	0.000	-4.3	-1.4
SLS	Run	-7.8	0.72	65	0.000	-9.2	-6.4
SLS	Cork	0.6	0.72	65	0.431	-.9	2.0
Run	Cork	8.4	0.72	65	0.000	7.0	9.8

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.16 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the pelvis in the transverse plane; there were statistically significant differences when comparing Walking to Running (mean difference=-4.9^0, p=0.000), when comparing Walking to the Trendelenburg Test (mean difference=6.3^0, p=0.000), when comparing Walking to the Single Leg Squat (mean difference=2.9^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference=3.5^0, p=0.000), Table 8.16.

There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference=-11.2^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference=-7.8^0, p=0.000), and when comparing Running to the Corkscrew Test (mean difference=8.4^0, p=0.000), Table 8.16.

However of interest is that the Trendelenburg Test exhibited consistently lower values than the functional tests for both left and right lower limb weight bearing, Table 8.14, Table 8.16. Furthermore the Single Leg Squat is currently thought to be a dynamic version of the Trendelenburg Test but the Single Leg Squat exhibited consistently greater range of movement than the Trendelenburg Test for both left and right lower limb weight bearing in the coronal, sagittal and transverse planes, Table 8.1, Table 8.3, Table 8.5, Table 8.7, Table 8.13, and Table 8.15.

8.5.2 Thoracic movement

8.5.2.1 Thoracic sagittal plane range of movement (left)

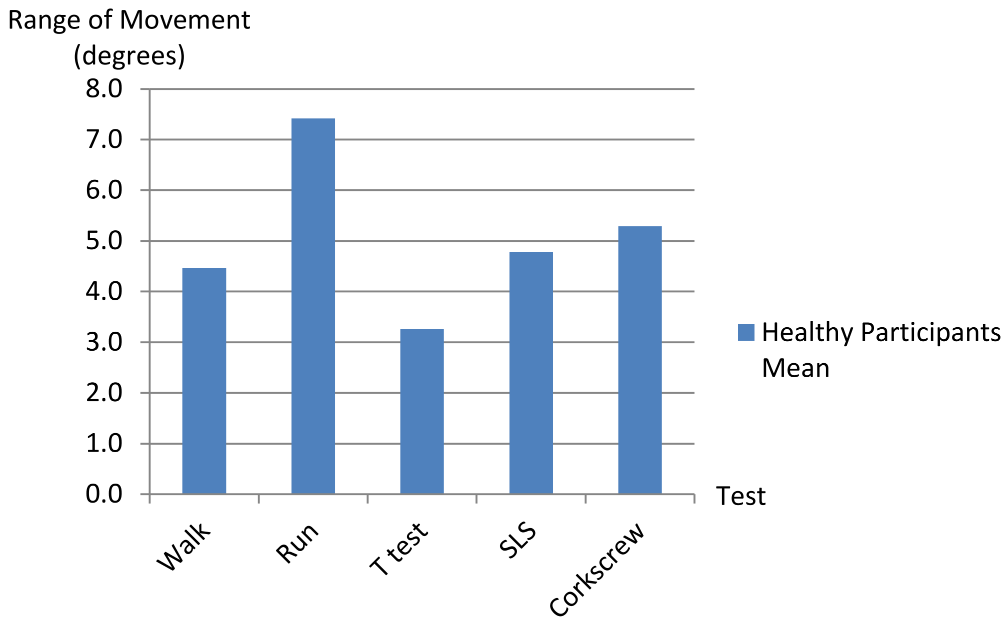


Figure 8.9 Thoracic sagittal plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	4.5	1.96
Run	7.4	3.21
T test	3.3	2.12
SLS	4.8	2.81
Corkscrew	5.3	1.66

Table 8.17 Thoracic sagittal plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	1.2	0.92	65	0.190	-.6	3.0
Walk	SLS	-0.3	0.92	65	0.732	-2.1	1.5
Walk	Run	-2.9	0.92	65	0.002	-4.8	-1.1
Walk	Cork	-0.8	0.92	65	0.375	-2.6	1.0
T Test	SLS	-1.5	0.92	65	0.100	-3.4	0.3
T Test	Run	-4.2	0.92	65	0.000	-6.0	-2.3
T Test	Cork	-2.0	0.92	65	0.030	-3.9	-0.2
SLS	Run	-2.6	0.92	65	0.005	-4.5	-0.8
SLS	Cork	-0.5	0.92	65	0.585	-2.3	1.3
Run	Cork	2.1	0.92	65	0.023	0.3	4.0

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.18 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the thoracic spine in the sagittal plane; there were no statistically significant differences when comparing Walking to the Trendelenburg Test (p=0.190), when comparing Walking to the Single Leg Squat (p=0.732), or when comparing Walking to the Corkscrew Test (p=0.375). There was a statistically significant difference when comparing Walking to Running (mean difference=-2.9^0, p=0.002), Table 8.18.

There was a statistically significant difference when comparing Running to the Trendelenburg Test (mean difference=-4.2^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference=-2.6^0, p=0.005), and when comparing Running to the Corkscrew Test (mean difference=2.1^0, p=0.023), Table 8.18.

8.5.2.2 Thoracic sagittal plane range of movement (right)

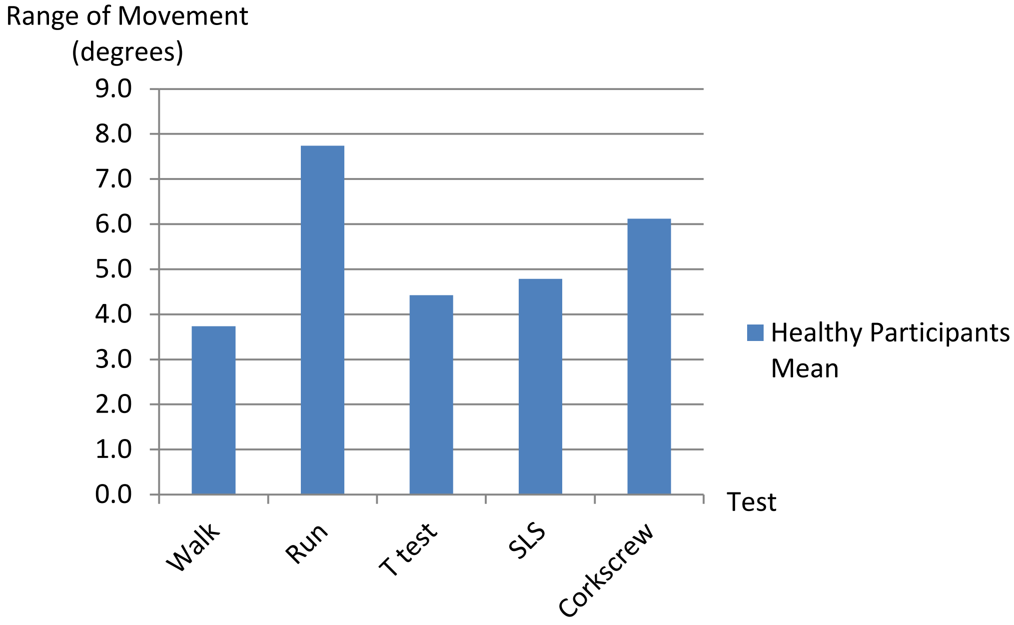


Figure 8.10 Thoracic sagittal plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	3.7	1.36
Run	7.7	3.11
T test	4.4	2.52
SLS	4.8	3.00
Corkscrew	6.1	3.41

Table 8.19 Thoracic sagittal plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	-0.7	1.05	65	0.514	-2.8	1.4
Walk	SLS	-1.1	1.05	65	0.321	-3.1	1.0
Walk	Run	-4.0	1.05	65	0.000	-6.1	-1.9
Walk	Cork	-2.4	1.05	65	0.026	-4.5	-0.3
T Test	SLS	-0.4	1.05	65	0.732	-2.5	1.7
T Test	Run	-3.3	1.05	65	0.002	-5.4	-1.2
T Test	Cork	-1.7	1.05	65	0.110	-3.8	0.4
SLS	Run	-3.0	1.05	65	0.006	-5.0	-0.9
SLS	Cork	-1.3	1.05	65	0.207	-3.4	0.8
Run	Cork	1.6	1.05	65	0.128	-0.5	3.7

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.20 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the thoracic spine in the sagittal plane; there was there was no statistically significant difference when comparing Walking to the Trendelenburg Test (p=0.514), or when comparing Walking to the Single Leg Squat (p=0.321). There were statistically significant differences when comparing Walking to Running (mean difference=-4.0^{0}, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference=-2.4^{0}, p=0.026),Table 8.20.

There was no statistically significant difference when comparing Running to the Corkscrew Test (p=0.128). There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference=-3.3^{0}, p=0.002), and when comparing Running to the Single Leg Squat (mean difference=-3.0^{0}, p=0.006),Table 8.20.

8.5.2.3 Thoracic coronal plane range of movement (left)

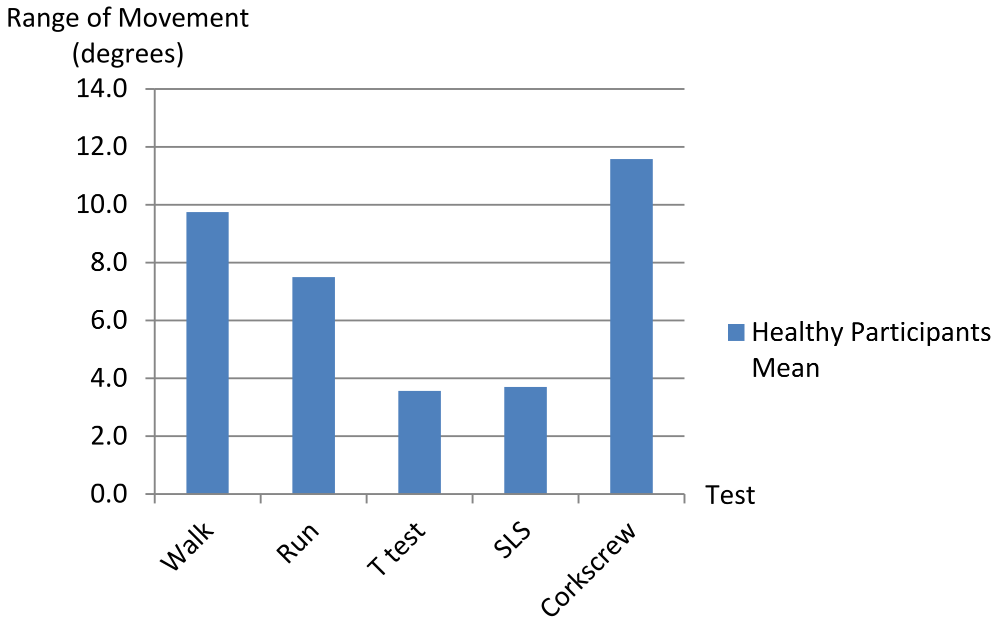


Figure 8.11 Thoracic coronal plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	9.7	2.67
Run	7.5	2.93
T test	3.6	0.78
SLS	3.7	2.01
Corkscrew	11.6	7.56

Table 8.21 Thoracic coronal plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	6.2	1.49	65	0.000	3.2	9.1
Walk	SLS	6.0	1.49	65	0.000	3.0	9.0
Walk	Run	2.3	1.49	65	0.135	-.7	5.2
Walk	Cork	-1.8	1.49	65	0.222	-4.8	1.1
T Test	SLS	-0.1	1.49	65	0.934	-3.1	2.8
T Test	Run	-3.9	1.49	65	0.011	-6.9	-0.9
T Test	Cork	-8.0	1.49	65	0.000	-11.0	-5.0
SLS	Run	-3.8	1.49	65	0.013	-6.8	-0.8
SLS	Cork	-7.9	1.49	65	0.000	-10.9	-4.9
Run	Cork	-4.1	1.49	65	0.008	-7.1	-1.1

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.22 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the thoracic spine in the coronal plane; there were no statistically significant differences when comparing Walking to Running (p=0.135), or when comparing Walking to the Corkscrew Test (p=0.222). There were statistically significant differences when comparing the Walking to Trendelenburg Test (mean difference=6.2^0, p=0.000), and when comparing the Walking to the Single Leg Squat (mean difference=6.0^0, p=0.000), Table 8.22.

There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference=-3.9^0, p=0.011), when comparing Running to the Single Leg Squat (mean difference=-3.8^0, p=0.013), and when comparing Running to the Corkscrew Test (mean difference=-4.1^0, p=0.008), Table 8.22.

8.5.2.4 Thoracic coronal plane range of movement (right)

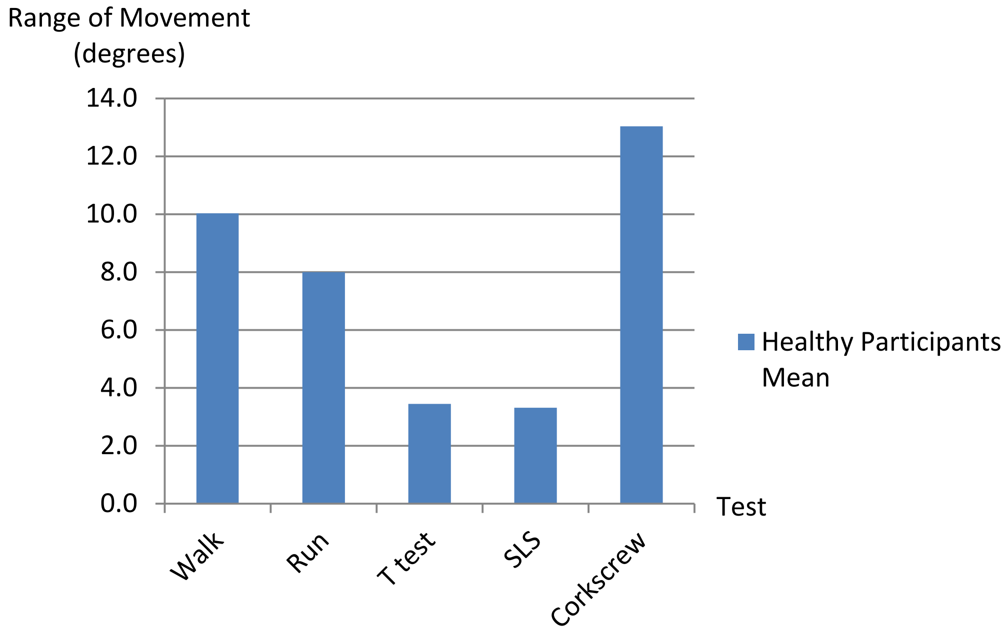


Figure 8.12 Thoracic coronal plane range of movement normative data(Right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	10.0	3.59
Run	8.0	2.65
T test	3.4	2.03
SLS	3.3	2.07
Corkscrew	13.0	9.97

Table 8.23 Thoracic coronal plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	6.6	1.91	65	0.001	2.8	10.4
Walk	SLS	6.7	1.91	65	0.001	2.9	10.5
Walk	Run	2.0	1.91	65	0.290	-1.7	5.9
Walk	Cork	-3.0	1.91	65	0.121	-6.8	0.8
T Test	SLS	0.1	1.91	65	0.944	-3.7	4.0
T Test	Run	-4.6	1.91	65	0.020	-8.4	-0.7
T Test	Cork	-9.6	1.91	65	0.000	-13.4	-5.78
SLS	Run	-4.7	1.91	65	0.017	-8.5	-0.9
SLS	Cork	-9.7	1.91	65	0.000	-13.5	-5.9
Run	Cork	-5.0	1.91	65	0.010	-8.9	-1.2

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.24 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the thoracic in the coronal plane; there were no statistically significant difference was found when comparing Walking to Running (p=0.290), or when comparing Walking to the Corkscrew Test (p=0.121). There were statistically significant differences when comparing Walking to the Trendelenburg Test (mean difference=6.6^0, p=0.001), and when comparing Walking to the Single Leg Squat (mean difference=6.7^0, p=0.001),Table 8.24.

There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference=-4.6^0, p=0.020), when comparing Running to the Single Leg Squat (mean difference=-4.7^0, p=0.017), and when comparing Running to the Corkscrew Test (mean difference=-5.0^0, p=0.010),Table 8.24.

8.5.2.5 Thoracic coronal plane peak value (left)

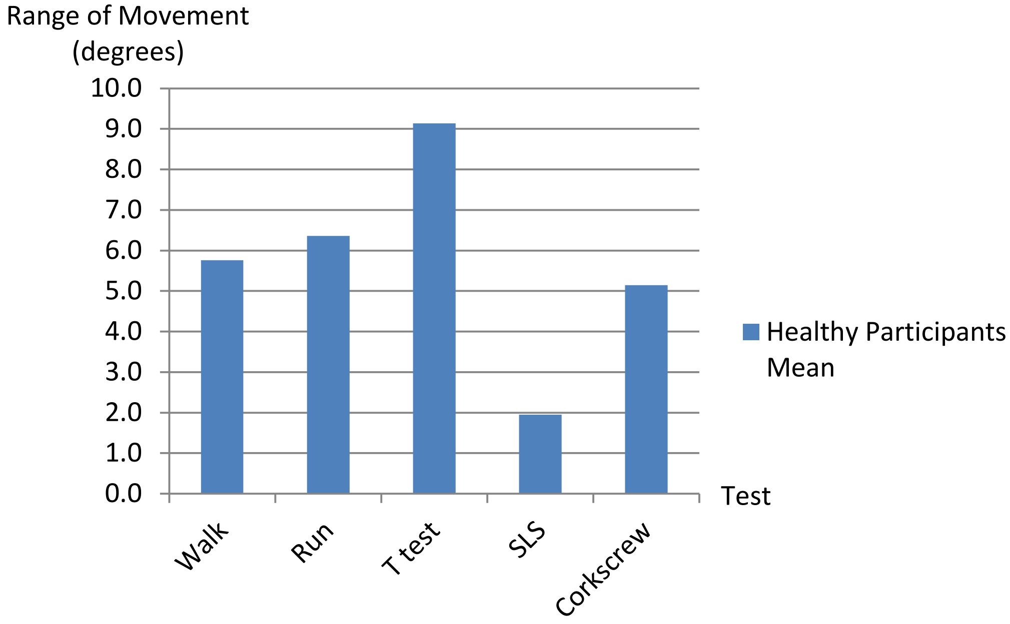


Figure 8.13 Thoracic coronal plane peak value normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	5.8	1.60
Run	6.4	2.58
T test	9.1	5.27
SLS	1.9	2.79
Corkscrew	5.1	5.75

Table 8.25 Thoracic coronal plane peak value normative data (Left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	-3.4	1.49	65	0.027	-6.4	-0.4
Walk	SLS	3.8	1.49	65	0.013	0.8	6.8
Walk	Run	-0.6	1.49	65	0.687	-3.6	2.4
Walk	Cork	0.6	1.49	65	0.683	-2.4	3.6
T Test	SLS	7.2	1.49	65	0.000	4.2	10.2
T Test	Run	2.8	1.49	65	0.067	-0.2	5.8
T Test	Cork	4.0	1.49	65	0.009	1.0	7.0
SLS	Run	-4.4	1.49	65	0.004	-7.4	-1.4
SLS	Cork	-3.2	1.49	65	0.035	-6.2	-0.2
Run	Cork	1.2	1.49	65	0.418	-1.8	4.2

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.26 Comparison between functional tests and clinical tests

For the peak value of the lumbar spine relative to the thoracic spine in the coronal plane; there were no statistically significant differences when comparing Walking to Running (p=0.687), or when comparing Walking to the Corkscrew Test (p=0.683). There were statistically significant differences when comparing Walking to the Trendelenburg Test (mean difference=-3.4^0, p=0.027), and when comparing Walking to the Single Leg Squat (mean difference=3.8^0, p=0.013), Table 8.26.

There were no statistically significant differences when comparing Running to the Trendelenburg Test (p=0.067), or when comparing Running to the Corkscrew Test (p=0.418). There was a statistically significant difference when comparing Running to the Single Leg Squat (mean difference=-4.4^0, p=0.004), Table 8.26.

8.5.2.6 Thoracic coronal plane peak value (right)

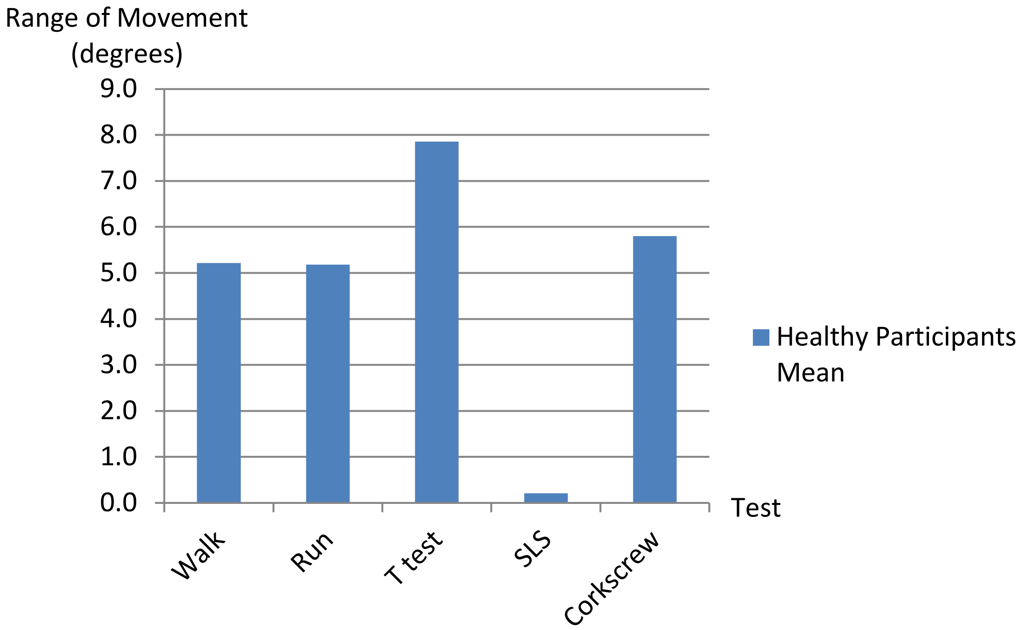


Figure 8.14 Thoracic coronal plane peak value normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	5.2	2.80
Run	5.2	4.05
T test	7.9	4.15
SLS	0.2	3.46
Corkscrew	5.8	6.37

Table 8.27 Thoracic coronal plane peak value normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	-2.6	1.64	65	0.112	-5.9	0.6
Walk	SLS	5.0	1.64	65	0.003	1.7	8.3
Walk	Run	0.0	1.64	65	0.983	-3.2	3.3
Walk	Cork	-0.6	1.64	65	0.722	-3.9	2.7
T Test	SLS	7.7	1.64	65	0.000	4.4	10.9
T Test	Run	2.7	1.64	65	0.108	-0.6	5.9
T Test	Cork	2.1	1.64	65	0.215	-1.2	5.3
SLS	Run	-5.0	1.64	65	0.003	-8.3	-1.7
SLS	Cork	-5.6	1.64	65	0.001	-8.9	-2.3
Run	Cork	-0.6	1.64	65	0.706	-3.9	2.7

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.28 Comparison between functional tests and clinical tests

For the peak value of the lumbar spine relative to the thoracic spine in the coronal plane; there were no statistically significant differences when comparing Walking to Running (p=0.983), when comparing Walking to the Trendelenburg Test (p=0.112), or when comparing Walking to the Corkscrew Test (p=0.722). There was a statistically significant difference when comparing Walking to the Single Leg Squat (mean difference=5.0^0, p=0.003),Table 8.28.

