Development and Application of the Pelvic Tracker

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This is to certify that the work presented in this thesis has been carried out at Imperial College London and has not been previously submitted to any other university or technical institution for a degree or award. The thesis comprises only my original work, except where due acknowledgment is made in the text.

بنام ایزد یکتا

یوسف گم گشته باز آید به کنعان غم مخور
کلبهٔ احزان شود روزی گلستان غم مخور
این دل غمدیده حالش به شود دل بد مکُن
وین سر شوریده باز آید به سامان غم مخور
گر بهار عُمر باشد باز بر تخت چمن
چتر گُل بر سرکشي ای مُرغ خوشخوان غم مخور
دور گردون گر دو روزی بر مُراد ما نرفت
دائماً یکسان نباشد حال دوران غم مخور
هان مشو نومید چون واقف نه ای از سر غیب
باشد اندر پرده بازیهای پنهان غم مخور
ای دل ار سیل فنا بُنیاد هستي بر کَند
چون ترا نوح است کشتيبان ز طوفان غم مخور
در بیابان گر به شوق کعبه خواهي زد قدم
سر زنشها گر کُند خار مغیلان غم مخور
گر چه منزل بس خطرناک است و مقصد بس بعید
هیچ راهي نیست کانرا نیست پایان غم مخور
حال ما در فرقت جانان و ابرام رقیب
جمله میداند خدای حال گردان غم مخور

In the name of God

Your lost Joseph will return to Canaan, do not grieve
This house of sorrows will become a garden, do not grieve

Oh grieving heart, you will mend do not despair
This frenzied mind will return to calm, do not grieve

When the spring of life sets again in the meadows
A crown of flowers you will bear, singing bird, do not grieve

If these turning epochs do not move with our will today
The state of time is not constant, do not grieve[3]

Lose hope not, for awareness cannot perceive the concealed
Behind the curtains hidden scenes play, do not grieve

Oh heart, should a flood of destruction engulf the world
If Noah is at your helm, do not grieve

As you step through the desert in desire of Ka’aba
The thorns may reproach you, do not grieve

Home may be perilous and destination out of reach
But there are no paths without an end, do not grieve

Our state in separation from friends and with demands of foes
The divine who turns circumstance knows all, do not grieve

Hafiz of Shiraz

Abstract

Backpacks are commonly used by students of all ages and there has been a growing concern in many countries in relation to the backpack loads carried by school children and its association with the rise in complaints of neck, shoulder and back pain. Of further concern is the work of Hestbaek et al. (2006) which has shown a correlation between experiencing back pain as an adolescent and experiencing low back pain as an adult. In recent years, a number of studies have investigated physiological and movement kinematic responses to load carriage, such as oxygen consumption, heart rate, gait pattern and trunk posture (Hong et al., 2000; Pascoe et al., 1997). However, most of the studies that focused on children carrying loads looked only at gait patterns and trunk and neck postures. None of the previous studies investigated the compensatory pelvic motions of school children due to increased loads. Also, it was reported that one of the major limitations of measuring pelvic kinematics whilst carrying a backpack was occlusion of retro-reflective markers, and consequently this limits the type of activity and subject to be measured using an optical motion tracking system. Despite the presence of a variety of models, there are still debates on their reliability and repeatability, and consequently there is no clearly defined standard or consensus.

In this thesis, a novel methodology was developed to measure pelvic kinematics. Its repeatability and reliability was validated experimentally by comparing it to the most relevant previous method. The result of this experiment showed that the new method improved the repeatability, reliability and reproducibility of kinematics data of the pelvis and overcomes a number of theoretical and experimental limitations, such as marker occlusion. The validated method was used to develop a protocol to measure the pelvic kinematics in adolescents whilst carrying loaded backpacks of 17% and 25% of their body weight during different activities of daily living on the basis of a survey which was conducted to explore the average daily weight that children carry to school in the UK. The result of this experiment revealed that as the load increased to 25% of the body weight, the instability in postural control increased and significant changes in pelvic tilt and rotation were noted in almost all activities. It was revealed in this study that female and

male subjects used different mechanism to compensate for the effect of a heavy backpack. It was evident that carriage of loaded backpack will result in alteration of the movement of the pelvis and may in future promote postural deviation and increase lower back pain.