There were no statistically significant differences when comparing Running to the Trendelenburg Test (p=0.108), or when comparing Running to the Corkscrew Test (p=0.706). There was a statistically significant difference when comparing Running to the Single Leg Squat (mean difference=-5.0^0, p=0.003),Table 8.28.

However of interest is that the Trendelenburg Test was shown to create movement along the kinetic chain with the thoracic spine peak values being approximately 50% greater than the functional tests for both left and right lower limb weight bearing, Table 8.25, Table 8.27.

8.5.2.7 Thoracic transverse plane range of movement (left)

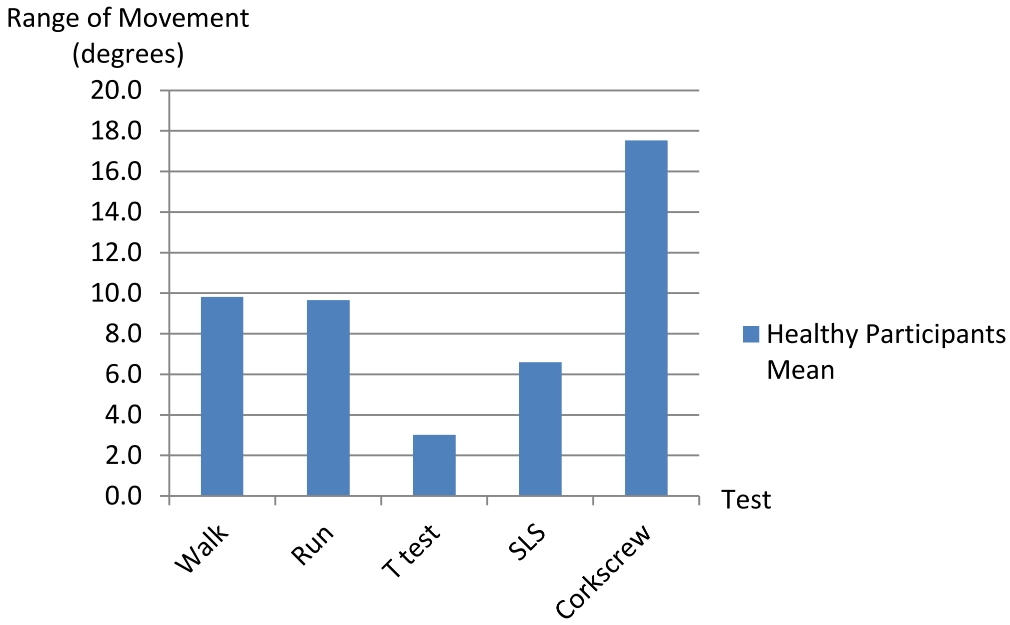


Figure 8.15 Thoracic transverse plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	9.8	5.06
Run	9.7	4.69
T test	3.0	2.22
SLS	6.6	2.91
Corkscrew	17.5	11.78

Table 8.29 Thoracic transverse plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	6.8	2.39	65	0.006	2.0	11.6
Walk	SLS	3.2	2.39	65	0.182	-1.5	8.0
Walk	Run	0.2	2.39	65	0.945	-4.6	4.9
Walk	Cork	-7.7	2.39	65	0.002	-12.5	-2.9
T Test	SLS	-3.6	2.39	65	0.138	-8.4	1.2
T Test	Run	-6.6	2.39	65	0.007	-11.4	-1.9
T Test	Cork	-14.5	2.39	65	0.000	-19.3	-9.7
SLS	Run	-3.1	2.39	65	0.205	-7.8	1.7
SLS	Cork	-10.9	2.39	65	0.000	-15.7	-6.2
Run	Cork	-7.9	2.39	65	0.002	-12.6	-3.1

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.30 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the thoracic in the transverse plane; there were no statistically significant differences when comparing Walking to Running (p=0.945), or when comparing Walking to the Single Leg Squat (p=0.182). There were statistically significant differences when comparing Walking to the Trendelenburg Test (mean difference=6.8, p=0.006), and when comparing Walking to the Corkscrew Test (mean difference=-7.7^0, p=0.002), Table 8.30.

There was no statistically significant difference when comparing Running to the Single Leg Squat (p=0.205). There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference=-6.6^0, p=0.007), and when comparing Running to the Corkscrew Test (mean difference=-7.9^0, p=0.002), Table 8.30.

8.5.2.8 Thoracic transverse plane range of movement (right)

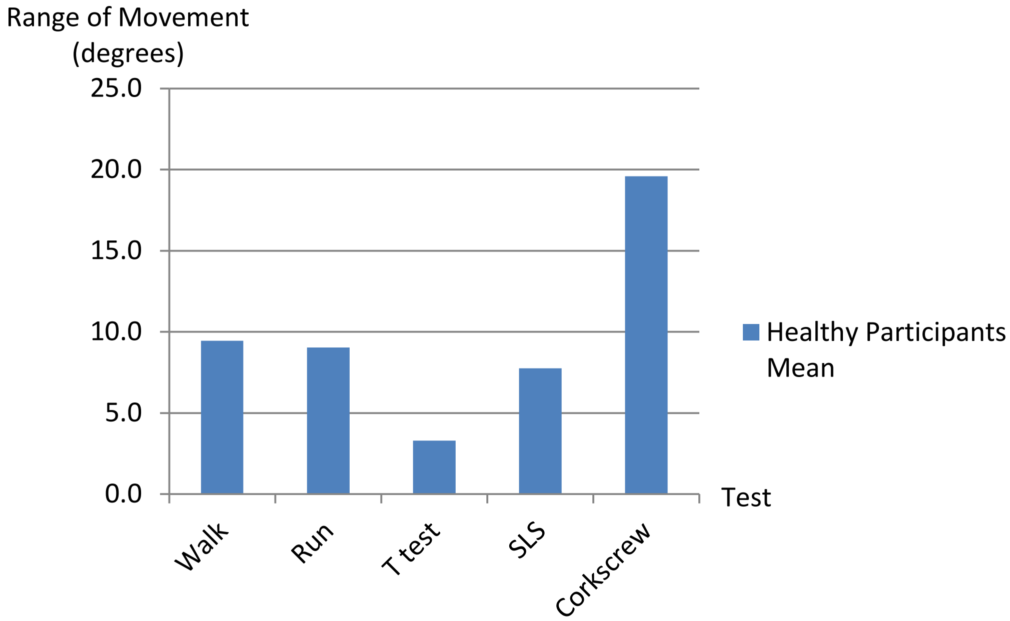


Figure 8.16 Thoracic transverse plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)
Walk	9.4	5.42
Run	9.0	3.82
T test	3.3	1.15
SLS	7.8	3.82
Corkscrew	19.6	13.26

Table 8.31 Thoracic transverse plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	6.2	2.60	65	0.021	1.0	11.3
Walk	SLS	1.7	2.60	65	0.517	-3.5	6.9
Walk	Run	0.4	2.60	65	0.876	-4.8	5.6
Walk	Cork	-10.1	2.60	65	0.000	-15.3	-5.0
T Test	SLS	-4.5	2.60	65	0.090	-9.6	0.7
T Test	Run	-5.8	2.60	65	0.030	-10.9	-0.6
T Test	Cork	-16.3	2.60	65	0.000	-21.5	-11.1
SLS	Run	-1.3	2.60	65	0.622	-6.5	3.9
SLS	Cork	-11.8	2.60	65	0.000	-17.0	-6.6
Run	Cork	-10.5	2.60	65	0.000	-15.7	-5.4

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.32 Comparison between functional tests and clinical tests

For the range of movement of the lumbar spine relative to the thoracic in the transverse plane; there were no statistically significant differences when comparing Walking to Running (p=0.876), or when comparing Walking to the Single Leg Squat (p=0.517). There were statistically significant differences when comparing Walking to the Trendelenburg Test (mean difference=6.2^0, p=0.021), and when comparing Walking to the Corkscrew Test (mean difference=-10.1^0, p=0.000), Table 8.32.

There was no statistically significant difference when comparing Running to the Single Leg Squat (p=0.622). There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference=-5.8^0, p=0.030), and when comparing Running to the Corkscrew Test (mean difference=-10.5^0, p=0.000), Table 8.32.

However of interest is that the Trendelenburg Test and Single Leg Squat often exhibited lower values than the functional tests for both left and right lower limb weight bearing, Figure 8.15, Table 8.29, and Figure 8.16, Table 8.31.

For the trunk, pelvis and hip there are no data for the Corkscrew Test for the professional football players. This test was an additional test to the Trendelenburg Test and Single Leg Squat and only completed by the healthy participants.

8.5.3 Trunk movement

8.5.3.1 Trunk sagittal plane range of movement (left)

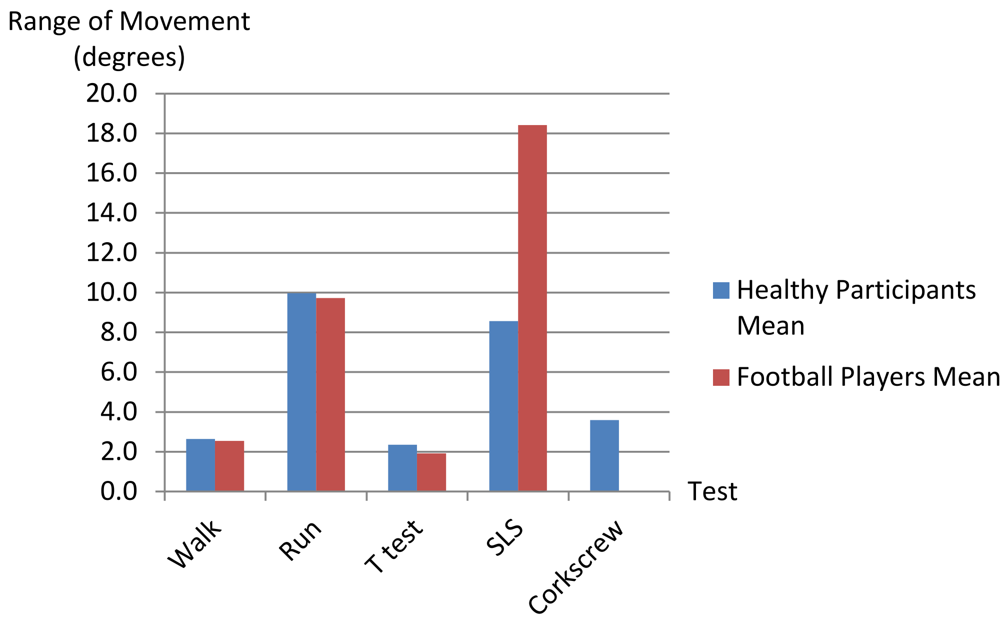


Figure 8.17 Trunk sagittal plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	2.6	0.98	2.5	0.95
Run	10.0	1.97	9.8	2.57
T test	2.3	1.35	1.9	0.65
SLS	8.6	5.16	18.4	5.39
Corkscrew	3.6	2.11		

Table 8.33 Trunk sagittal plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	0.5	0.77	124	0.554	-1.1	2.0
Walk	SLS	-11.0	0.75	124	0.000	-12.4	-9.4
Walk	Run	-7.3	0.74	124	0.000	-8.7	-5.8
Walk	Cork	-1.0	0.94	124	0.285	-2.9	0.9
T Test	SLS	-11.4	0.77	124	0.000	-12.9	-9.8
T Test	Run	-7.7	0.77	124	0.000	-9.2	-6.2
T Test	Cork	-1.5	0.96	124	0.129	-3.4	0.4
SLS	Run	3.7	0.75	124	0.000	2.2	5.1
SLS	Cork	9.9	0.94	124	0.000	8.0	11.8
Run	Cork	6.3	0.94	124	0.000	4.4	8.1

Table 8.34 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-2.7	0.51	124	0.000	-3.7	-1.7

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.35 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the trunk relative to the pelvis in the sagittal plane; there were no statistically significant differences between Walking and the Trendelenburg Test (p=0.554), and between Walking and the Corkscrew Test (p=0.285), Table 8.34. There were statistically significant differences in the range of movement of trunk relative to the pelvis in the sagittal plane between Walking and Running (mean difference= -7.3^0, p=0.000), and between Walking and the Single Leg Squat (mean difference= -10.9^0, p=0.000), Table 8.34.

There were statistically significant differences in the range of movement trunk relative to the pelvis in the sagittal plane between Running and the Trendelenburg Test (mean=-7.7^0, p=0.000), between Running and the Single Leg Squat (mean difference= 3.7^0, p=0.000) and between Running and the Corkscrew Test (mean difference= 6.3^0, p=0.000),Table 8.34.

A significant difference was also seen between the professional football players and healthy participants (mean difference = -2.7^0, p=0.000),Table 8.35.

8.5.3.2 Trunk sagittal plane range of movement (right)

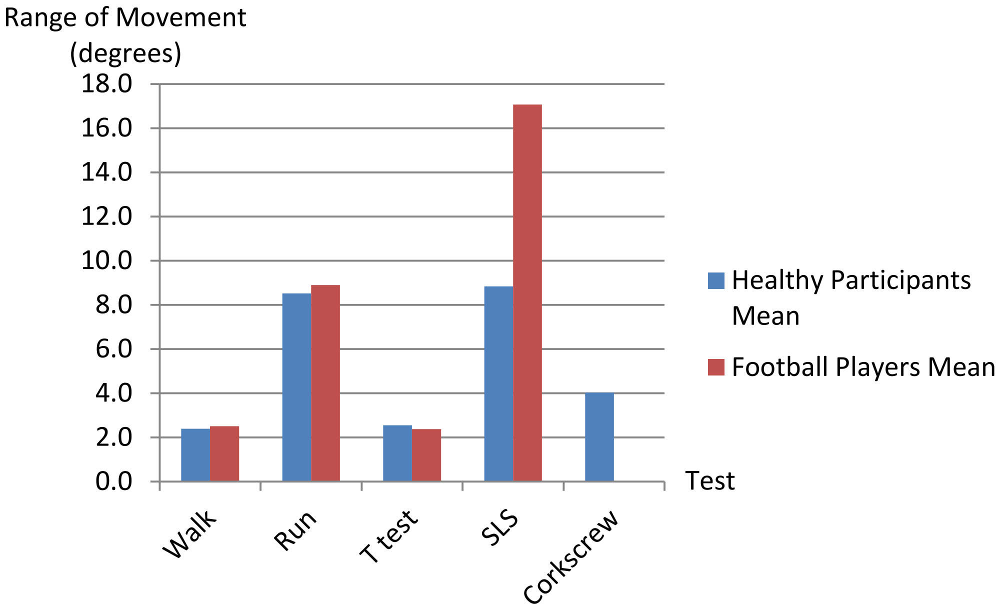


Figure 8.18 Trunk sagittal plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	2.4	0.86	2.5	0.81
Run	8.5	1.84	8.9	3.13
T test	2.5	1.82	2.4	0.98
SLS	8.8	5.25	17.1	6.72
Corkscrew	4.0	2.03		

Table 8.36 Trunk sagittal plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	-0.0	0.88	124	0.986	-1.7	1.7
Walk	SLS	-10.5	0.85	124	0.000	-12.2	-8.8
Walk	Run	-6.3	0.85	124	0.000	-7.9	-4.6
Walk	Cork	-1.5	1.07	124	0.143	-3.7	0.5
T Test	SLS	-10.5	0.88	124	0.000	-12.2	-8.7
T Test	Run	-6.2	0.88	124	0.000	-8.0	-4.5
T Test	Cork	-1.6	1.09	124	0.156	-3.7	0.6
SLS	Run	4.2	0.85	124	0.000	2.6	5.9
SLS	Cork	8.9	1.08	124	0.000	6.8	11.1
Run	Cork	4.7	1.07	124	0.000	2.6	6.8

Table 8.37 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-2.4	0.58	124	0.000	-3.6	-1.3

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.38 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the trunk relative to the pelvis in the sagittal plane; there were no statistically significant differences when comparing Walking to the Trendelenburg Test (p=0.986), or when comparing Walking to the Corkscrew Test (p=0.143). There were statistically significant differences when comparing Walking to Running (mean difference= -6.3^0, p=0.000), or when comparing Walking to the Single Leg Squat (mean difference= -10.5^0, p=0.000), Table 8.37.

There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference= -6.2^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference= 4.2^0, p=0.000), or when comparing Running to the Corkscrew Test (mean difference=4.7^0, p=0.000), Table 8.37.

A significant difference was also seen between the professional football players and healthy participants (mean difference = -2.4^0, p=0.000), Table 8.38.

However of interest is that the healthy participants and professional football players exhibited different trunk sagittal plane range of movement during the Single Leg Squat, where the healthy participants exhibited lower values (approximately 50%) than the professional football players for both left and right lower limb weight bearing, Table 8.33 and Table 8.36.

8.5.3.3 Trunk coronal plane range of movement (left)

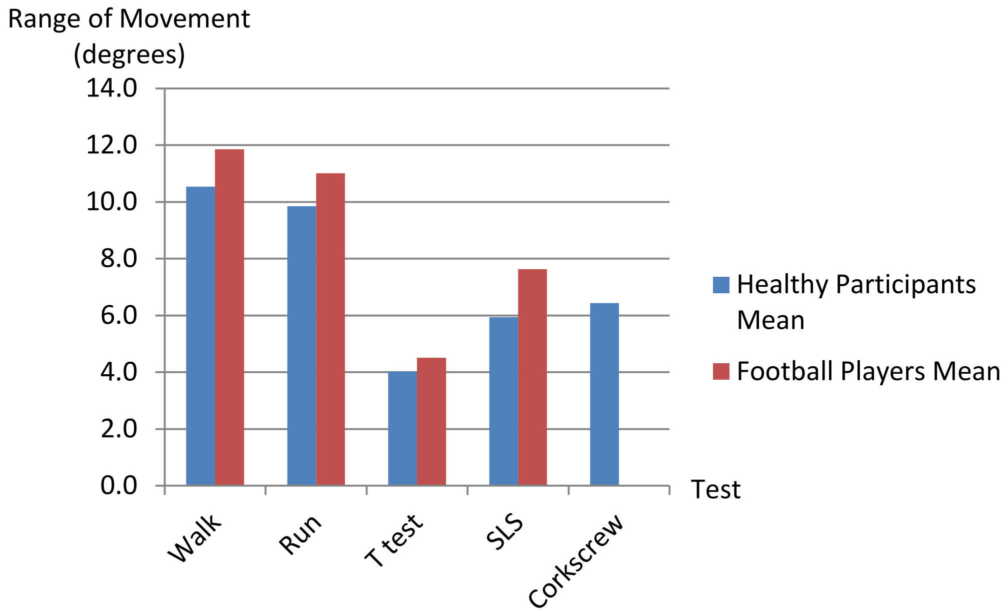


Figure 8.19 Trunk coronal plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	10.5	2.87	11.9	2.27
Run	9.9	3.00	11.0	2.43
T test	4.0	1.36	4.5	1.46
SLS	5.9	2.62	7.6	2.89
Corkscrew	6.4	3.50		

Table 8.39 Trunk coronal plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	6.9	0.68	124	0.000	5.6	8.3
Walk	SLS	4.4	0.66	124	0.000	3.1	5.7
Walk	Run	0.8	0.66	124	0.249	-0.5	2.1
Walk	Cork	4.8	0.83	124	0.000	3.1	6.4
T Test	SLS	-2.5	0.69	124	0.000	-3.9	-1.2
T Test	Run	-6.2	0.68	124	0.000	-7.5	-4.8
T Test	Cork	-2.2	0.85	124	0.012	-3.8	-0.5
SLS	Run	-3.6	0.66	124	0.000	-5.0	-2.3
SLS	Cork	0.4	0.83	124	0.673	-1.3	2.0
Run	Cork	4.0	0.83	124	0.000	2.4	5.6

Table 8.40 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-1.4	0.45	124	0.002	-2.3	-0.5

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.41 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the trunk relative to the pelvis in the coronal plane; there was no statistically significant difference between Walking and Running (p=0.249). There were statistically significant differences between Walking and the Trendelenburg Test (mean difference= 6.9^0, p=0.000), Walking and the Single Leg Squat (mean difference= 4.4^0, p=0.000), and Walking and the Corkscrew Test (mean difference= 4.8^0, p=0.000), Table 8.40.

There were statistically significant differences in the range of movement trunk relative to the pelvis in the coronal plane between Running and the Trendelenburg Test (mean difference= -6.2^0, p=0.000), Running and the Single Leg Squat (mean difference= -3.6^0, p=0.000), and Running Test and the Corkscrew Test (mean difference= 4.0^0, p=0.000), Table 8.40.

A significant difference was also seen between the professional football players and healthy participants (mean difference = -1.4^0, p=0.002), Table 8.41.

8.5.3.4 Trunk coronal plane range of movement (right)

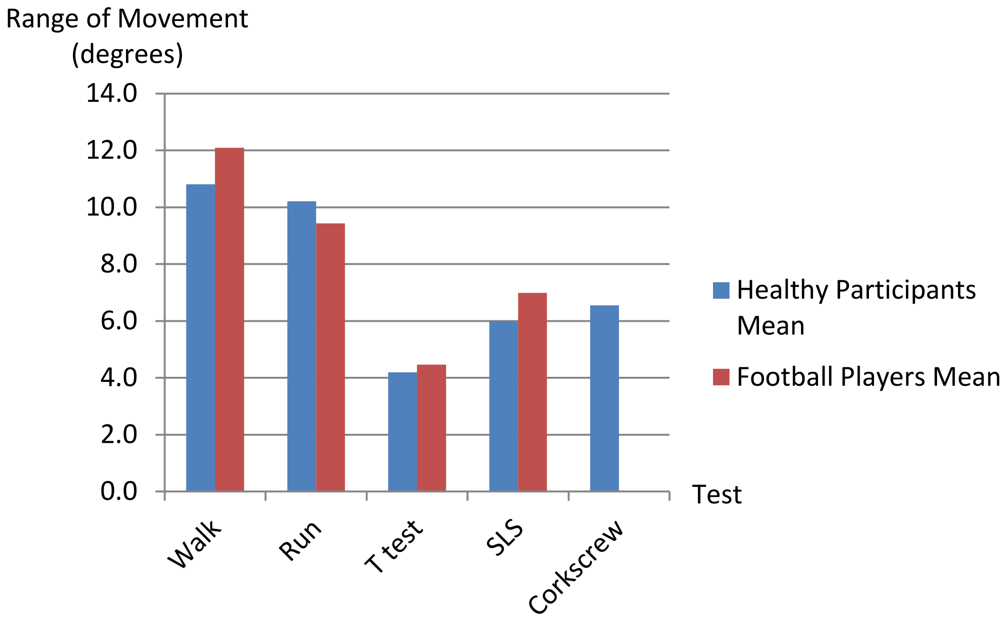


Figure 8.20 Trunk coronal plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	10.8	3.14	12.1	2.37
Run	10.2	2.54	9.4	2.55
T test	4.2	2.93	4.5	1.54
SLS	6.0	2.93	7.0	3.30
Corkscrew	6.5	5.55		

Table 8.42 Trunk coronal plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	7.1	0.83	124	0.000	5.5	8.8
Walk	SLS	5.0	0.81	124	0.000	3.4	6.5
Walk	Run	1.6	0.80	124	0.044	0.0	3.2
Walk	Cork	4.9	1.01	124	0.000	2.9	6.9
T Test	SLS	-2.2	0.83	124	0.011	-3.8	-0.5
T Test	Run	-5.5	0.83	124	0.000	-7.1	-3.9
T Test	Cork	-2.2	1.03	124	0.034	-4.3	-.2
SLS	Run	-3.3	0.81	124	0.000	-4.9	-1.7
SLS	Cork	-0.1	1.02	124	0.958	-2.1	2.0
Run	Cork	3.3	1.01	124	0.002	1.3	5.3

Table 8.43 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-0.7	0.55	124	0.212	-1.8	0.4

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.44 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the trunk relative to the pelvis in the coronal plane; there were statistically significant differences when comparing Walking and Running (mean difference=1.6^0, p=0.044), when comparing Walking to the Trendelenburg Test (mean difference= 7.1^0, p=0.000), or when comparing Walking to Single Leg Squat (mean difference= 5.0^0, p=0.000), or when comparing Walking to the Corkscrew Test (mean difference= 4.9^0, p=0.000), Table 8.43.

There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference= -5.5^0, p=0.000), when comparing Running to Single Leg Squat (mean difference= -3.3^0, p=0.000), or when comparing Running to the Corkscrew Test (mean difference= 3.3^0, p=0.002), Table 8.43.

No significant difference was also seen between the professional football players and healthy participants (p=0.212), Table 8.44.

8.5.3.5 Trunk coronal plane peak value (left)

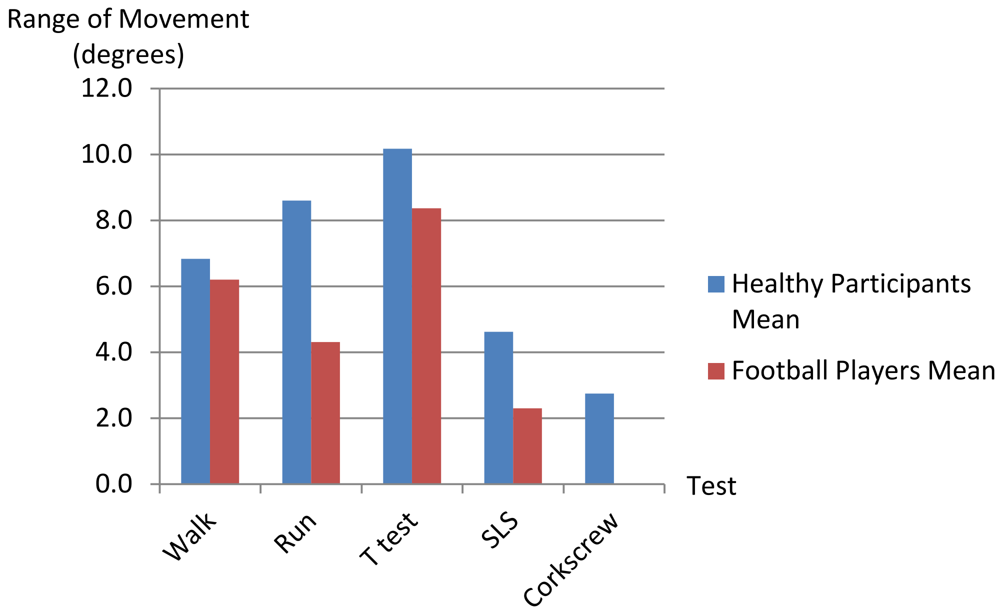


Figure 8.21 Trunk coronal plane peak value normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	6.8	2.15	6.2	2.91
Run	8.6	2.48	4.3	4.29
T test	10.2	5.81	8.4	6.28
SLS	4.6	3.91	2.3	4.62
Corkscrew	2.7	3.98		

Table 8.45 Trunk coronal plane peak value normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	-2.8	1.11	124	0.015	-5.0	-0.5
Walk	SLS	3.1	1.08	124	0.006	0.9	5.2
Walk	Run	0.1	1.08	124	0.952	-2.16	2.2
Walk	Cork	3.8	1.36	124	0.006	1.1	6.5
T Test	SLS	5.8	1.12	124	0.000	3.6	8.0
T Test	Run	2.8	1.11	124	0.013	0.6	5.0
T Test	Cork	6.5	1.39	124	0.000	3.8	9.3
SLS	Run	-3.0	1.08	124	0.007	-5.1	-0.8
SLS	Cork	0.7	1.37	124	0.600	-2.0	3.4
Run	Cork	3.7	1.36	124	0.007	1.0	6.4

Table 8.46 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	1.3	0.73	124	0.079	-0.2	2.8

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.47 Comparison between professional football players and healthy participants (tests combined)

For the peak value of the trunk relative to the pelvis in the coronal plane; there were no statistically significant differences between Walking and Running (p=0.952). There was a statistically significant difference when comparing Walking and the Trendelenburg Test (mean=-2.8^0, p=0.015), when comparing Walking to the Single Leg Squat (mean=3.1^0, p=0.006), or when comparing Walking with the Corkscrew Test (mean=3.8^0, p=0.006), Table 8.46

There was a statistically significant difference when comparing Running and the Trendelenburg Test (mean=2.8^0, p=0.013), when comparing Running to the Single Leg Squat (mean=-3.0^0, p=0.007), or when comparing Running to the Corkscrew Test (mean=3.7^0, p=0.007), Table 8.46.

No significant difference was seen between the professional football players and healthy participants (p=0.079), Table 8.47. Of interest is that the during all of the tests the healthy participants exhibited larger trunk coronal plane peak value than the professional football players, Table 8.45.

8.5.3.6 Trunk coronal plane peak value (right)

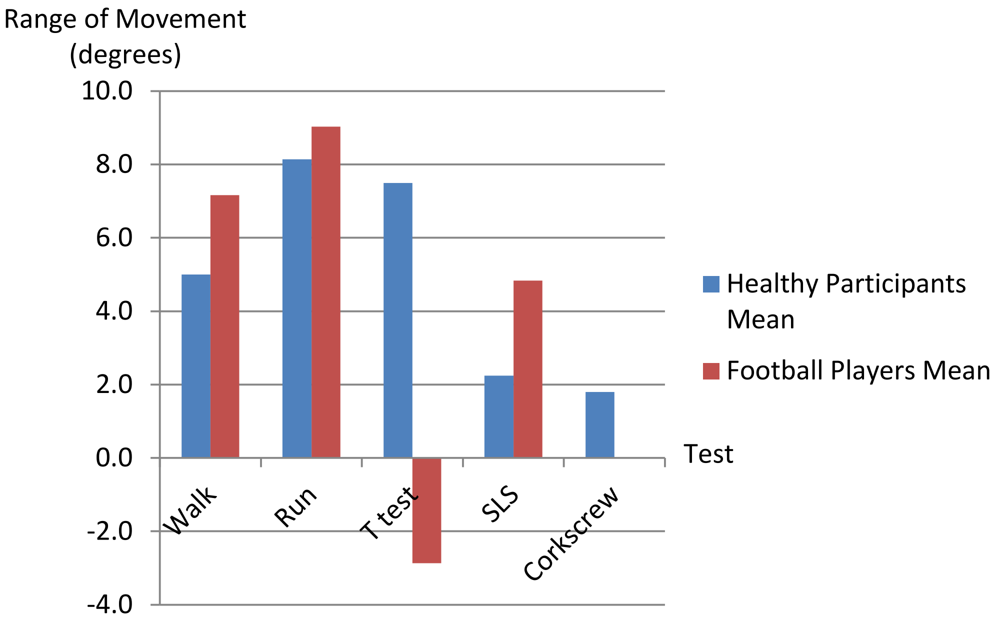


Figure 8.22 Trunk coronal plane peak value normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	5.0	3.04	7.2	2.77
Run	8.1	2.27	9.0	3.51
T test	7.5	5.64	-2.9	5.61
SLS	2.2	4.42	4.8	3.27
Corkscrew	1.8	3.87		

Table 8.48 Trunk coronal plane peak value normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	3.8	1.04	124	0.000	1.7	5.8
Walk	SLS	2.5	1.01	124	0.013	0.6	4.5
Walk	Run	-2.5	1.00	124	0.014	-4.5	-0.5
Walk	Cork	4.3	1.27	124	0.001	1.8	6.8
T Test	SLS	-1.2	1.04	124	0.241	-3.3	0.8
T Test	Run	-6.3	1.04	124	0.000	-8.3	-4.2
T Test	Cork	0.5	1.29	124	0.692	-2.0	3.1
SLS	Run	-5.0	1.01	124	0.000	-7.0	-3.1
SLS	Cork	1.7	1.27	124	0.173	-0.8	4.3
Run	Cork	6.8	1.27	124	0.000	4.3	9.3

Table 8.49 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	0.4	0.68	124	0.563	-1.0	1.7

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.50 Comparison between professional football players and healthy participants (tests combined)

For the peak value of the trunk relative to the pelvis in the coronal plane; there were statistically significant differences between Walking and Running (mean=-2.5^0, p=0.014), when comparing Walking with the Trendelenburg Test (mean=3.8^0, p=0.000), when comparing Walking with the Single Leg Squat (mean=2.5^0, p=0.013), or when comparing Walking with the Corkscrew Test (mean=4.3^0, p=0.001), Table 8.49.

There were statistically significant differences between Running and the Trendelenburg Test (mean=-6.3^0, p=0.000), when comparing Running with the Single Leg Squat (mean=-5.0^0, p=0.000), or when comparing Running with the Corkscrew Test (mean=6.8^0, p=0.000), Table 8.49.

No significant difference was seen overall between the Professional Football Players and Healthy Participants (p=0.563), Table 8.50.

However of interest is that the during the Trendelenburg Test the healthy participants exhibited a coronal plane peak value of 7.5^0 but the professional football players a coronal plane peak value of 2.9^0 in the opposite direction, Table 8.48.

8.5.3.7 Trunk transverse plane range of movement (left)

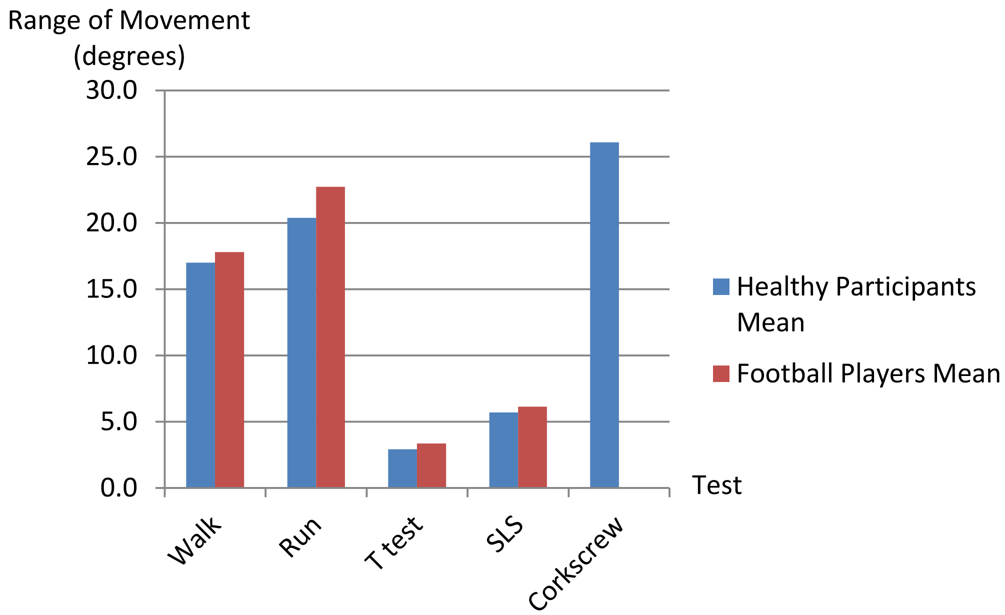


Figure 8.23 Trunk transverse plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	17.0	5.27	17.8	4.82
Run	20.4	5.01	22.7	5.60
T test	2.9	2.60	3.4	2.42
SLS	5.7	2.58	6.1	2.24
Corkscrew	26.1	17.40		

Table 8.51 Trunk transverse plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	14.3	1.81	124	0.000	10.7	17.8
Walk	SLS	11.5	1.76	124	0.000	8.0	15.0
Walk	Run	-4.2	1.75	124	0.019	-7.6	-0.7
Walk	Cork	-8.7	2.21	124	0.000	-13.0	-4.3
T Test	SLS	-2.8	1.82	124	0.129	-6.4	0.8
T Test	Run	-18.4	1.81	124	0.000	-22.0	-14.8
T Test	Cork	-22.9	2.26	124	0.000	-27.4	-18.5
SLS	Run	-15.6	1.76	124	0.000	-19.1	-12.1
SLS	Cork	-20.1	2.22	124	0.000	-24.5	-15.8
Run	Cork	-4.5	2.20	124	0.043	-8.9	-0.1

Table 8.52 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	1.9	1.19	124	0.113	-0.46	4.3

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.53 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the trunk relative to the pelvis in the transverse plane; there were statistically significant differences when comparing Walking and Running (mean difference=-4.2^0, p=0.019), when comparing the Walking to the Trendelenburg Test (mean difference= 14.3^0, p=0.000), when comparing Walking to the Single Leg Squat (mean difference= 11.5^0, p=0.000), or when comparing Walking to the Corkscrew Test (mean difference= -8.7^0, p=0.000), Table 8.52.

There were statistically significant difference when comparing Running to the Trendelenburg Test (mean difference= -18.4^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference= -15.6^0, p=0.000), or when comparing Running to the Corkscrew Test (mean difference=-4.5^0, p=0.043), Table 8.52.

No significant difference was seen between the professional football players and healthy participants (p=0.113), Table 8.53.

8.5.3.8 Trunk transverse plane range of movement (right)

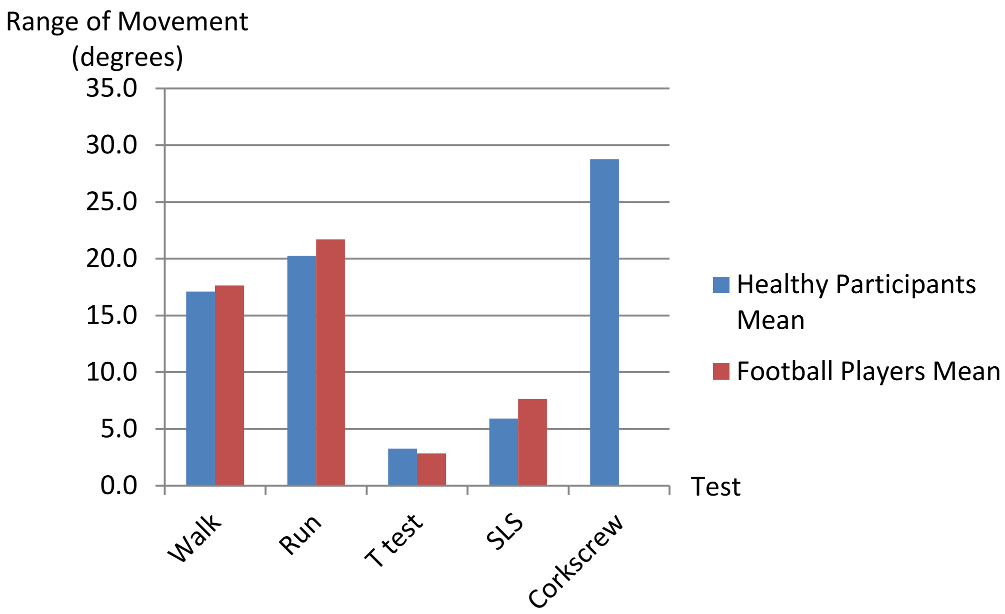


Figure 8.24 Trunk transverse plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	17.1	5.10	17.6	4.36
Run	20.3	3.84	21.7	6.34
T test	3.3	1.40	2.8	0.93
SLS	5.9	3.12	7.6	2.94
Corkscrew	28.8	16.00		

Table 8.54 Trunk transverse plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	14.3	1.69	124	0.000	11.0	17.7
Walk	SLS	10.6	1.65	124	0.000	7.3	13.9
Walk	Run	-3.6	1.64	124	0.029	-6.8	-0.4
Walk	Cork	-11.4	2.07	124	0.000	-15.5	-7.3
T Test	SLS	-3.7	1.70	124	0.031	-7.1	-0.3
T Test	Run	-17.9	1.69	124	0.000	-21.3	-14.6
T Test	Cork	-25.7	2.11	124	0.000	-29.9	-21.5
SLS	Run	-14.2	1.65	124	0.000	-17.5	-11.0
SLS	Cork	-22.0	2.08	124	0.000	-26.1	-17.9
Run	Cork	-7.8	2.07	124	0.000	-11.9	-3.7

Table 8.55 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	2.6	1.12	124	0.021	0.4	4.8

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.56 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the trunk relative to the pelvis in the transverse plane; there were statistically significant differences when comparing Walking to Running (mean difference=-3.6^0, p=0.029), when comparing Walking to the Trendelenburg Test (mean difference= 14.3^0, p=0.000), when comparing Walking to Single Leg Squat (mean difference= 10.6^0, p=0.000), or when comparing Walking to the Corkscrew Test (mean difference= -11.4^0, p=0.000), Table 8.55.

There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference= -17.9^0, p=0.000), when comparing Running to Single Leg Squat (mean difference= -14.2^0, p=0.000), or when comparing Running to the Corkscrew Test (mean difference= -7.8^0, p=0.000), Table 8.55.

A significant difference was also seen between the professional football players and healthy participants (mean difference=2.6^0, p=0.021), Table 8.56.

8.5.4 Pelvis movement

8.5.4.1 Pelvis sagittal plane range of movement (left)

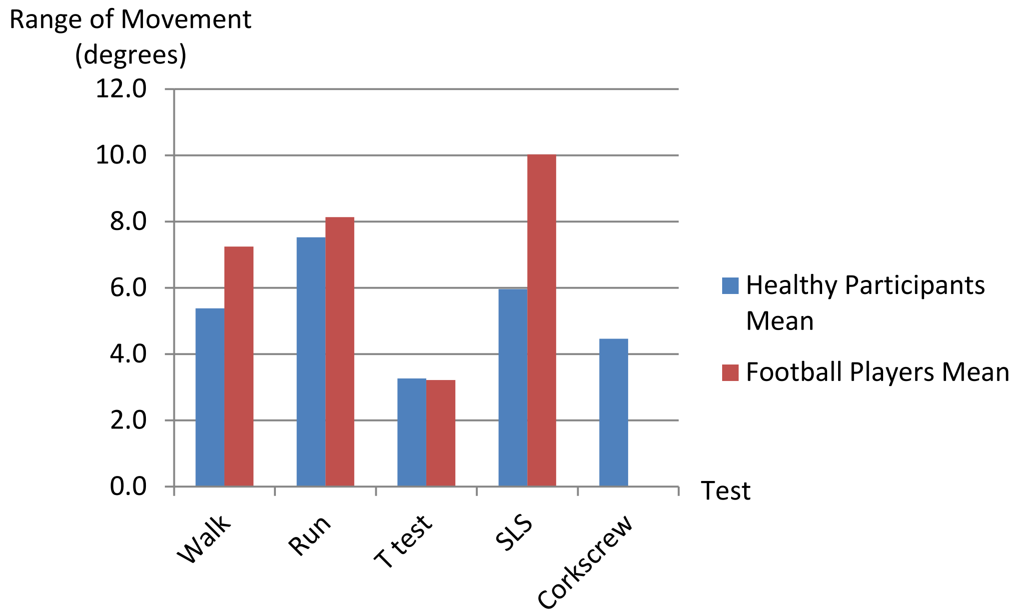


Figure 8.25 Pelvis sagittal plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	5.4	1.59	7.2	1.73
Run	7.5	1.75	8.1	1.96
T test	3.3	1.75	3.2	1.15
SLS	6.0	3.11	10.0	4.28
Corkscrew	4.5	2.51		

Table 8.57 Pelvis sagittal plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	3.1	0.64	124	0.000	1.8	4.3
Walk	SLS	-1.7	0.62	124	0.008	-2.9	-0.5
Walk	Run	-1.5	0.62	124	0.015	-2.7	-0.3
Walk	Cork	1.9	0.78	124	0.019	0.31	3.4
T Test	SLS	-4.8	0.64	124	0.000	-6.0	-3.5
T Test	Run	-4.6	0.64	124	0.000	-5.9	-3.3
T Test	Cork	-1.2	0.79	124	0.126	-2.8	0.35
SLS	Run	0.2	0.62	124	0.797	-1.1	1.4
SLS	Cork	3.5	0.78	124	0.000	2.0	5.1
Run	Cork	3.4	0.78	124	0.000	1.8	4.9

Table 8.58 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-1.8	0.42	124	0.000	-2.7	-1.0

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.59 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the laboratory relative to the pelvis in the sagittal plane; there were statistically significant differences when comparing Walking to Running (mean difference=-1.5^0, p=0.015), when comparing Walking to the Trendelenburg Test (mean difference= 3.1^0, p=0.000), when comparing Walking to the Single Leg Squat (mean difference=-1.7^0, p=0.008), and when comparing Walking to the Corkscrew Test (mean difference=1.9^0, p=0.019), Table 8.58.

There was no statistically significant difference when comparing Running to the Single Leg Squat (p=0.797). There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference= -4.6^0, p=0.000), and when comparing Running to the Corkscrew Test (mean difference= 3.4^0, p=0.000), Table 8.58.

A significant difference was also seen between the professional football players and healthy participants (mean difference = -1.8^0, p=0.000), Table 8.59.