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Abbreviations

AC	alternating current
AIS	Adolescent idiopathic scoliosis
ASIS	Anterior superior iliac spines
BW	Body weight
CAST	Calibrated anatomical system technique
COG	Centre of gravity
COM	Centre of mass
COMF	Comfort backpack
CoP	Centre of pressure
CVA	Craniovertebral angle
DC	direct current
DoF	degree-of-freedom
EMG	Eletromyography
ERGO	Ergonomic backpack
FEV	Forced expiratory volume
FVC	Force vital capacity
GCS	Global coordinate system
HH	Helen Hayes
HJC	Hip joint centre
ICREC	Imperial College Research Ethics Committee
JCS	Joint coordinate system
LCS	Local coordinate system
L7	Lumbar 7
MRI	Magnetic resonance imaging
PCA	Principal Component Analysis
PEF	Peak expiratory flow rate
PSIS	Posterior superior iliac spines
RMSE	Root-Mean-Square-Error
RSA	Roentgen Stereophotogrammetric Analysis
SIJ	sacroiliac joint
STA	Soft tissue artifact

STS	Sit to stand
T7	Thoracic 7
T12	Thoracic 12
TFL	Trunk forward lean

Chapter 1

Introduction

1.1 Introduction

The backpack is one of the forms of load carriage that provides versatility and is often used by school children. Studies indicate that at least 90% of students in developed countries use a backpack to carry books and other school materials (Brackley et al., 2004; Grimmer et al., 2000; Pascoe et al., 1997; Negrini, 2002; Sheir-Neiss et al., 2003; Goodgold et al., 2002). However, health professionals concerned about the long-term effects of carrying heavy backpacks have recently reported back pain increase amongst school children aged between 9 to 18 years of age (Grimmer et al., 2000; Pascoe et al., 1997; Negrini et al., 2002; Sheir-Neiss et al., 2003). Although a strong relationship exists between the incorrect use of a backpacks and musculoskeletal injuries, the association of actual load and back pain is not consistent and has led to a debate over the potential causes for this rise in back pain reporting (Goodgold et al., 2002; Brackley et al., 2004). An Italian study into backpack use showed that the backpack load was not a good predictor of back pain however, reports of fatigue were highly correlated with reports of back pain (Negrini et al., 2002). Fatigue can be associated with physical fitness, backpack design, time of the carriage and load. In addition to back pain, children reported shoulder and neck pain (Pascoe et al., 1997). It is important to note that the relationship between the cause and effect may be affected by factors other than the backpack related variables (for example, load carried, duration of backpack use, backpack design and fit), which include physical activity, child’s growth and development, and spinal posture (Brackley et al., 2004).

Despite the lack of scientific evidence on the short- and long-term effects of carrying heavy backpacks on adolescents, guidelines limit the weight of the backpacks to 10-15% of the body weight (BW). The majority of biomechanical studies into use of backpacks by children have examined and shown the effect of the different loads on forward lean of the trunk, neck posture, and gait parameters and none have investigated their effect on pelvic kinematics (Chow et al., 2006; Chow et al., 2005; Abdrahman et al., 2009; Chansirinukor et al., 2001; Pascoe et al., 1997; Forjuoh et al., 2003; Grimmer et al., 2000).

1.2 Aim and thesis layout

Due to increased attention to the subject of children and backpack loads, additional research in this area would strengthen the understanding of the effects of the backpack carriage. Some authors have investigated the effects of loaded backpacks on pelvic movement, but only used adults in their research (Smith et al., 2006). However, studies from adults cannot be transferred to children, as the children's bodies are constantly changing as they grow and develop. During this time, particularly in early adolescence (age 11-14 years), it has been found that they are at greater risk from low back pain when carrying a loaded backpack, which could be due to the developing tendons, ligaments and muscles, but this is speculative (Lueder et al., 2007). This age is also vital for spinal growth, which it is believed causes the adolescent spine to be less able to withstand stresses than the adult spine (Grimmer et al., 2000). In addition, it has been shown that if children suffer from back pain then they are more likely to experience back pain as an adult (Lueder et al., 2007).