8.5.4.2 Pelvis sagittal plane range of movement (right)

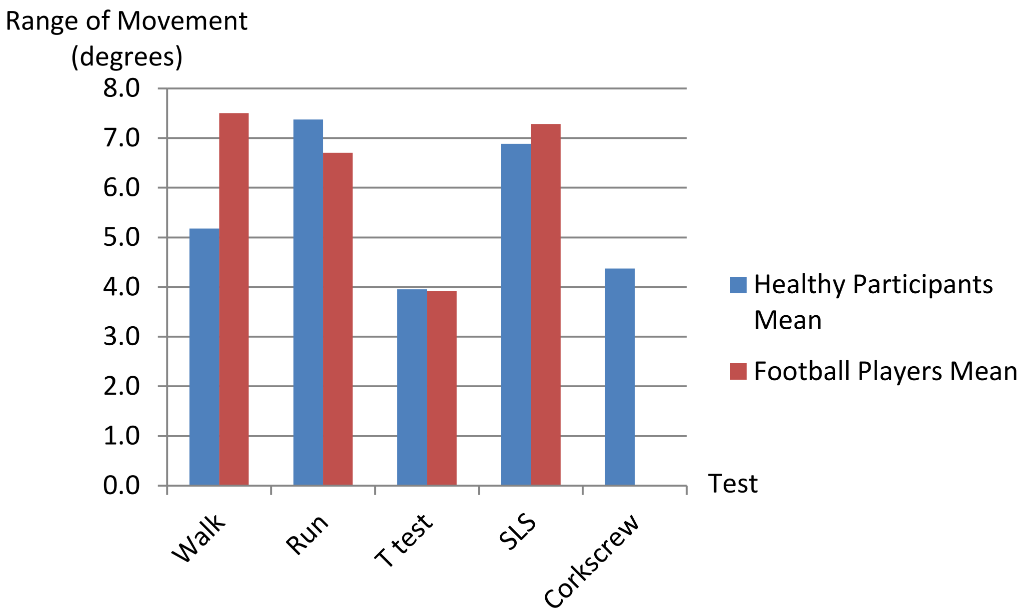


Figure 8.26 Pelvis sagittal plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	5.2	1.22	7.5	1.44
Run	7.4	2.18	6.7	1.82
T test	4.0	2.32	3.9	1.42
SLS	6.9	4.08	7.3	3.31
Corkscrew	4.4	2.93		

Table 8.60 Pelvis sagittal plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	2.4	0.65	124	0.000	1.1	3.7
Walk	SLS	-0.7	0.63	124	0.242	-2.0	0.5
Walk	Run	-0.7	0.63	124	0.268	-1.9	0.5
Walk	Cork	2.0	0.80	124	0.015	0.4	3.5
T Test	SLS	-3.1	0.66	124	0.000	-4.4	-1.9
T Test	Run	-3.1	0.65	124	0.000	-4.4	-1.8
T Test	Cork	-0.4	0.81	124	0.594	-2.0	1.2
SLS	Run	0.0	0.63	124	0.944	-1.2	1.3
SLS	Cork	2.7	0.80	124	0.001	1.1	4.3
Run	Cork	2.7	0.80	124	0.001	1.1	4.2

Table 8.61 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-0.8	0.43	124	0.064	-1.7	0.0

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.62 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the pelvis relative to the laboratory in the sagittal plane; there was no statistically significant difference when comparing Walking to Running (p=0.268), or when comparing Walking to the Single Leg Squat (p=0.242). There were statistically significant differences when comparing Walking to the Trendelenburg Test (mean difference= 2.4^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference=2.0^0, p=0.015), Table 8.61.

There was no statistically significant differences when comparing Running to the Single Leg Squat (p=0.944). There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference=-3.1^0, p=0.000), and when comparing Running to the Corkscrew Test (mean difference=2.7^0, p=0.001), Table 8.61.

No significant difference was also seen between the professional football players and healthy participants (p=0.064), Table 8.62.

However of interest is that the professional football players and healthy participants exhibited different pelvis sagittal plane range of movement during the Single Leg Squat, where the healthy participants exhibited lower values (approximately 40% lower) than the professional football players during left lower limb weight bearing but similar during right lower limb weight bearing, Figure 8.25, Table 8.57, and Figure 8.26, Table 8.60.

8.5.4.3 Pelvis coronal plane range of movement (left)

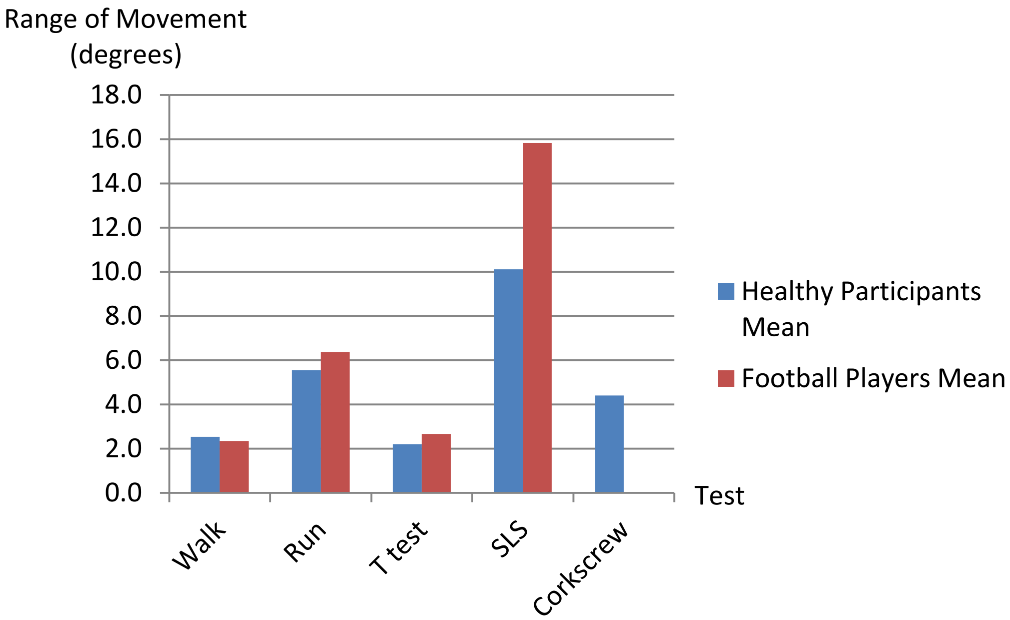


Figure 8.27 Pelvis coronal plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	2.5	0.70	2.3	0.92
Run	5.5	1.01	6.4	1.30
T test	2.2	0.92	2.7	1.41
SLS	10.1	5.56	15.8	9.11
Corkscrew	4.4	1.68		

Table 8.63 Pelvis coronal plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	0.0	1.00	124	1.000	-2.0	2.0
Walk	SLS	-10.5	0.97	124	0.000	-12.5	-8.6
Walk	Run	-3.5	0.97	124	0.000	-5.4	-1.6
Walk	Cork	-2.0	1.22	124	0.110	-4.4	0.5
T Test	SLS	-10.5	1.01	124	0.000	-12.5	-8.5
T Test	Run	-3.5	1.00	124	0.001	-5.5	-1.5
T Test	Cork	-2.0	1.245	124	0.118	-4.4	0.5
SLS	Run	7.0	0.97	124	0.000	5.1	8.9
SLS	Cork	8.6	1.23	124	0.000	6.1	11.0
Run	Cork	1.6	1.22	124	0.204	-0.9	4.0

Table 8.64 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-1.8	0.66	124	0.006	-3.2	-0.5

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.65 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the pelvis relative to the laboratory in the coronal plane; there was no statistically significant difference between Walking and the Trendelenburg Test (p=1.000). There was a statistically significant difference when comparing Walking to Running (mean difference= -3.5^0, p=0.000), when comparing Walking to the Single Leg Squat (mean difference= -10.5^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference=-2.0^0, p=0.110), Table 8.64.

There was no statistically significant difference when comparing Running to the Corkscrew Test (p=0.204). There was a statistically significant difference when comparing Running to the Trendelenburg Test (mean difference= -3.5^0, p=0.001), and when comparing Running to the Single Leg Squat (mean difference= 7.0^0, p=0.000), Table 8.64.

A significant difference was also seen between the professional football players and healthy participants (mean difference = -1.8^0, p=0.006), Table 8.65.

8.5.4.4 Pelvis coronal plane range of movement (right)

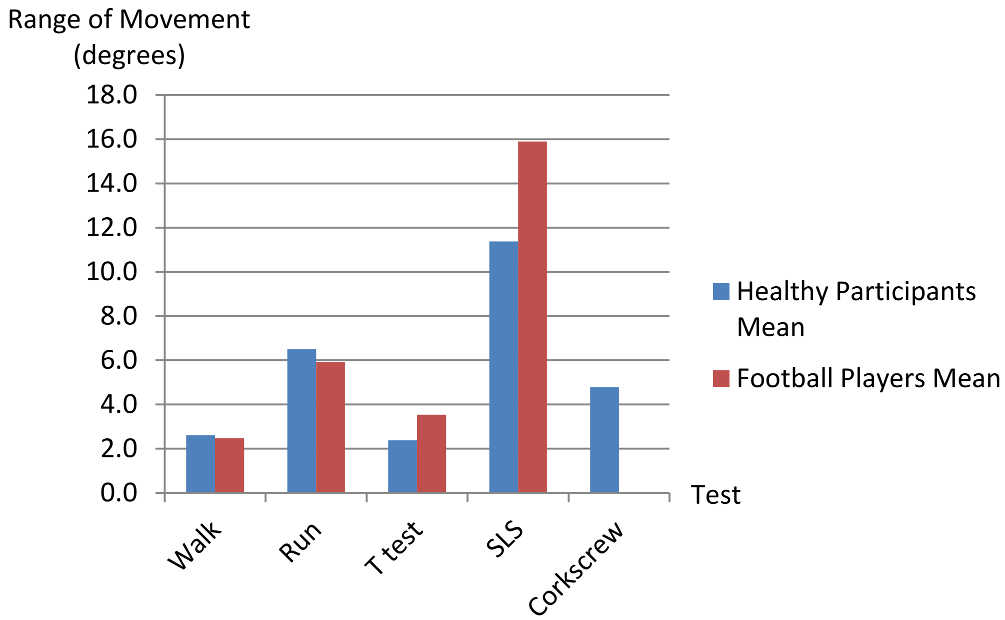


Figure 8.28 Pelvis coronal plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	2.6	0.95	2.5	0.70
Run	6.5	1.50	5.9	1.64
T test	2.4	1.14	3.5	1.95
SLS	11.4	7.20	15.9	7.06
Corkscrew	4.8	2.35		

Table 8.66 Pelvis coronal plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	-0.4	0.96	124	0.664	-2.3	1.5
Walk	SLS	-11.1	0.94	124	0.000	-12.9	-9.2
Walk	Run	-3.7	0.93	124	0.000	-5.5	-1.8
Walk	Cork	-2.2	1.18	124	0.059	-4.6	0.1
T Test	SLS	-10.7	0.97	124	0.000	-12.6	-8.8
T Test	Run	-3.3	0.96	124	0.001	-5.2	-1.4
T Test	Cork	-1.8	1.20	124	0.132	-4.2	0.6
SLS	Run	7.4	0.94	124	0.000	5.6	9.3
SLS	Cork	8.8	1.18	124	0.000	6.5	11.2
Run	Cork	1.4	1.18	124	0.224	-0.9	3.8

Table 8.67 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-1.4	0.64	124	0.026	-2.7	-0.2

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.68 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the pelvis relative to the laboratory in the coronal plane; there was no statistically significant difference when comparing Walking to the Trendelenburg Test (p=0.664), or when comparing Walking to the Corkscrew Test (p=0.059). There were statistically significant differences when comparing Walking to Running (mean difference= -3.7^0, p=0.000), and when comparing Walking to the Single Leg Squat (mean difference= -11.1^0, p=0.000), Table 8.67.

There were no statistically significant differences when comparing Running to the Corkscrew Test (p=0.224). There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference= -3.3^0, p=0.001), and when comparing Running to the Single Leg Squat (mean difference= 7.4^0, p=0.000), Table 8.67.

A significant difference was seen between the professional football players and healthy participants (mean difference=-1.4^0, p=0.026), Table 8.68.

However of interest is that the professional football players and healthy participants exhibited different pelvis coronal plane range of movement during the Single Leg Squat, where the healthy participants exhibited lower values than the professional football players for both left and right lower limb weight bearing, Table 8.63 and Table 8.66.

8.5.4.5 Pelvis coronal plane peak value (left)

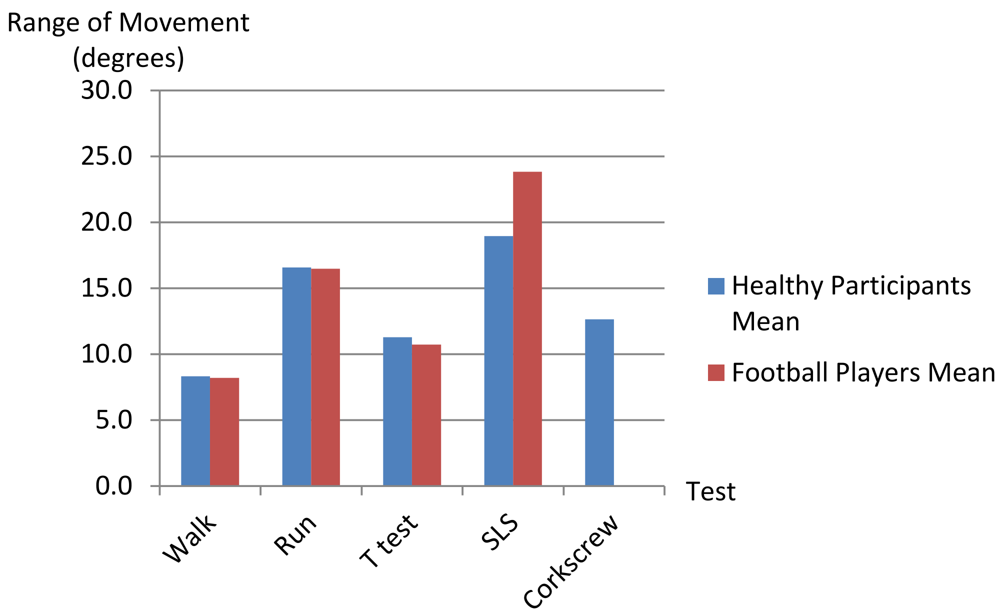


Figure 8.29 Pelvis coronal plane peak value normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	8.3	4.82	8.2	4.07
Run	16.6	5.26	16.5	3.82
T test	11.3	4.81	10.7	9.91
SLS	18.9	9.46	23.8	11.52
Corkscrew	12.6	5.38		

Table 8.69 Pelvis coronal plane peak value normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	-2.7	1.86	124	0.143	-6.4	0.9
Walk	SLS	-13.1	1.81	124	0.000	-16.7	-9.5
Walk	Run	-8.3	1.80	124	0.000	-11.8	-4.7
Walk	Cork	-4.4	2.28	124	0.056	-8.9	0.1
T Test	SLS	-10.4	1.87	124	0.000	-14.1	-6.7
T Test	Run	-5.5	1.86	124	0.004	-9.2	-1.8
T Test	Cork	-1.6	2.32	124	0.481	-6.2	3.0
SLS	Run	4.9	1.81	124	0.008	1.3	8.4
SLS	Cork	8.7	2.29	124	0.000	4.2	13.3
Run	Cork	3.9	2.28	124	0.090	-0.6	8.4

Table 8.70 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-1.2	1.23	124	0.312	-3.682	1.2

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.71 Comparison between professional football players and healthy participants (tests combined)

For the peak value of the pelvis relative to the laboratory in the coronal plane; there were no statistically significant differences between the Walking and Trendelenburg Test (p=0.143), or when comparing Walking and Corkscrew Test (p=0.056). There was a difference between Walking and Running (mean difference=-8.3^0, p=0.000), and Walking and the Single Leg Squat (mean difference=-13.1^0, p=0.000), Table 8.70.

There was no significant difference between Running and the Corkscrew Test (p=0.090). There was a significant difference between Running and Trendelenburg Test (mean difference=-5.5^0, p=0.004), and Running and Single Leg Squat (mean difference=4.9^0, p=0.008), Table 8.70.

No significant difference was seen between the professional football players and healthy participants (p=0.312), Table 8.71.

8.5.4.6 Pelvis coronal plane peak value (right)

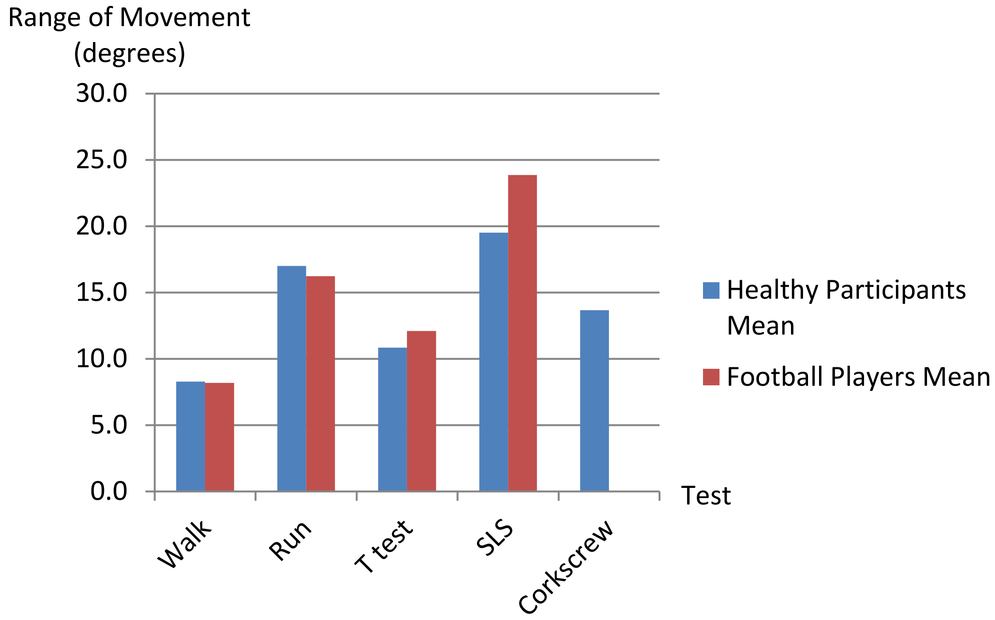


Figure 8.30 Pelvis coronal plane peak value normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	8.3	5.14	8.2	3.91
Run	17.0	5.88	16.2	4.25
T test	10.8	4.96	12.1	8.53
SLS	19.5	11.04	23.9	8.21
Corkscrew	13.7	5.34		

Table 8.72 Pelvis coronal plane peak value normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	-3.2	1.76	124	0.068	-6.7	.2
Walk	SLS	-13.5	1.71	124	0.000	-16.8	-10.1
Walk	Run	-8.4	1.70	124	0.000	-11.7	-5.0
Walk	Cork	-5.4	2.15	124	0.013	-9.7	-1.2
T Test	SLS	-10.2	1.77	124	0.000	-13.7	-6.7
T Test	Run	-5.1	1.76	124	0.004	-8.6	-1.7
T Test	Cork	-2.2	2.19	124	0.319	-6.5	2.1
SLS	Run	5.1	1.71	124	0.004	1.7	8.5
SLS	Cork	8.0	2.16	124	0.000	3.8	12.3
Run	Cork	3.0	2.15	124	0.171	-1.3	7.2

Table 8.73 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-1.2	1.16	124	0.290	-3.526	1.1

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.74 Comparison between professional football players and healthy participants (tests combined)

For the peak value of the pelvis relative to the laboratory in the coronal plane; there were no statistically significant differences between Walking and the Trendelenburg Test (p=0.068). There were statistically significant differences between the Walking and Running (mean difference=-8.4^0, p=0.000), Walking and the Single Leg Squat (mean difference=-13.5^0, p=0.000), and Walking and the Corkscrew Test (mean difference=-5.4^0, p=0.013), Table 8.73.

There was no statistically significant difference between Running and the Corkscrew Test (p=0.171). There was a significant difference between the Running and the Trendelenburg Test (mean difference=-5.1^0, p=0.004), and Running and the Single Leg Squat (mean difference=-5.1^0, p=0.004), Table 8.73.

No significant difference was seen between the professional football players and healthy participants (p=0.290), Table 8.74.

However of interest is that the healthy participants and professional football players exhibited similar pelvis coronal plane peak value during the tests, except for the Single Leg Squat where the healthy participants exhibited lower values than the professional football players for both left and right lower limb weight bearing, Table 8.69 and Table 8.72.

8.5.4.7 Pelvis transverse plane range of movement (left)

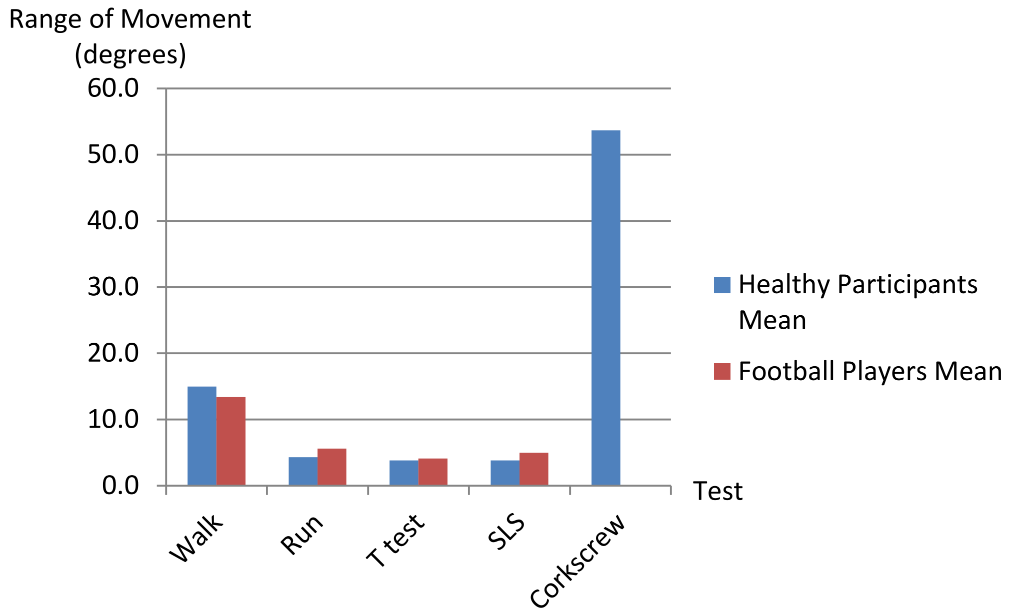


Figure 8.31 Pelvis transverse plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	15.0	5.24	13.4	4.06
Run	4.3	3.05	5.6	3.10
T test	3.8	1.43	4.1	1.28
SLS	3.8	1.03	5.0	3.00
Corkscrew	53.6	17.48		

Table 8.75 Pelvis transverse plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	10.2	1.69	124	0.000	6.9	13.5
Walk	SLS	9.8	1.64	124	0.000	6.5	13.0
Walk	Run	9.2	1.63	124	0.000	6.0	12.4
Walk	Cork	-39.5	2.06	124	0.000	-43.6	-35.4
T Test	SLS	-0.4	1.70	124	0.801	-3.8	2.9
T Test	Run	-1.0	1.69	124	0.559	-4.3	2.3
T Test	Cork	-49.7	2.11	124	0.000	-53.8	-45.5
SLS	Run	-0.6	1.64	124	0.734	-3.8	2.7
SLS	Cork	-49.3	2.70	124	0.000	-53.4	-45.2
Run	Cork	-48.7	2.06	124	0.000	-52.8	-44.6

Table 8.76 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	9.1	1.11	124	0.000	6.9	11.3

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.77 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the pelvis relative to the laboratory in the transverse plane; there was a statistically significant difference when comparing Walking to Running (mean difference= 9.2^0, p=0.000), when comparing Walking to the Trendelenburg Test (mean difference= 10.2^0, p=0.000), when comparing Walking to the Single Leg Squat (mean difference= 9.8^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference= -39.5^0, p=0.000), Table 8.76.

There was no statistically significant difference in the range of movement of the pelvis relative to the laboratory in the transverse plane when comparing Running to the Trendelenburg Test (p=0.559), or when comparing Running to the Single Leg Squat (p=0.734). There was a statistically significant difference when comparing Running to the Corkscrew Test (mean difference= -48.7^0, p=0.000), Table 8.76.

A significant difference was seen between the professional football players and healthy participants (mean difference=9.1^0, p=0.000), Table 8.77.

8.5.4.8 Pelvis transverse plane range of movement (right)

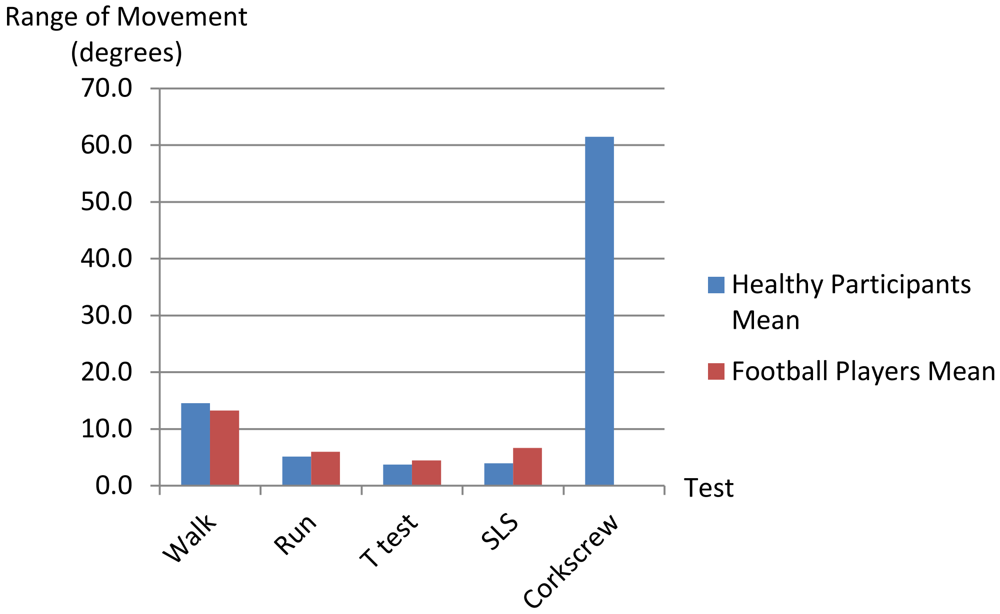


Figure 8.32 Pelvis transverse plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	14.6	5.28	13.3	3.68
Run	3.7	2.07	4.5	1.56
T test	4.0	2.19	6.6	3.41
SLS	5.1	2.50	6.0	2.96
Corkscrew	61.5	18.82		

Table 8.78 Pelvis transverse plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	9.8	1.79	124	0.000	6.3	13.4
Walk	SLS	8.6	1.75	124	0.000	5.1	12.1
Walk	Run	8.4	1.73	124	0.000	4.9	11.8
Walk	Cork	-47.6	2.19	124	0.000	-51.9	-43.2
T Test	SLS	-1.2	1.81	124	0.503	-4.8	2.4
T Test	Run	-1.4	1.79	124	0.423	-5.0	2.1
T Test	Cork	-57.4	2.24	124	0.000	-61.8	-53.0
SLS	Run	-0.2	1.75	124	0.895	-3.7	3.2
SLS	Cork	-56.2	2.20	124	0.000	-60.5	-51.8
Run	Cork	-55.9	2.19	124	0.000	-60.3	-51.6

Table 8.79 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	10.2	1.18	124	0.000	7.8	12.5

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.80 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the pelvis relative to the laboratory in the transverse plane; there was a statistically significant difference when comparing Walking to Running (mean difference= 8.4^0, p=0.000), when comparing Walking to the Trendelenburg Test (mean difference= 9.8^0,p=0.000), when comparing Walking to the Single Leg Squat (mean difference= 8.6^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference= -47.6^0, p=0.000), Table 8.79.

There were no statistically significant differences when comparing Running to the Trendelenburg Test (p=0.423), or when comparing Running to the Single Leg Squat (p=0.895). There was a statistically significant when comparing Running to the Corkscrew Test (mean difference= -55.9^0, p=0.000), Table 8.79.

A significant difference was seen between the professional football players and healthy participants (mean difference=10.2^0, p=0.000), Table 8.80.

However of interest is that the Corkscrew Test exhibited approximately four times greater pelvis transverse plane range of movement for both left and right lower limb weight bearing than the other tests, Figure 8.31, Table 8.75, and Figure 8.32, Table 8.78.

8.5.5 Hip movement

8.5.5.1 Hip sagittal plane range of movement (left)

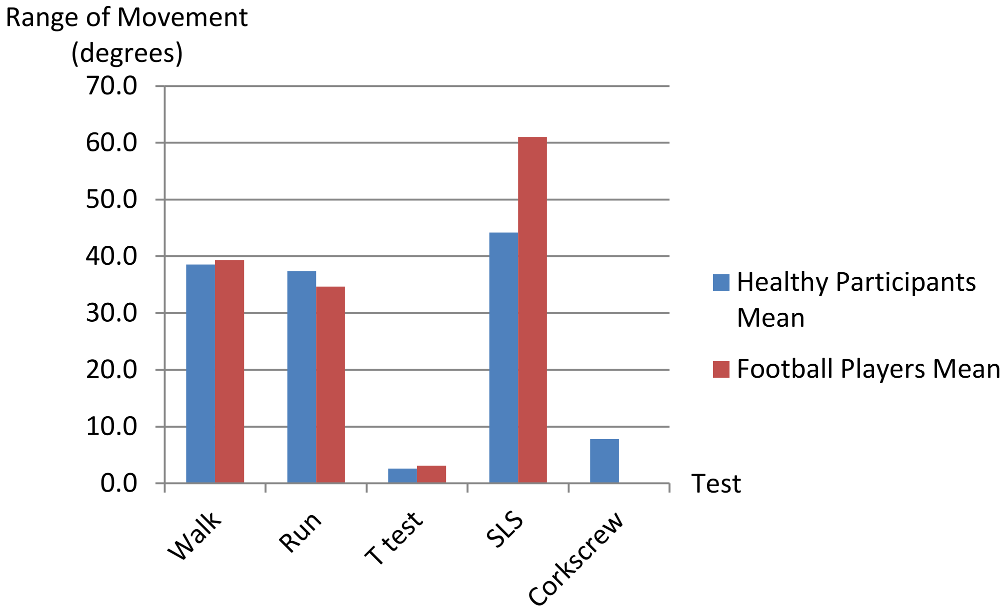


Figure 8.33 Hip sagittal plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (Standard Deviation)
Walk	38.6	6.89	39.3	5.17
Run	37.4	5.12	34.7	7.66
T test	2.6	1.60	3.1	0.95
SLS	44.2	13.70	61.0	11.58
Corkscrew	7.8	4.30		

Table 8.81 Hip sagittal plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	36.1	1.99	124	0.000	32.2	40.1
Walk	SLS	-13.6	1.939	124	0.000	-17.5	-9.8
Walk	Run	2.9	1.94	124	0.131	-0.9	6.7
Walk	Cork	31.2	2.43	124	0.000	26.4	36.0
T Test	SLS	-49.7	2.00	124	0.000	-53.7	-45.8
T Test	Run	-33.2	1.99	124	0.000	-37.1	-29.2
T Test	Cork	-4.9	2.49	124	0.050	-9.8	0.0
SLS	Run	16.6	1.94	124	0.000	12.7	20.4
SLS	Cork	44.8	2.44	124	0.000	40.0	49.7
Run	Cork	28.3	2.43	124	0.000	23.4	33.1

Table 8.82 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-8.4	1.32	124	0.000	-11.0	-0.8

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.83 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the thigh relative to the pelvis in the sagittal plane; there was no statistically significant difference when comparing Walking to Running (p=0.131). There were statistically significant differences when comparing Walking to the Trendelenburg Test (mean difference= 36.1^0, p=0.000), when comparing Walking to the Single Leg Squat (mean difference= -13.6^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference= 31.2^0, p=0.000), Table 8.82.

There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference= -33.2^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference= 16.6^0, p=0.000), and when comparing Running to the Corkscrew Test (mean difference= 28.3^0, p=0.000), Table 8.82.

A significant difference was also seen between the professional football players and healthy participants (mean difference = -8.4^0, p=0.000), Table 8.83.

8.5.5.2 Hip sagittal plane range of movement (right)

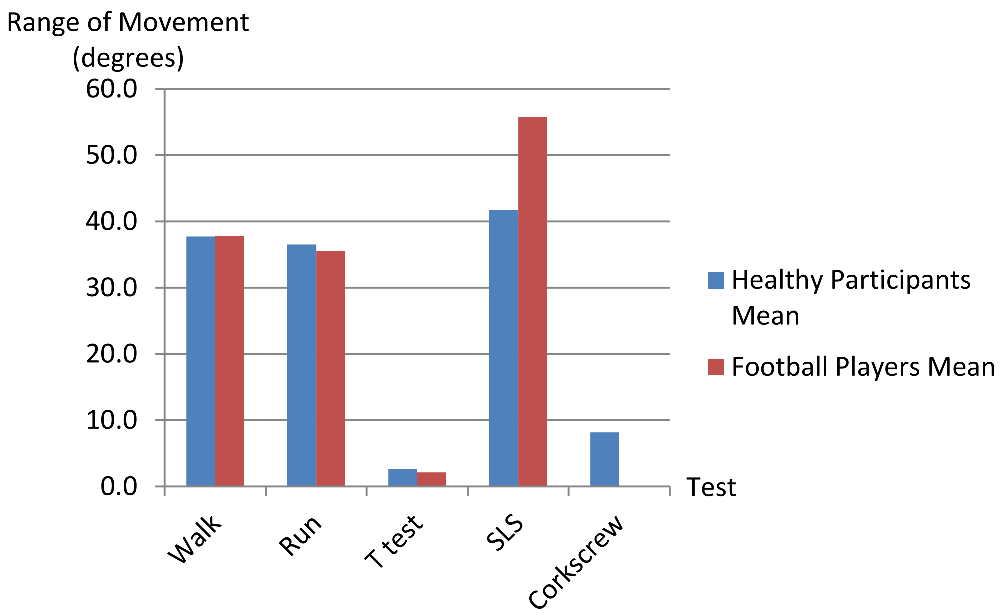


Figure 8.34 Hip sagittal plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	37.8	5.11	37.8	3.63
Run	36.5	4.23	35.5	6.00
T test	2.7	1.98	2.1	0.75
SLS	41.7	10.89	55.8	13.42
Corkscrew	8.2	4.09		

Table 8.84 Hip sagittal plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	35.4	1.82	124	0.000	31.8	39.0
Walk	SLS	-11.0	1.77	124	0.000	-14.5	-7.5
Walk	Run	1.8	1.76	124	0.320	-1.7	5.2
Walk	Cork	29.6	2.22	124	0.000	25.2	34.0
T Test	SLS	-46.4	1.83	124	0.000	-50.0	-42.7
T Test	Run	-33.6	1.82	124	0.000	-37.2	-30.0
T Test	Cork	-5.8	2.27	124	0.012	-10.3	-1.3
SLS	Run	12.7	1.77	124	0.000	9.2	16.2
SLS	Cork	40.6	2.23	124	0.000	36.1	45.0
Run	Cork	27.8	2.22	124	0.000	23.4	32.2

Table 8.85 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-7.5	1.20	124	0.000	-9.8	-5.1

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.86 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the thigh relative to the pelvis in the sagittal plane; there was no statistically significant difference when comparing Walking to Running (p=0.320). There were statistically significant differences when comparing Walking to the Trendelenburg Test (mean difference= 35.4^0, p=0.000), when comparing Walking to the Single Leg Squat (mean difference= -11.0^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference= 29.6^0, p=0.000), Table 8.85.

For the range of movement of the thigh relative to the pelvis in the sagittal plane; there were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference= -33.6^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference= 12.7^0, p=0.000), and when comparing Running to the Corkscrew Test (mean difference= 27.8^0, p=0.000), Table 8.85.

A significant difference was seen between the professional football players and healthy participants (mean difference=-7.5^0, p=0.000), Table 8.86.

However of interest is that the professional football players and healthy participants exhibited different hip sagittal plane range of movement for the Single Leg Squat, where the healthy participants exhibited lower values than the professional football players for both left and right lower limb weight bearing, Figure 8.3, Table 8.15, and Figure 8.4, Table 8.18.

8.5.5.3 Hip coronal plane range of movement (left)

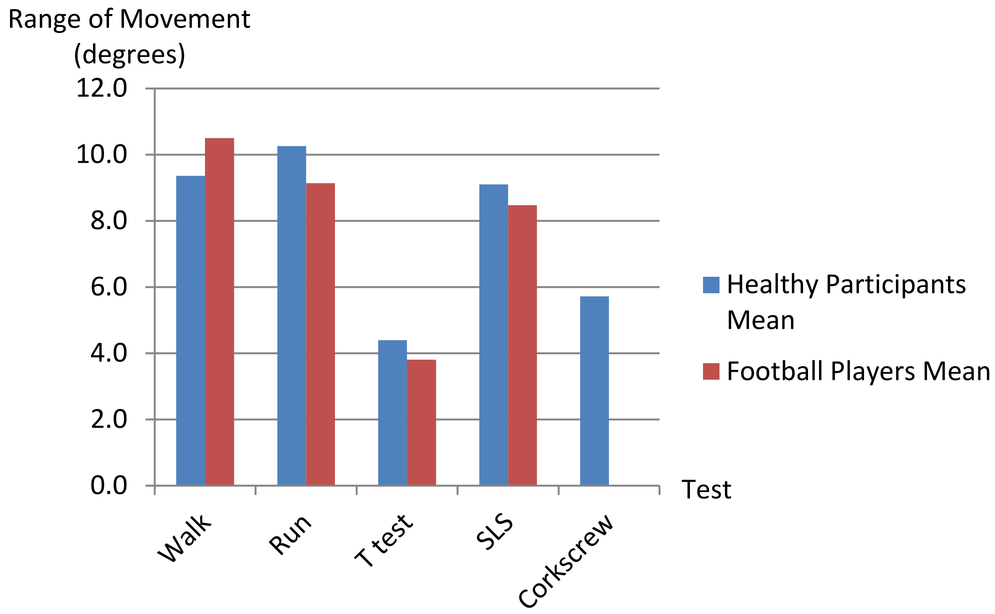


Figure 8.35 Hip coronal plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	9.4	2.31	10.5	2.23
Run	10.3	2.51	9.1	2.99
T test	4.4	2.61	3.8	1.46
SLS	9.1	5.76	8.5	5.59
Corkscrew	5.7	3.26		

Table 8.87 Hip coronal plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	5.8	0.93	124	0.000	4.0	7.7
Walk	SLS	1.1	0.90	124	0.207	-0.6	2.9
Walk	Run	0.2	0.90	124	0.799	-1.5	2.0
Walk	Cork	4.2	1.13	124	0.000	2.0	6.4
T Test	SLS	-4.7	0.93	124	0.000	-6.5	-2.8
T Test	Run	-5.6	0.93	124	0.000	-7.4	-3.8
T Test	Cork	-1.6	1.16	124	0.163	-4.0	0.7
SLS	Run	-0.9	0.90	124	0.312	-2.7	0.9
SLS	Cork	3.1	1.14	124	0.008	0.8	5.3
Run	Cork	4.0	1.13	124	0.001	1.7	6.2

Table 8.88 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-0.2	0.61	124	0.731	-1.4	1.0

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.89 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the thigh relative to the pelvis in the coronal plane; there was no statistically significant difference when comparing Walking to Running (p=0.799), or when comparing Walking to the Single Leg Squat (p=0.207). There were statistically significant differences when comparing Walking to the Trendelenburg Test (mean difference= 5.8^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference= 4.2^0, p=0.000), Table 8.88.

There was no statistically significant difference when comparing Running to the Single Leg Squat (p=0.312). There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference= -5.6^0, p=0.000), and when comparing Running to the Corkscrew Test (mean difference= 4.0^0, p=0.001), Table 8.88.

No significant difference was seen between the professional football players and healthy participants (p=0.731), Table 8.89.

8.5.5.4 Hip coronal plane range of movement (right)

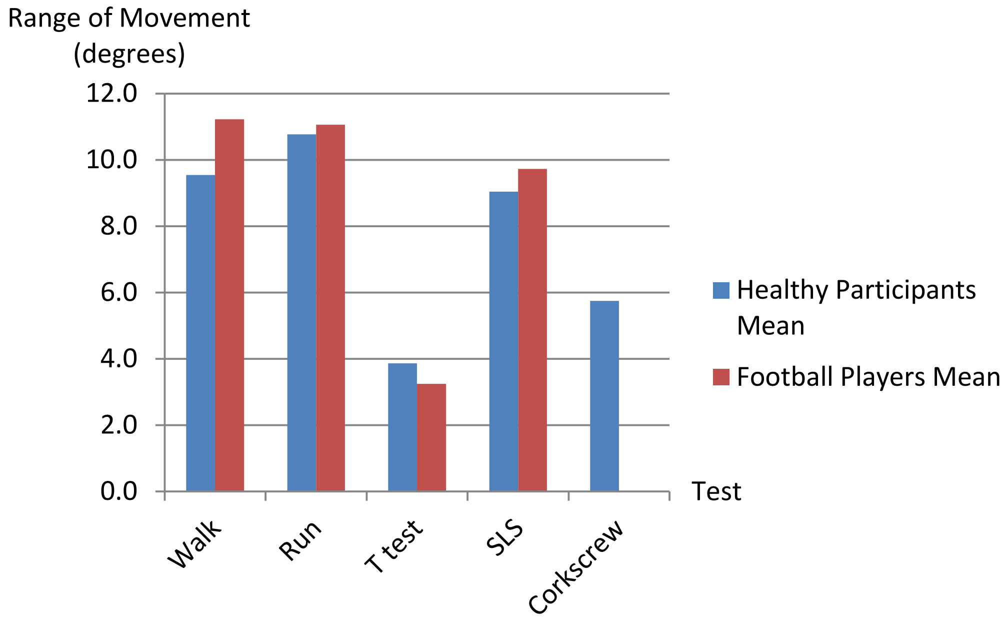


Figure 8.36 Hip coronal plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	9.5	1.92	11.2	2.60
Run	10.8	2.78	11.1	3.75
T test	3.9	2.19	3.2	1.06
SLS	9.0	4.55	9.7	4.47
Corkscrew	5.7	3.17		

Table 8.90 Hip coronal plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	6.8	0.84	124	0.000	5.2	8.5
Walk	SLS	1.0	0.82	124	0.223	-0.6	2.6
Walk	Run	-0.5	0.81	124	0.517	-2.1	1.1
Walk	Cork	4.6	1.03	124	0.000	2.6	6.7
T Test	SLS	-5.8	0.85	124	0.000	-7.5	-4.2
T Test	Run	-7.4	0.84	124	0.000	-9.0	-5.7
T Test	Cork	-2.2	1.05	124	0.039	-4.3	-0.1
SLS	Run	-1.5	0.82	124	0.064	-3.1	0.1
SLS	Cork	3.6	1.03	124	0.001	1.6	5.7
Run	Cork	5.2	1.03	124	0.000	3.1	7.2

Table 8.91 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-1.0	0.56	124	0.069	-2.1	0.1

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.92 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the thigh relative to the pelvis in the coronal plane; there were no statistically significant differences when comparing Walking to Running (p=0.517), or when comparing Walking to the Single Leg Squat (p=0.223). There was a statistically significant when comparing Walking to the Trendelenburg Test (mean difference=6.8^{0}, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference= 4.6^{0}, p=0.000), Table 8.91.

There was no statistically significant difference when comparing Running to the Single Leg Squat (p=0.064). There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference= -7.4^{0}, p=0.000), and when comparing Running to the Corkscrew Test (mean difference= 5.2^{0}, p=0.000), Table 8.91.

No significant difference was seen between the professional football players and healthy participants (p=0.069), Table 8.92.

8.5.5.5 Hip coronal plane peak value (left)

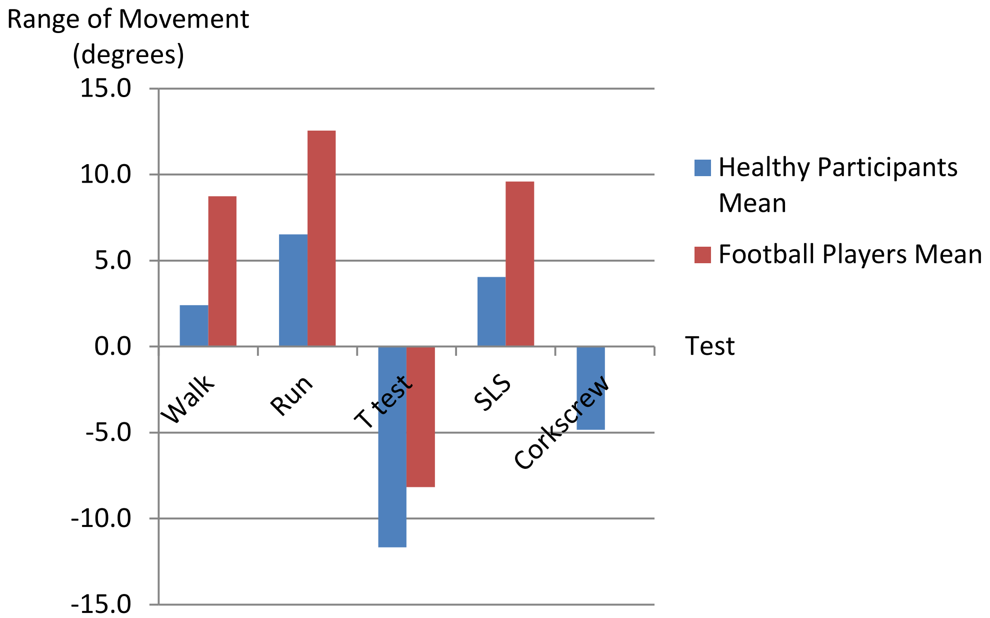


Figure 8.37 Hip coronal plane peak value normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	2.4	3.63	8.7	2.67
Run	6.5	2.69	12.6	4.10
T test	-11.7	4.47	-8.2	4.52
SLS	4.0	5.92	9.6	5.45
Corkscrew	-4.8	4.40		

Table 8.93 Hip coronal plane peak value normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	15.5	1.14	124	0.000	13.2	17.8
Walk	SLS	-1.2	1.11	124	0.265	-3.4	1.0
Walk	Run	-4.0	1.10	124	0.000	-6.1	-1.8
Walk	Cork	10.4	1.39	124	0.000	7.7	13.2
T Test	SLS	-16.7	1.15	124	0.000	-19.0	-14.5
T Test	Run	-19.5	1.14	124	0.000	-21.7	-17.2
T Test	Cork	-5.1	1.42	124	0.000	-7.9	-2.3
SLS	Run	-2.7	1.11	124	0.015	-4.9	-0.5
SLS	Cork	11.7	1.40	124	0.000	8.9	14.4
Run	Cork	14.4	1.39	124	0.000	11.6	17.1

Table 8.94 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-6.4	0.751	124	0.000	-7.878	-4.9

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.95 Comparison between professional football players and healthy participants (tests combined)

For the peak value of the thigh relative to the pelvis in the coronal plane; there was no statistically significant difference between the Walking to the Single Leg Squat (p=0.265). There was a statistically significant between the Walking to Running (mean difference=-4.0^0, p=0.000), when comparing the Walking to the Trendelenburg Test (mean difference= 15.5^0, p=0.000), or when comparing Walking to the Corkscrew Test (mean difference= 10.4^0, p=0.000), Table 8.94.