A few studies, which will be discussed in subsequent chapters, have discussed the biomechanical and physiological consequences of backpack use in children and have discussed different backpack load limits. It has been shown that compensatory motion due to increased loads results in gait alteration, and additional movements at superior levels of the spine, as well as increased torque and linear forces on bodily structures (Smith et al., 2006; Pascoe et al., 1997), but none of the studies have investigated the compensatory pelvic motion due to the loaded backpack in adolescents.

The aim of this study is to investigate the influence of loaded backpacks on pelvic kinematics in adolescents. This thesis has also investigated the effect of gender and backpack type on pelvic motion among 12 to 15 year old school children. This study plans not only to add to the literature on the subject of load carriage by children, but also to contribute to the development of a reliable method for tracking the motion of the pelvis, using an optical motion tracking system.

The aims of this thesis required the understanding of the previous studies on the subject of backpack use in children, as well as pelvic kinematics. Therefore, in Chapters 2 and 3 thorough literature reviews are provided on the effect of backpack loads on adolescents and on pelvic kinematics and methods available to track the pelvic movements. A mathematical model is then developed to track the motion of the pelvis, and investigation of its repeatability and reliability in a series of studies is presented in Chapters 4 and 5. The validated method is then used to investigate the effect of backpack carriage in adolescents, and this is presented in Chapters 6 and 7.

In detail, this thesis is divided into eight chapters as follows:

Chapter 1: Introduction

This chapter describes the motivation and aim of the thesis.

Chapter 2: Gait and posture responses to backpack loads: a review of the literature

In this chapter, the literature in relation to school children carrying heavy bags and the implication of this with respect to back pain is reviewed and presented.

Chapter 3: Pelvic kinematics: a review of the literature

This chapter represents a summary of the current literature on the assessment of pelvic kinematics.

Chapter 4: Pelvic tracker development

In Chapter 4, a novel approach, known as a pelvic tracker for measuring pelvic kinematics, is developed and its sensitivity to the digitised bony landmarks of the pelvis is investigated.

Chapter 5: Pelvic tracker validation

In this chapter the developed pelvic tracker from Chapter 4 is validated by investigating its repeatability and reliability within different body weight groups. This chapter is published in part as: “An alternative technical marker set for pelvis is more repeatable than the standard pelvic marker set” Borhani, M., McGregor, A.H., Bull, A.M.J. 2013, Gait and Posture, 38(4), p.1032-37 (Appendix G).

Chapter 6: Survey of backpack use amongst adolescents

In this chapter a survey is conducted among school children to investigate their backpack use and the load they carry to school. The results of chapters 6 and 7 are submitted for publication to the British Medical Journal and Spine, respectively.

Chapter 7: Kinematics of backpack wearing

In this chapter, a protocol developed from Chapter 6 is used to investigate the effect of backpack load on pelvic kinematics among adolescents. Different types of backpack were used to explore the compensatory movement of the pelvis.

Chapter 8: Discussion and recommendations for future work

The final chapter is a summary of the main results and discussion, the limitation of the study, and future works and recommendations.

Chapter 2

Gait and posture responses to backpack load: A review of the literature

Aim This chapter reviews the literature in relation to school children carrying heavy bags and the implications of this with respect to injury and back pain. Particular focus will be given to the use of backpacks.

2.1 Introduction

Backpacks are commonly used by students of all ages with more than 90% of school children worldwide carrying backpacks. Adults regularly use backpacks for recreational hiking, carrying equipment or as part of their job for example in the military large loads are carried in this way (Abdrahman et al., 2009). There has been a growing concern in many countries in relation to the loads carried within backpacks by school children. Research has linked backpack use with complaint shoulder, neck and back pain, physiological and cardio-respiratory changes such as increased oxygen intakes and heart palpations, kinematic and postural changes such as changes in gait pattern and trunk forward lean in adolescents (Goodgold et al., 2002; Pascoe et al., 1997; Brackley et al., 2004). It is reported that the amount of load carried increases as children progress through school (Singh et al., 2009). There has also been speculation that the weight that school children carry in their bags and backpacks has increased over recent years and this has been attributed to increased homework, larger textbooks, and the transport of sports or music equipment, lunch boxes and after-school clothes and as a result of the decreased availability of school lockers. One of the commonest complaints in adolescents in relation to backpack use is back pain. There is a demonstrated correlation between experiencing back pain as an adolescent and experiencing low back pain as an adult which potentially has far reaching implications (Hestbaek et al., 2006). Consequently attention has been focused on educating parents and children about the loads carried within backpacks with a view to reducing risk of both long and short term injuries.