There was a statistically significant difference between the Running to the Trendelenburg Test (mean difference= -19.5^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference=-2.7^0, p=0.015), or when comparing Running to the Corkscrew Test (mean difference= 14.4^0, p=0.000), Table 8.94.

A statistically significant difference was seen between the healthy participants and professional football players (mean difference=-6.4, p=0.000), Table 8.95.

8.5.5.6 Hip coronal plane peak value (right)

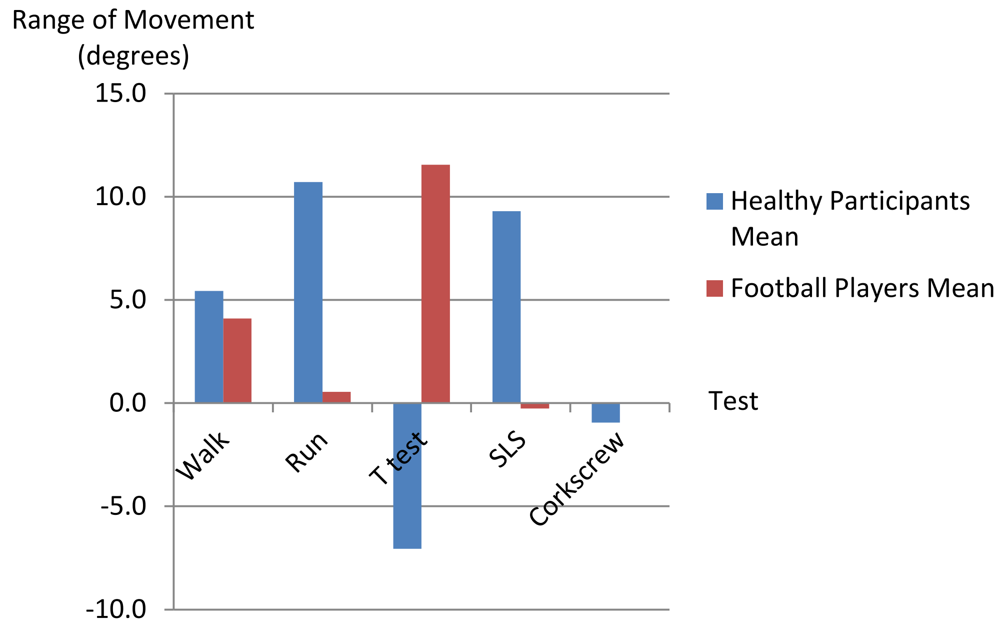


Figure 8.38 Hip coronal plane peak value normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	5.4	2.82	4.1	2.61
Run	10.7	2.18	0.5	5.45
T test	-7.1	5.12	11.6	4.53
SLS	9.3	5.19	-0.3	5.61
Corkscrew	-1.0	4.65		

Table 8.96 Hip coronal plane peak value normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	2.5	1.17	124	0.033	0.2	4.8
Walk	SLS	0.3	1.14	124	0.824	-2.0	2.5
Walk	Run	-0.9	1.13	124	0.452	-3.1	1.4
Walk	Cork	5.7	1.43	124	0.000	2.9	8.6
T Test	SLS	-2.3	1.18	124	0.057	-4.6	0.1
T Test	Run	-3.4	1.17	124	0.005	-5.7	-1.06
T Test	Cork	3.2	1.46	124	0.030	0.3	6.1
SLS	Run	-1.1	1.14	124	0.333	-3.4	1.1
SLS	Cork	5.5	1.44	124	0.000	2.6	8.3
Run	Cork	6.6	1.43	124	0.000	3.7	9.4

Table 8.97 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-0.50	0.77	124	0.522	-2.0	1.0

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.98 Comparison between professional football players and healthy participants (tests combined)

For the peak value of the thigh relative to the pelvis in the coronal plane; there were no statistically significant differences between the Walking and Running (p=0.452), or when comparing Walking to the Single Leg Squat (p=0.824). There were statistically significant differences when comparing Walking to the Trendelenburg Test (Mean difference=2.5^0, p=0.033) or when comparing Walking to the Corkscrew Test (Mean difference=5.7^0, p=0.000), Table 8.97.

There was no statistically significant difference between Running and the Single Leg Squat (p=0.333). There were statistically significant differences when comparing Running to the Trendelenburg Test (Mean difference=-3.4^0, p=0.005), and when comparing Running to the Corkscrew Test (Mean difference=6.6^0, p=0.000), Table 8.97.

No significant difference was seen between the professional football players and healthy participants (p=0.522), Table 8.98.

8.5.5.7 Hip transverse plane range of movement (left)

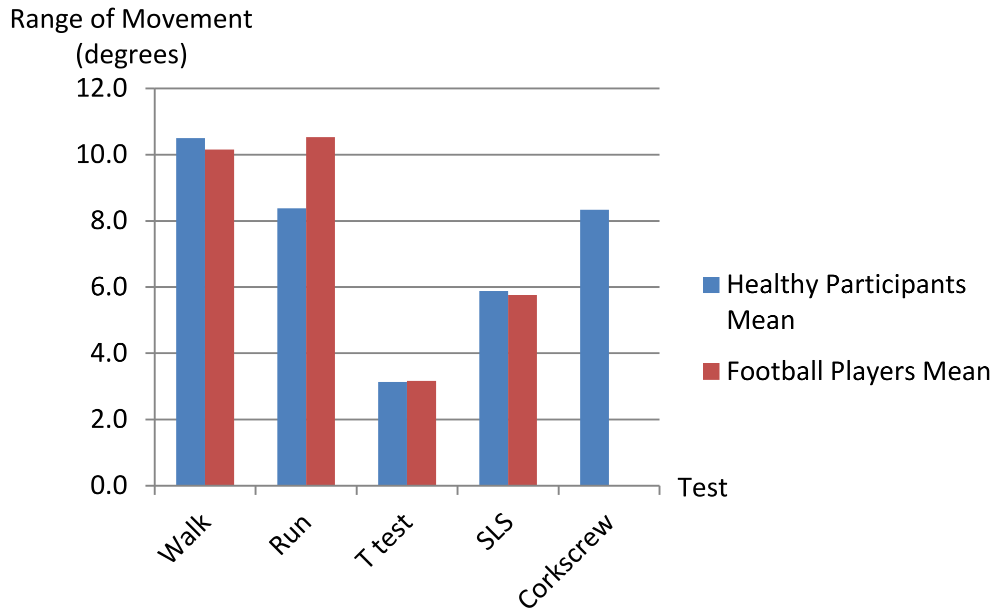


Figure 8.39 Hip transverse plane range of movement normative data (left)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard deviation)
Walk	10.5	3.97	10.2	3.52
Run	8.4	3.22	10.5	4.97
T test	3.1	1.24	3.2	1.10
SLS	5.9	2.41	5.8	2.74
Corkscrew	8.3	3.50		

Table 8.99 Hip transverse plane range of movement normative data (left)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	7.2	0.86	124	0.000	5.5	8.9
Walk	SLS	4.5	0.84	124	0.000	2.9	6.2
Walk	Run	0.9	0.83	124	0.295	-0.8	2.5
Walk	Cork	2.0	1.05	124	0.060	-0.1	4.1
T Test	SLS	-2.7	0.87	124	0.002	-4.4	-1.0
T Test	Run	-6.3	0.86	124	0.000	-8.0	-4.6
T Test	Cork	-5.2	1.07	124	0.000	-7.3	-3.1
SLS	Run	-3.6	0.84	124	0.000	-5.3	-2.0
SLS	Cork	-2.5	1.06	124	0.019	-4.6	-0.4
Run	Cork	1.1	1.05	124	0.289	-1.0	3.2

Table 8.100 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-0.2	0.57	124	0.780	-1.3	1.0

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.101 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the thigh relative to the pelvis in the transverse plane; there was no statistically significant difference when comparing Walking to Running (p=0.295), or when comparing Walking to the Corkscrew Test (p=0.060). There were statistically significant differences when comparing Walking to the Trendelenburg Test (mean difference= 7.2^0, p=0.000), and when comparing Walking to the Single Leg Squat (mean difference= 4.5^0, p=0.000), Table 8.100.

There was no statistically significant difference when comparing Running to the Corkscrew Test (p=0.289). There was a statistically significant difference when comparing Running to the Trendelenburg Test (mean difference= -6.3^0, p=0.000), and when comparing Running to the Single Leg Squat (mean difference= -3.6^0, p=0.000), Table 8.100.

No significant difference was also seen between the professional football players and healthy participants (p=0.780), Table 8.101.

8.5.5.8 Hip transverse plane range of movement (right)

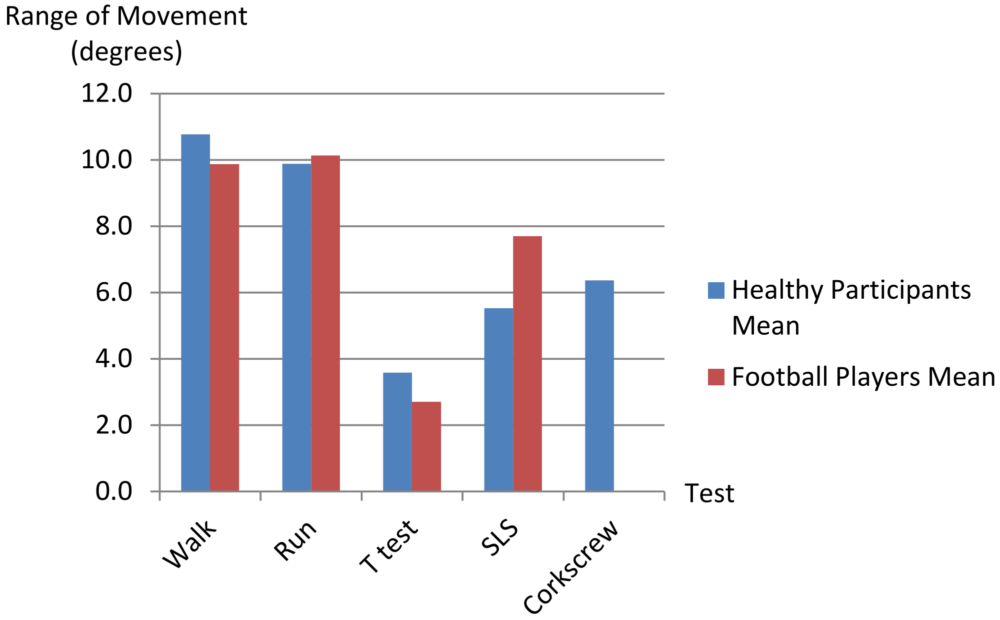


Figure 8.40 Hip transverse plane range of movement normative data (right)

Trial	Healthy Participants Mean (degrees)	Healthy Participants (standard deviation)	Football Players Mean (degrees)	Football Players (standard Deviation)
Walk	10.8	3.37	9.9	2.79
Run	9.9	4.44	10.1	2.76
T test	3.6	1.24	2.7	.68
SLS	5.5	3.06	7.7	4.33
Corkscrew	6.4	3.30		

Table 8.102 Hip transverse plane range of movement normative data (right)

Walk, T Test, SLS, Run, Cork		Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Walk	T Test	7.2	0.83	124	0.000	5.5	8.8
Walk	SLS	3.7	0.81	124	0.000	2.1	5.3
Walk	Run	0.3	0.80	124	0.696	-1.3	1.9
Walk	Cork	4.0	1.01	124	0.000	2.0	6.0
T Test	SLS	-3.5	0.83	124	0.000	-5.1	-1.8
T Test	Run	-6.9	0.83	124	0.000	-8.5	-5.2
T Test	Cork	-3.2	1.03	124	0.002	-5.3	-1.2
SLS	Run	-3.4	0.81	124	0.000	-5.0	-1.8
SLS	Cork	0.2	1.02	124	0.809	-1.8	2.3
Run	Cork	3.6	1.01	124	0.000	1.6	5.6

Table 8.103 Comparison between functional tests and clinical tests (groups combined)

	Mean Difference (I-J)	Std. Error	df	Sig.[a]	95% CIs Lower Bound	95% CIs Upper Bound
Football Players versus Healthy Participants	-0.4	0.55	124	0.491	-1.5	0.7

Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 8.104 Comparison between professional football players and healthy participants (tests combined)

For the range of movement of the thigh relative to the pelvis in the transverse plane; there was no statistically significant difference when comparing Walking to Running (p=0.696). There was a statistically significant difference when comparing Walking to the Trendelenburg Test (mean difference= 7.2^0, p=0.000), when comparing Walking to the Single Leg Squat (mean difference= 3.7^0, p=0.000), and when comparing Walking to the Corkscrew Test (mean difference= 4.0^0, p=0.000), Table 8.103.

There were statistically significant differences when comparing Running to the Trendelenburg Test (mean difference= -6.9^0, p=0.000), when comparing Running to the Single Leg Squat (mean difference= -3.4^0, p=0.000), and when comparing Running to the Corkscrew Test (mean difference= 3.6^0, p=0.000), Table 8.103.

No significant difference was also seen between the professional football players and healthy participants (p=0.491), Table 8.104.

Appendix 5, Detailed results

8.6 Appendix 6

Trunk			
ROM	Sagittal	Coronal	Transverse
Healthy	L: 2.6^0 R: 2.4^0	L: 10.5^0 R: 10.8^0	L: 17.0^0 R: 17.1^0
Football	L: 2.5^0 R: 2.5^0	L: 11.9^0 R:12.1^0	L: 17.8^0 R: 17.6^0
Movement	No observable	Observable	Observable
Thoracic Spine			
Healthy	L: 4.5^0 R: 3.7^0	L: 9.7^0 R: 10.0^0	L: 9.8^0 R: 9.4^0
Movement	No observable	Observable	Observable
Lumbar Spine			
Healthy	L: 4.0^0 R: 3.7^0	L: 4.8^0 R: 4.7^0	L: 7.9^0 R: 7.8^0
Movement	No observable	No observable	Observable
Pelvis			
Healthy	L: 5.4^0 R: 5.2^0	L: 2.5^0 R: 2.6^0	L: 15.0^0 R: 14.6^0
Football	L: 7.2^0 R: 7.5^0	L: 2.3^0 R: 2.5^0	L: 13.4^0 R: 13.3^0
Movement	Observable	No observable	Observable
Hip			
Healthy	L: 38.6^0 R: 37.8^0	L: 9.4^0 R: 9.5^0	L: 10.5^0 R: 10.8^0
Football	L: 39.3^0 R: 37.8^0	L: 10.5^0 R: 11.2^0	L: 10.2^0 R: 9.9^0
Movement	Observable	Observable	Observable

Figure 8.41 Walking normative data for healthy participants and professional football players

Appendix 6, Walking normative data for healthy participants and professional football players

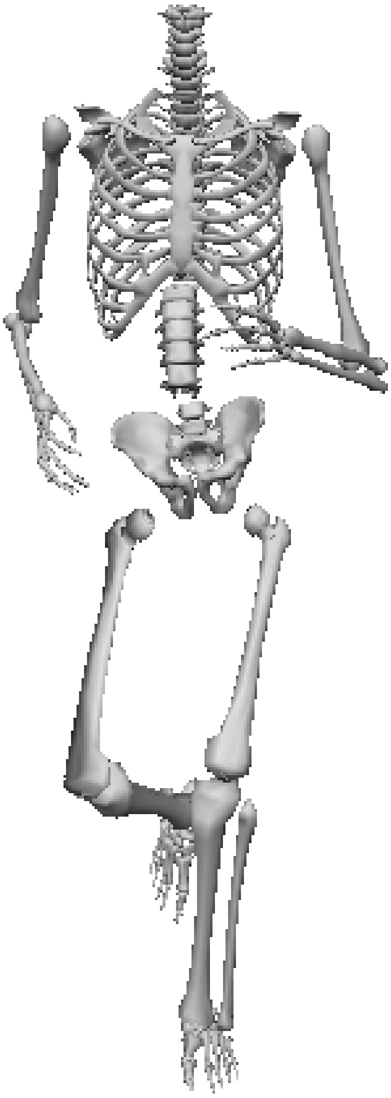
8.7 Appendix 7

	Appropriate clinical test for examining components of walking		
Region	Sagittal	Coronal	Transverse
Lumbar spine	Trendelenburg or Corkscrew	Trendelenburg	None
Thoracic spine	Trendelenburg or Single Leg Squat	Corkscrew	Single Leg Squat
Trunk	Trendelenburg or Corkscrew	None	None
Pelvis	Trendelenburg	Trendelenburg or Corkscrew	None
Hip	None	Single Leg Squat	None

Figure 8.42 Appropriate clinical test for examining components of walking

Appendix 7, Appropriate clinical test for examining components of walking

8.8 Appendix 8

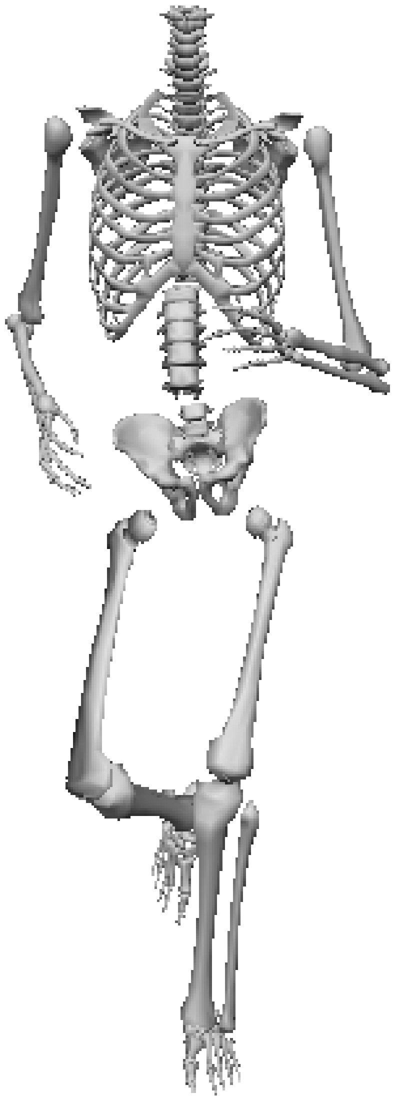


Trunk			
ROM	Sagittal	Coronal	Transverse
Healthy	L:10.0^0 R: 8.5^0	L: 9.9^0 R: 10.2^0	L:20.4^0 R: 20.3^0
Football	L: 9.7^0 R: 8.9^0	L: 11.0^0 R: 9.4^0	L: 22.7^0 R: 21.7^0
Movement	Observable	Observable	Observable
Thoracic Spine			
Healthy	L: 7.4^0 R: 7.7^0	L: 7.4^0 R: 7.7^0	L: 9.7^0 R: 9.0^0
Movement	Observable	Observable	Observable
Lumbar Spine			
Healthy	L: 9.0^0 R: 8.8^0	L: 6.5^0 R: 6.3^0	L: 11.8^0 R: 12.7^0
Movement	Observable	Observable	Observable
Pelvis			
Healthy	L: 7.5^0 R: 7.4^0	L: 5.5^0 R: 6.5^0	L: 4.3^0 R: 5.1^0
Football	L: 8.1^0 R: 6.7^0	L: 6.4^0 R: 5.9^0	L: 5.6^0 R: 6.0^0
Movement	Observable	Observable	Observable
Hip			
Healthy	L: 37.4^0 R: 36.5^0	L: 10.3^0 R: 10.8^0	L: 8.4^0 R: 9.9^0
Football	L: 34.7^0 R: 35.5^0	L: 9.1^0 R: 11.1^0	L: 10.5^0 R: 10.1^0
Movement	Observable	Observable	Observable

Figure 8.43 Running normative data for healthy participants and professional football players

Appendix 8, Running normative data for healthy participants and professional football players

8.9 Appendix 9



	Appropriate clinical test for examining components of running		
Region	Sagittal	Coronal	Transverse
Lumbar spine	None	None	None
Thoracic spine	None	None	Single Leg Squat
Trunk	None	None	None
Pelvis	Single Leg Squat	Corkscrew	Trendelenburg Test or Single Leg Squat
Hip	None	Single Leg Squat	None

Figure 8.44 Appropriate clinical test for examining components of running

Appendix 9, Appropriate clinical test for examining components of running

8.10 Appendix 10

Title of study:

An investigation of the reliability and validity of the Trendelenburg Test as a measure of dynamic pelvic stability in normal healthy adults.

Name	Date of Birth	Date

Height (m)	
Weight (Kg)	
Main Sport	
Total hours per week playing and training	
Do you wear special insoles or orthotics for sport or leisure?	

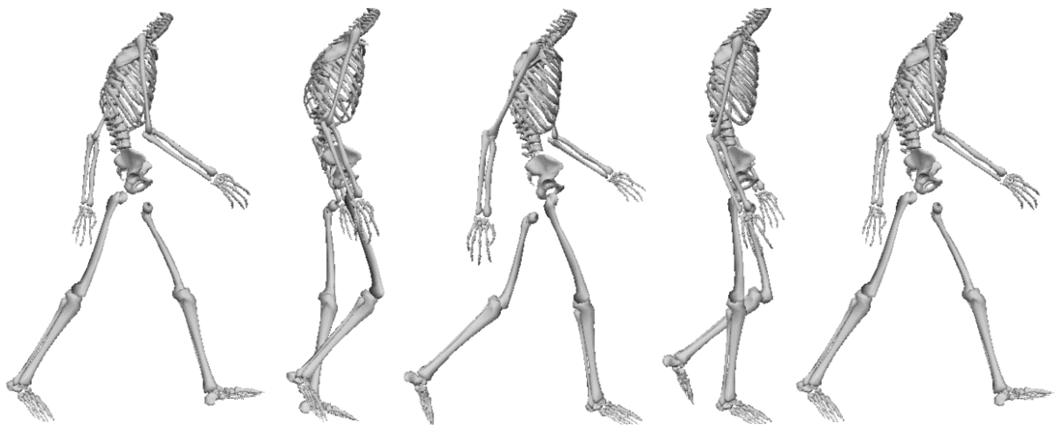
Appendix 10, Anthropometric data

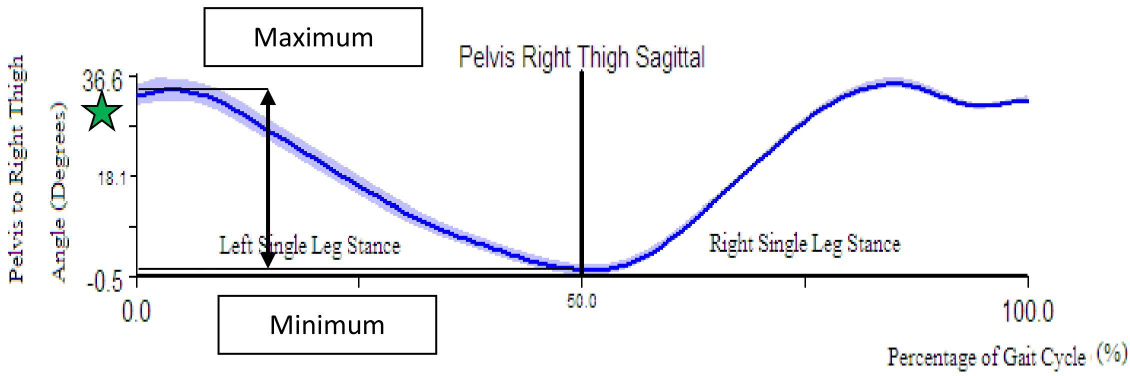
8.11 Appendix 11

For the graphical representation of data the horizontal (X) axis is the time taken for the trial. Where the range is 0-100 this represents 0-100% of the trial, where the range is 0-30 this represents 0-30 seconds. The vertical (Y) axis is the angle between the right thigh and pelvis.

Walking

Walking Sagittal Plane

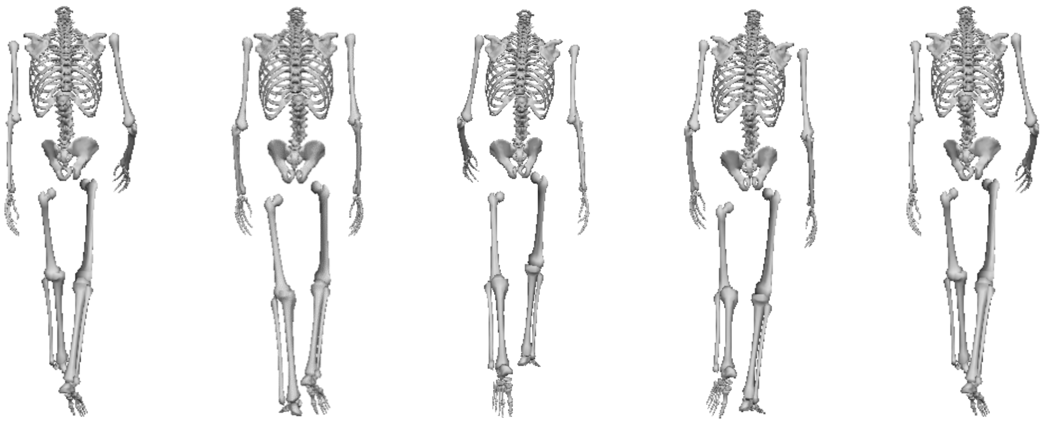


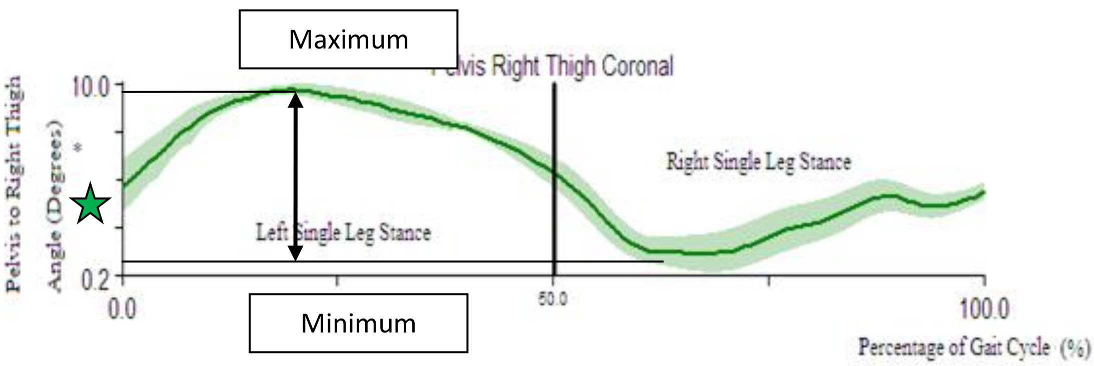


Indicates that at the start as the participant commenced left single limb stance there was a 36.6^0 angle between the pelvis and right thigh (flexion), this angle decreased steadily and reached a minimum of 0^0 (neutral) at 50% of movement cycle. This demonstrates that the participant therefore did not move into a position of hip extension. These participants were walking at a self selected speed, and if this was a slow speed then the shorter stride length may be why they did not move into hip extension. A second explanation is that this is a local co-ordinate parameter; hence if the pelvis was anteriorly tilted relative to the thigh then the thigh would potentially not pass into extension during gait. This is the point of double limb stance.

The participant at this point moved into double limb support. They then commenced right single limb stance, increased the angle between the pelvis and right thigh by a similar 36^0 angle but reached this significantly earlier at 60% of right single limb stance. In the final 25% of right leg single limb stance the pelvis to thigh angle increases, decreases then increases again.

Walking Coronal Plane

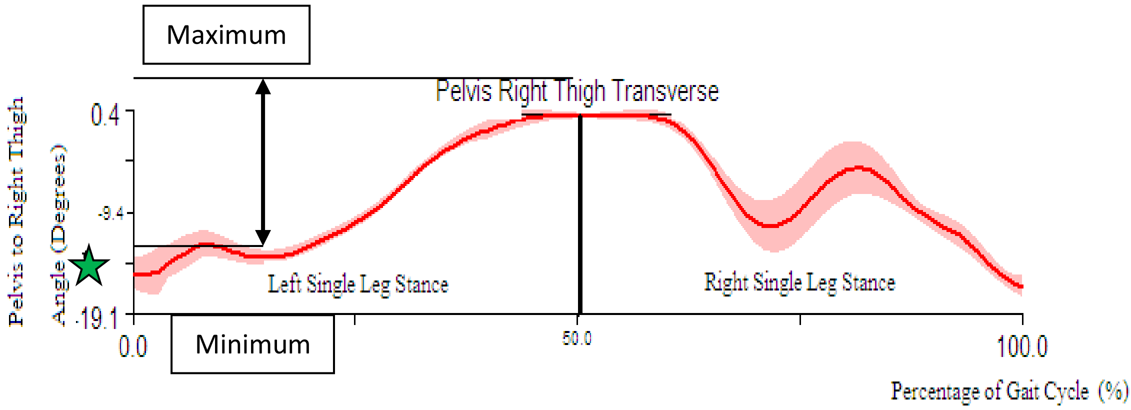




Indicates that at the start as the participant commenced left single limb stance there was a 5^0 angle between the pelvis and right thigh (abduction), this angle increased steadily and reached a peak of 10^0 at 15% of left single limb stance. It then reduced at a slower rate until 50% of the movement cycle was reached. This is the point of double limb stance.

The participant then commenced right single limb stance, increased the angle between the pelvis and right thigh by a similar 5^0 angle but significantly earlier at 20% of right single limb stance. In the final 25% of right leg single limb stance the pelvis to thigh angle increases, decreases then increases again.

Walking Transverse Plane



★ Indicates that at the start as the participant commenced left single limb stance there was a 13^0 angle between the pelvis and right thigh (medial rotation), this angle reduced steadily and reached a minimum of 0^0 at the end of left leg single leg stance. This is the point of double limb stance.

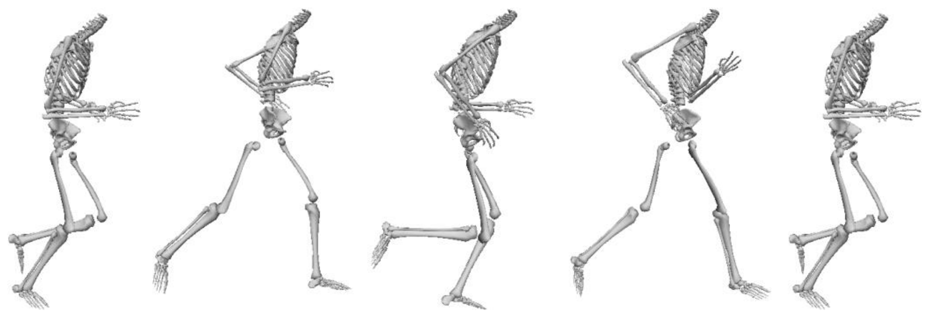
The participant then commenced right single limb stance; increased the angle between the pelvis and right thigh by a similar 13^0 angle but there was a significant phase of alternating medial and lateral rotation in the middle of right leg single limb stance.

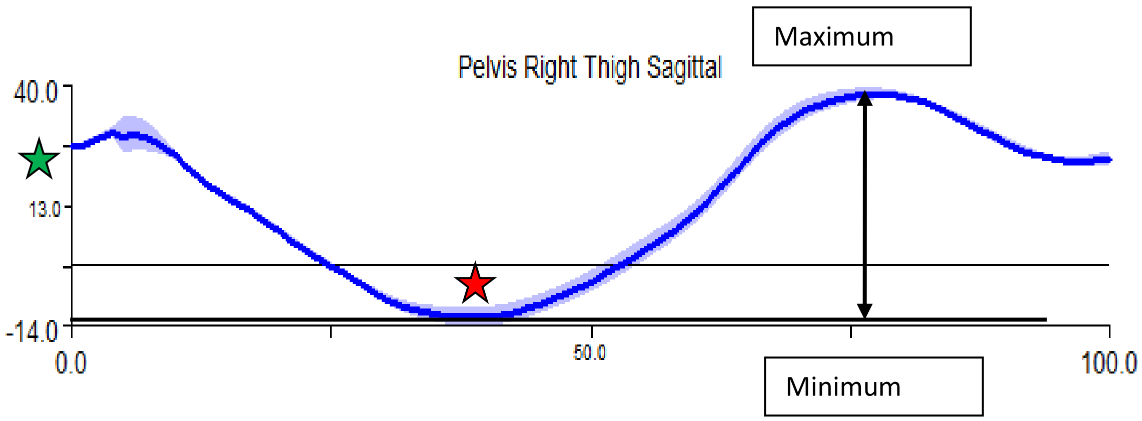
Walking Summary

The graphs of data show how the pelvis moves relative to the right thigh during gait. This gait cycle is divided into the left and right single limb stance phases. When the participant is in left single limb stance the right thigh is in open kinetic chain, when the subject is in right single limb stance the right thigh is in closed kinetic chain. These graphs show that the movement of the pelvis relative to the right thigh is different when the limb is in closed kinetic chain compared to open kinetic chain in the coronal, sagittal and transverse planes. A greater variation in control of movement was seen during stance phase than swing phase for all three planes of movement.

Running

Running Sagittal Plane

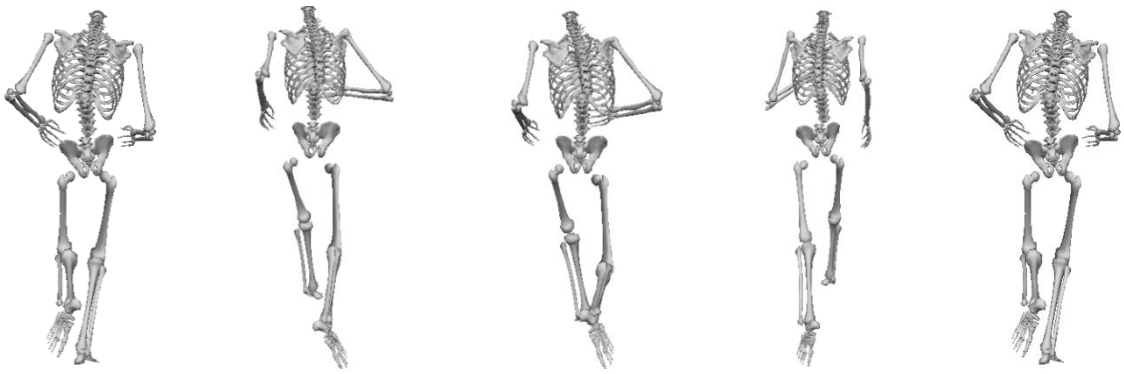


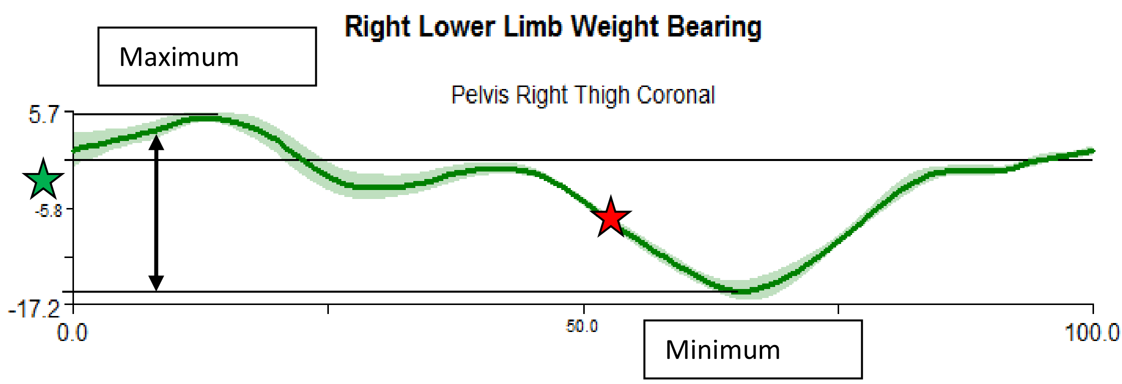


★ Indicates that at the start, heel strike, the participant commenced right single limb stance there was a 30^0 degree angle between the pelvis and right thigh (flexion), this angle increased briefly by approximately 5^0 and reached a Peak Value for stance phase of 35^0 at 15%. It then reduced steadily to approximately 15^0 of extension at 40^0 of stance where toe off occurred.

The participant then commenced left single limb stance, the angle between the pelvis and right thigh increased steadily by a similar 50^0 range of movement reaching a Peak Value at approximately 55% of 37^0 left single limb stance. This participant showed a small difference in hip sagittal plane peak value of 2^0 indicating a small asymmetry of hip sagittal plane movement when running. The right lower limb hip sagittal range of movement during stance phase was 50^0.

Running Coronal Plane



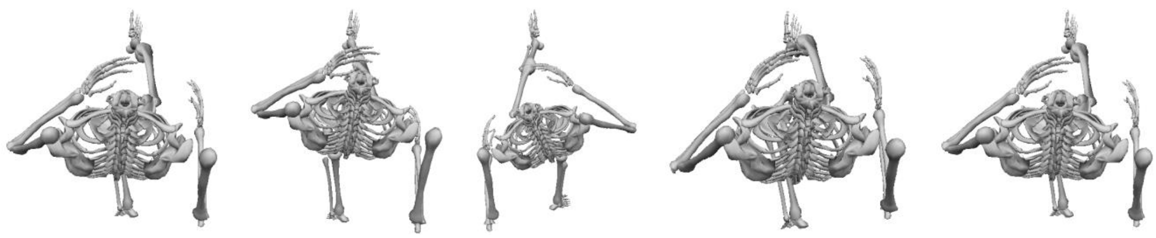


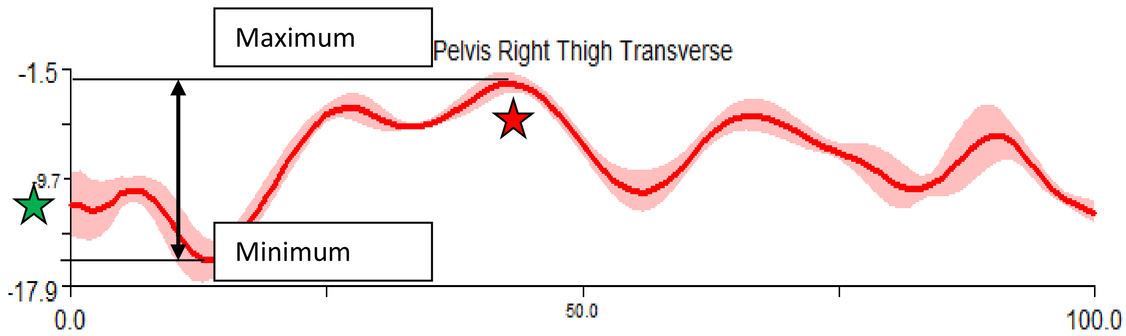
Indicates that at the start, heel strike, the participant commenced right single limb stance there was a 3^0 degree angle between the pelvis and right thigh (adduction), this angle decreased briefly by approximately 3^0 and reached a Peak Value for stance phase of 6^0 at 30%.

It then reduced steadily to approximately 3^0 of adduction at 60^0 of stance and then increased smoothly again to nearly 0^0 where toe off occurred.

The participant then commenced left single limb stance, the angle between the pelvis and right thigh increased steadily by a larger amount to a Peak Value of 12^0 at approximately 25% of left single limb stance. The pelvis and right thigh angle then steadily returned to neutral. The right lower limb hip coronal plane range of movement during stance phase was 18^0 with far greater abduction occurring in stance phase than adduction in swing phase.

Running Transverse Plane





★Indicates that at the start, heel strike, the participant commenced right single limb stance there was a 10^0 degree angle between the pelvis and right thigh (external rotation), this angle increased and decreased rapidly over 15% of early stance then steadily reduced to during the first 10% of stance phase and reached a Peak Value of 17^0. This then reduced steadily to approximately 0^0 at the end of stance where toe off occurred. ★The hip transverse plane range of movement during stance phase was 17^0.

The participant then commenced left single limb stance, the angle between the pelvis and right thigh increased with repeated internal and external movements to neutral. The right lower limb hip coronal plane range of movement during stance phase was 17^0.

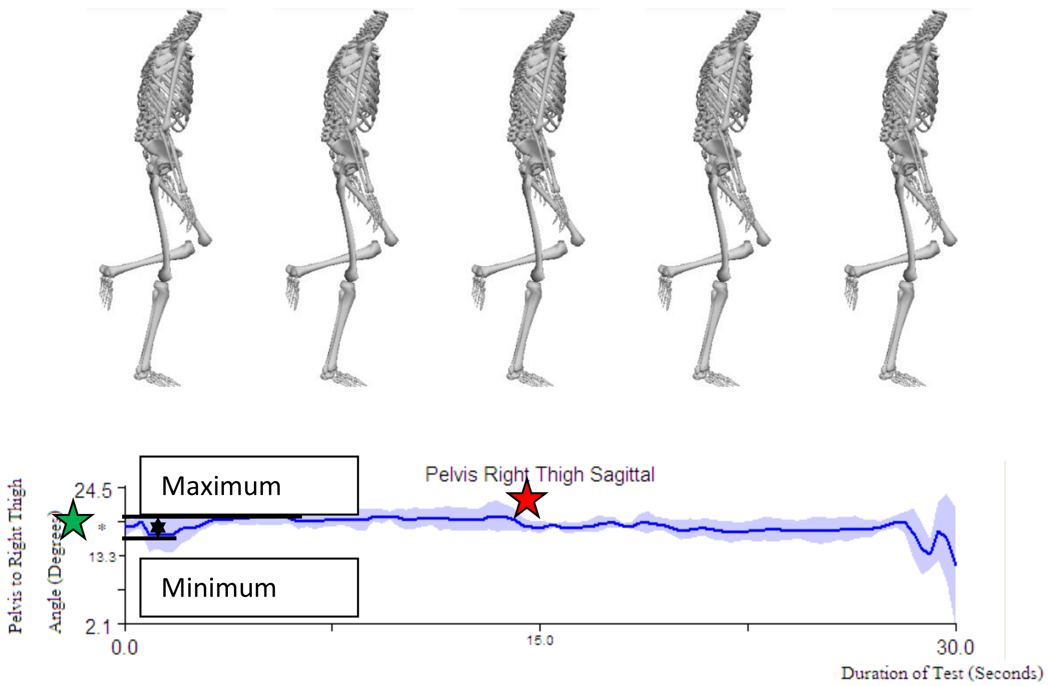
There were significant phases of alternating medial and lateral rotation during both the stance and swing phases of running suggesting reduced control of the pelvis to right thigh during both of these open and closed chain phases.

Running Summary

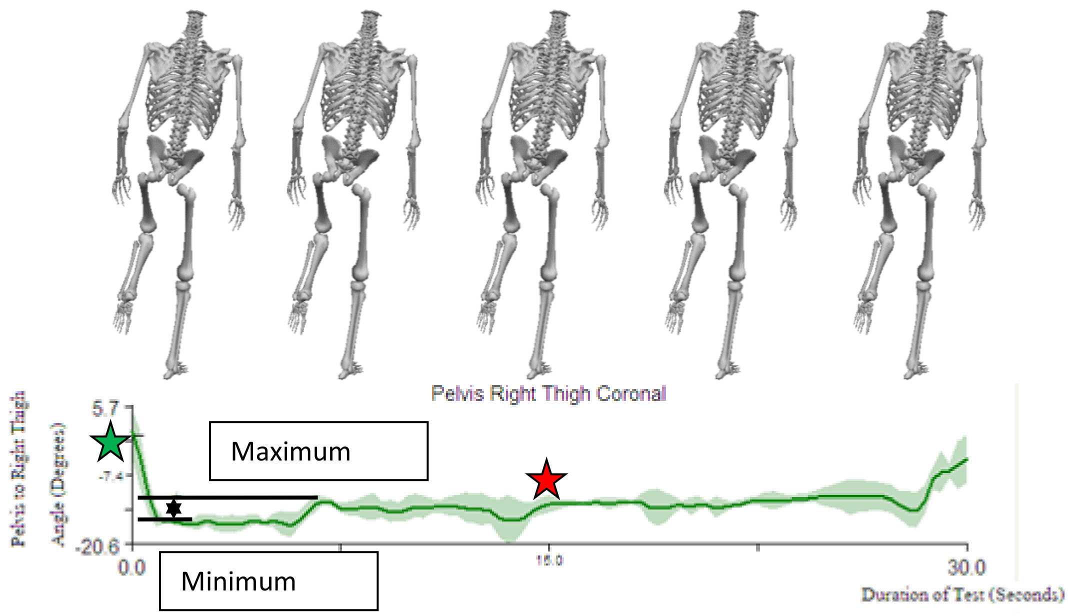
The graphs of data show how the pelvis moves relative to the right thigh during running gait. These graphs illustrate that this participant had good control of pelvis to thigh movement in the sagittal and coronal plane but not transverse. Hence this participant illustrates a different control pattern when running compared to walking, where all three planes were poorly controlled and forms an example of how the central locomotor command is unique to that joint, in that plane and during that function.

Trendelenburg Test

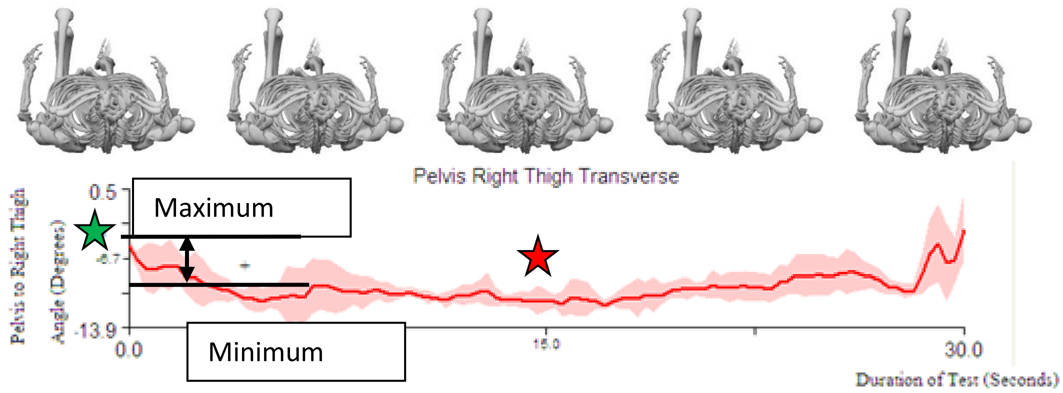
Trendelenburg Test Sagittal Plane



Trendelenburg Test Coronal Plane



Trendelenburg Test Transverse Plane



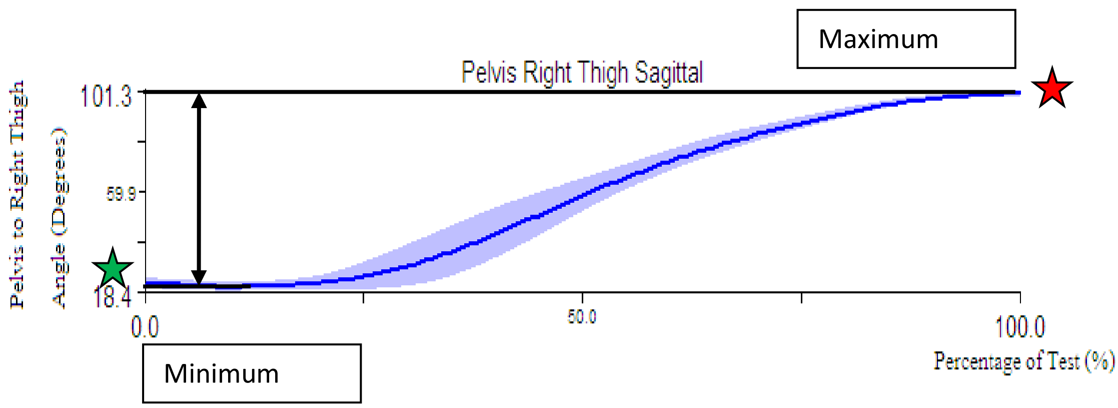
Indicates that at the start as the participant commenced the Trendelenburg Test on the right lower limb there was a 3^0 angle between the pelvis and right thigh in the coronal plane (abduction), a 6^0 in the transverse plane (rotation)and 17^0 in the sagittal plane (flexion). The right thigh to pelvis angle increased by 10^0 in the coronal plane within 2 seconds of starting the test. The pelvis remained relatively static in all other planes until the final 2 seconds of the test where a loss of control became apparent in all planes.

Trendelenburg Test Summary

The objective of the test is to raise and hold the pelvis in the coronal plane. These graphs show that initially movement occurred only in the coronal plane as desired. The right thigh to pelvis movement occurring in the final 2 seconds of the test in all could be explained by the participant finishing the test prematurely or a delayed response.

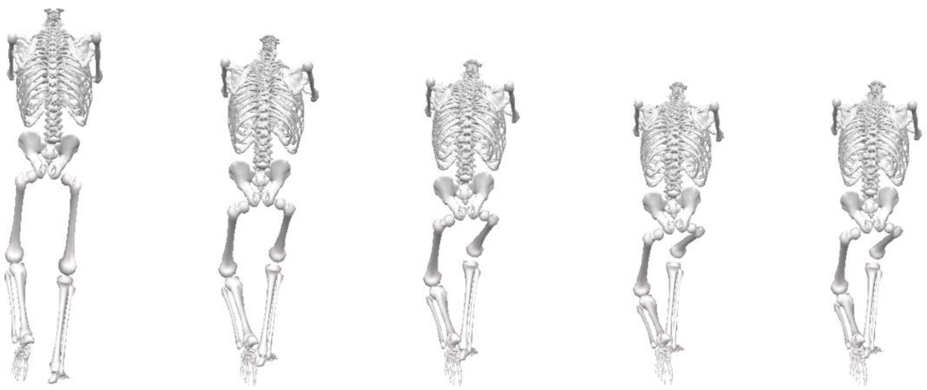
Single Leg Squat

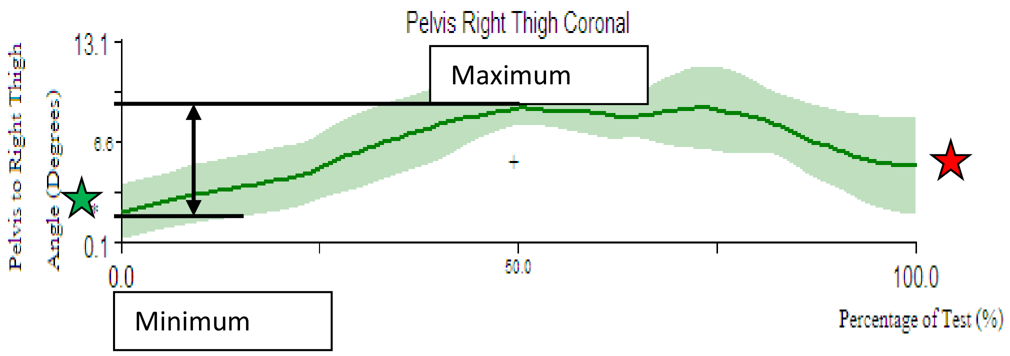
Single Leg Squat Sagittal Plane



★ Indicates that at the start as the participant commenced the Single Leg Squat on the right lower limb there was an 18^0 angle between the pelvis and right thigh (flexion), hence the thigh was not aligned vertically below the pelvis. This angle increased steadily in a curvilinear progression.

Single Leg Squat Coronal Plane



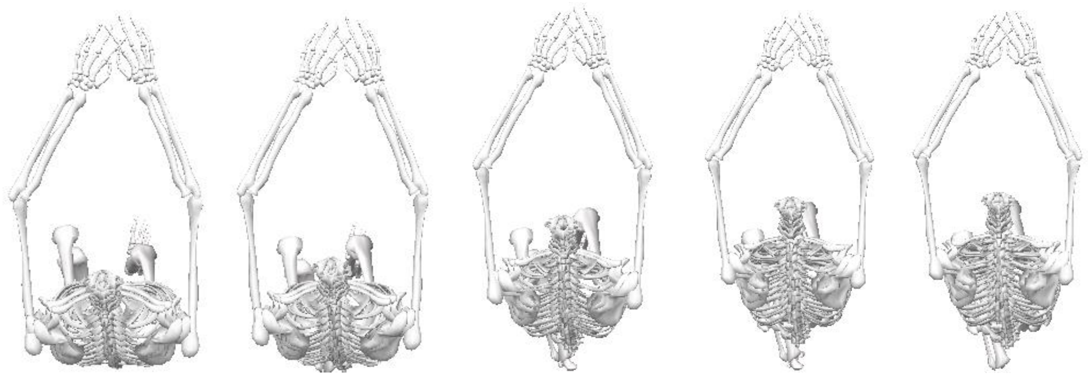


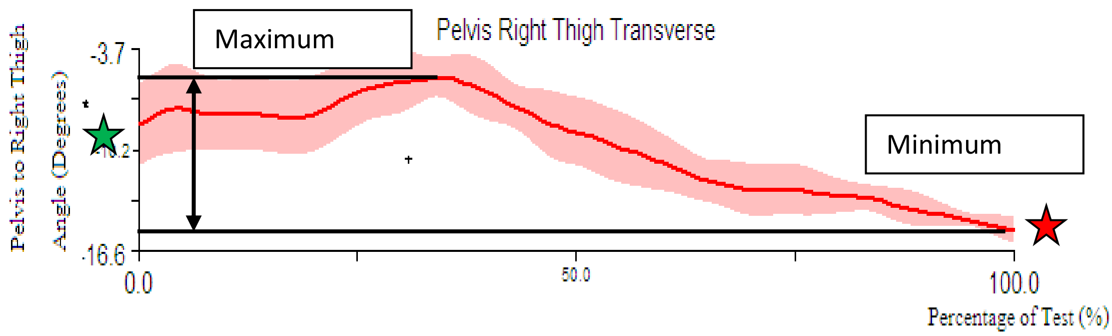
★ Indicates that at the start as the participant commenced the Single Leg Squat on the right lower limb there was a 0^0 angle between the pelvis and right thigh (abduction), hence the pelvis was neutral. This angle increased steadily and reached a minimum of 10^0 at 50% of motion cycle. This is the point of the lowest part of the squat.

The participant then commenced the concentric phase pulling themselves up to the start position and the pelvis to thigh angle decreased steadily to 0^0.

During the action of lowering the body and raising it back to the start position the Lumbo-Pelvic Hip region undergoes a smooth increase in pelvis to right thigh angle and then decrease in the coronal plane.

Single Leg Squat Transverse Plane





Indicates that at the start as the participant commenced the Single Leg Squat on the right lower limb there was a 7^0 angle between the pelvis and right thigh (lateral rotation), hence the thigh was not facing directly forward. Initially this angle increased but the rate varied until the participant was 30% through the eccentric lowering phase of the squat.

As the participant then commenced the concentric phase moving back up to the start position the pelvis to thigh angle decreased steadily to 0^0.

During the action of lowering the body and raising it back to the start position the Lumbo-Pelvic and Hip region undergoes an initial erratic increase in pelvis to right thigh angle and then steady decrease in the transverse plane during the lowering, eccentric phase of the test.

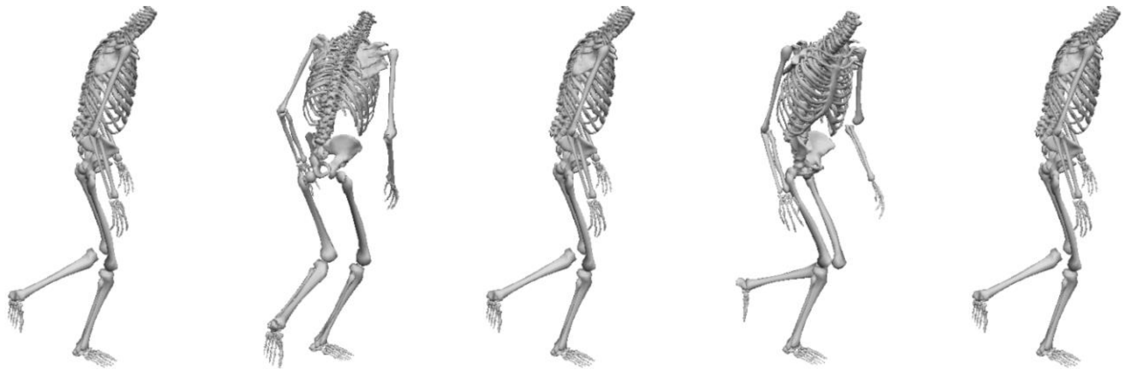
Single Leg Squat Summary

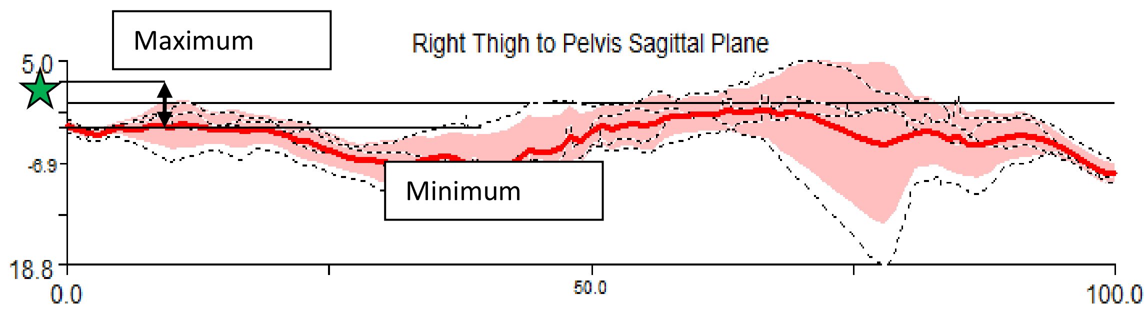
The graphs of data show how the pelvis moves relative to the right thigh during a Single Leg Squat. The participants are in right leg single limb stance throughout the test and therefore the whole of the test is completed in closed chain.

These graphs show that the movement of the pelvis relative to the right thigh is regular for the eccentric lowering and concentric raising elements of the Single Leg Squat except in the transverse plane. In this plane there is an early irregular change of the right thigh to pelvis angle but this becomes more regular during the raising phase of the test.

Corkscrew Test

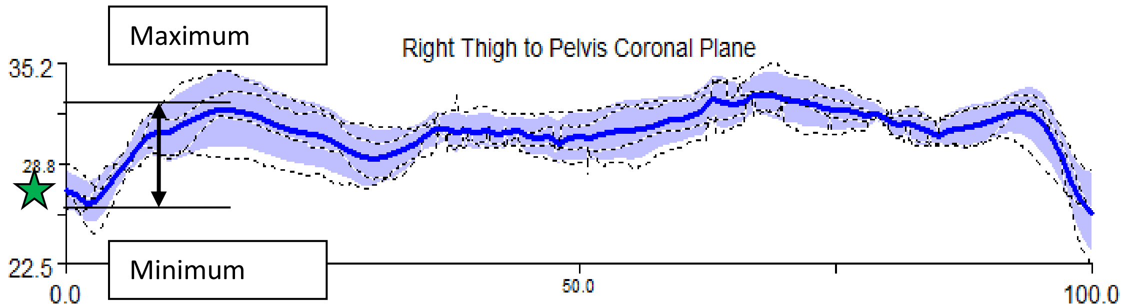
Corkscrew Test Sagittal Plane





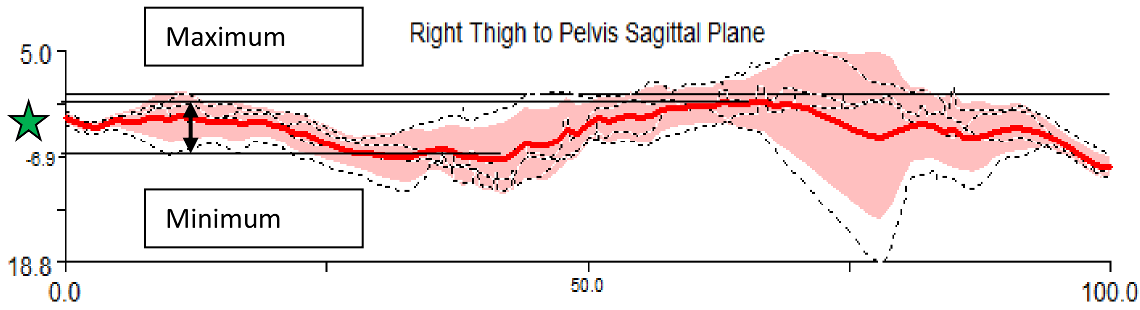
★ Indicates that at the start as the participant commenced the Corkscrew Test on the right lower limb there was a 3^0 angle between the pelvis and right thigh (flexion), hence the thigh was not aligned vertically below the pelvis. This angle remained virtually unchanged during the test. The hip sagittal range of movement was approximately 3^0.

Corkscrew Test Coronal Plane



★ Indicates that at the start as the participant commenced the Corkscrew Test on the right lower limb there was a 25^0 angle between the pelvis and right thigh (adduction), hence the thigh was not aligned vertically below the pelvis. This angle increased during the initial 10% of the test to 30^0 as the participant got into the start position. A similar reduction in hip adduction was seen at the end of the test but in common with the sagittal plane movement during the test the position of the thigh compared to the pelvis in the coronal plane was relatively stable. The hip coronal plane range of movement was approximately 3^0.

Corkscrew Test Transverse Plane



★ Indicates that at the start as the participant commenced the Corkscrew Test on the right lower limb there was a 0^0 angle between the pelvis and right thigh (neutral), hence the thigh was facing directly forward. Initially this angle increased then decreased but the rate varied indicating a loss of control through range. The hip transverse plane range of movement was approximately 6^0.

Corkscrew Test Summary

The graphs of data show how the pelvis moves relative to the right thigh during the Corkscrew Test. In the sagittal and coronal plane the range of movement is less than 3^0. The transverse plane movement indicates loss of control.

Typical Graphs of Results Overall Conclusion

Interestingly when considering movement in the coronal, sagittal and transverse planes of the right thigh relative to the pelvis, the transverse plane (rotation) graphs have shown consistently reduced control of the right lower limb. Hence within this participant redcued hip transverse plane control appears normal.

8.12 Appendix 12

Title of study:

An investigation of the reliability and validity of the Trendelenburg Test as a measure of dynamic pelvic stability in normal healthy adults.

Name	Date of Birth	Date

Point		**Marker Type**
AC joint		Single
Medial epicondyle		Single
Lateral epicondyle		Single
Humerus		Cluster
Forearm		Cluster
Ulna styloid		Single
Radial styloid		Single
Pelvis		Cumberbund (singles on ASIS, PSIS)
Greater trochanter		Single
Shank		Cluster
Medial condyle		Single
Lateral condyle		Single
Leg		Cluster
Medial maleolus		Single
Lateral maleolus		Single
First MTP		Single
Third MTP		Single
Fifth MTP		Single
Calcaneus		Single

***** To be removed after static taken

Appendix 12, CAST marker placement (single segment spine)

8.13 Appendix 13

Title of study:

An investigation of the reliability and validity of the Trendelenburg Test as a measure of dynamic pelvic stability in normal healthy adults.

Name	Date of Birth	Date

Point		**Marker Type**
AC joint		Single
Medial epicondyle		Single
Lateral epicondyle		Single
Humerus		Cluster
Forearm		Cluster
Ulna styloid		Single
Radial styloid		Single
T6		Cluster
L3		Cluster
Pelvis		Cumberbund (singles on ASIS, PSIS)
Greater trochanter		Single
Shank		Cluster
Medial condyle		Single
Lateral condyle		Single
Leg		Cluster
Medial maleolus		Single
Lateral maleolus		Single
First MTP		Single
Third MTP		Single
Fifth MTP		Single
Calcaneus		Single

***** To be removed after static taken

Appendix 13, CAST marker placement (two segment spine)

8.14 Appendix 14

Title of study:

An investigation of the reliability and validity of the Trendelenburg Test as a measure of dynamic pelvic stability in normal healthy adults.

Gait Tests

Walking:
"Stand facing the force plate with both feet at the side of the cone and make yourself comfortable. On my command *walk* towards the other cone. When you arrive at the other cone stop. I will tell you when to walk back to this cone."

Running:
The instructions for the running test were the same. The italicised word walk was replaced by the word "jog, as if you are warming up."

Kicking:
"Stand facing the ball with both feet at the side of the cone and make yourself comfortable. On my command chip the ball to the catcher."

Clinical Tests

Single leg squat:
"Stand facing the force plate with both feet at the edge of it and make yourself comfortable. On my command step onto the plate and place both feet comfortably apart. *Next stand onto one leg and lift the other off the ground so that your Hip is flexed to approximately 45 degrees and the knee to 90 degrees. The shoulders are forward flexed to 90 degrees, with the elbows in full extension and the hands clasped together in front. Squat down to approximately 60 degrees and return to the start position in less than 6s*. Change legs and repeat. When you have done both legs place both feet onto the force plate and step off back to the position you started from. "

Trendelenburg Test:
The instructions for the Balance Test were the same. The italicised text was replaced by the words "Raise one foot from the ground, holding the Hip joint at between neutral and 30^0 of flexion. The knee should be flexed enough to allow the foot to be clear of the ground. Once balanced raise the non-stance side of the pelvis as high as possible and hold. Maintain the position for 30s. I will tell you when to change legs."

Corkscrew Test:
The instructions for the Corkscrew Test were the same. The italicised text was replaced by the words "Raise one foot from the ground, holding the Hip joint at between neutral and 30^0 of flexion. The knee should be flexed enough to allow the foot to be clear of the ground. Turn your body towarss the leg you are standing on, then away, and return to the start position in less than 12 seconds. I will tell you when to change legs."

Appendix 14, Instructions to Participants

8.15 Appendix 15

Title of study:

An investigation of the reliability and validity of the Trendelenburg Test as a measure of dynamic pelvic stability in normal healthy adults.

Name	Date of Birth	Date

<u>Test Duration / Frequency</u>

Order	Test	Duration	Sampling Frequency	Repetitions
1	Static	1 second	100hz	1
2	Trendelenburg	75 seconds	100hz	3 each leg
3	Single leg dip	15 seconds	100hz	3 each leg
4	Balance	75 seconds	100hz	3 each leg
5	Walking	30 seconds	100hz	3 each leg
6	Running	15 seconds	100hz	3 each leg
7	Kicking	7 seconds	100hz	3 each leg

Appendix 15, Study sampling rates / duration

8.16 Appendix 16

Poster Presentations

"An investigation of the use of the Trendelenburg Test as an outcome measure of Lumbo-Pelvic Dysfunction in Professional Football Players" was submitted to the committee for the International Conference for Movement Dysfunction on the 30.03.09. This is a conference held every three years in Edinburgh, Scotland. It is attended by approximately 2000 delegates including biomechanists, physiotherapists and doctors.

Conference Presentations

"Cutting Edge – The Role of Lumbo-Pelvic Testing in the Examination of Gait" to be presented in 2010 Organisation of Chartered Physiotherapists in Private Practice. Nottingham, England. It is attended by approximately 1000 delegates.

Presentations completed

Presentation to UCLAN's FoH staff (2006) "The Trendelenburg Test"

Annual Presentation at UCLAN at the FoH and SC Research Student Presentation conference (2008) "The Trendelenburg Test and Gait"

Presentation at the North West Study Day (2009) for Chartered Physiotherapists "The role of clinical Lumbo-Pelvic Tests in the Examination of Gait"

Annual Presentation at UCLAN at the FoH and SC Research Student Presentation conference (2009) "Gait and its relationship to Lumbo-Pelvic testing"

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