2.2 Use of backpack by adolescents

Backpacks are a regular item of school children’s attire and around 90% of school children worldwide use them (Brackley et al., 2004). The weight carried by students varies considerably. Negrini et al. (2002) reported that on average the daily load carried by Italian school children ranged from 22% to 27.5% of their body weight (BW). In the same study, 34% of the students carried more than 30% BW with one student carrying 46.2% BW (n=237). Other studies have reported loads ranging from 10% to 20% BW (Pascoe et al., 1997; Goodgold et al., 2002; Sheir-Neiss et al., 2003; Negrini et al., 2002). There is an on-going debate in relation to the loads carried in backpacks and the onset of back pain in children; however, current unenforceable guidelines suggest that loads should be limited to 10% to 15% of a child’s BW (American Academy of Pediatrics, 2012; Ontario Chiropractic Association).

Different methods of carrying a backpack are also reported in the literature, with fashion trends often influencing the way children wear their backpack. For instance, Negrini et al. (2002) reported that 94.5% of Italian students carry their backpack over two shoulders while Pascoe reported 73.2% of American students carry their backpacks with only one strap only over one shoulder (Negrini et al., 2002; Pascoe et al., 1997). The main reason for designing a backpack with two straps was to distribute the weight of the backpack evenly across the spine and shoulders. Indeed, health professionals discourage children and adults from wearing a backpack on one shoulder (American Academy of Pediatrics, 2012; Brackley et al., 2004). There is speculation that the standard backpacks that are available frequently display thin and poorly padded shoulder straps which may cause soreness and redness in the neck and shoulder areas while wide padded shoulder straps improve the comfort for children by distribution of weight across the shoulders.

Some standard backpacks have a lumbar cushion and back padding system, but to minimize the cost of backpack production padding is compromised allowing the backpack’s content to apply pressure directly on the user’s spine during carriage, minimizing both protection and comfort (Mackie et al., 2003). New ergonomic backpacks have been developed that include standard features such as chest and pelvic belts, compression straps and rigid frames. However, this increases the cost and therefore the availability to school children.

As well as considering the standard features of a backpack one has to consider its proportional size, as often these are designed for adults and not children. Not surprisingly most children wear a backpack that is too big for their body frame and thus can be easily overloaded with heavy textbooks, folders, lunch boxes, after-school clothes, sports kit and electronic gadgets.

The poor design of some backpacks and lack of information for parents on how to choose a backpack for their children will increase the financial impact on National Health Service (NHS), on the economy as well as their quality of life if they began the adulthood with existing dysfunction of back pain (Maniadakis et al., 2000). The NHS reported that around one third of the UK adult population suffers from non-specific back pain each year and in 1998 the total NHS and community care cost was £1,067 million which was one of the most costly conditions in the UK (National Institute for Health and Clinical Excellence 2009; Maniadakis et al., 2000). Therefore prevention of any low back pain or postural deformity for adolescents by choosing a right carriage load and backpack size is a very important fact and may reduce future problems during adulthood.

2.3 Back pain reporting in adolescents and known risk factors

Previous studies indicated that the prevalence of back pain, shoulder pain and muscle ache increased from secondary school children to high school children with a lifetime prevalence of low back pain ranging from 12% for 12 year old to 74% in 17 year old students (Sheir-Neiss et al., 2003; Williams, 2002). Low back pain in adolescence is frequently referred to as non-specific low back pain as there is no specific or identifiable cause. Potential risk factors of back, neck and shoulder pain in children could include: age, growth rate, thoracic kyphosis, hyperlordosis, weak abdominal muscles, low thigh muscle flexibility, depression, stress, time spending sitting, or watching television and a family history of back pain (Williams, 2002; Balague et al., 1999; Grimmer et al., 2000). Furthermore, 59% of low back pain in adolescents has been linked to backpack use and load carried, both increased load and duration of carriage increasing the risk (Sheir-Neiss et al., 2003; Wang et al., 2001; Wiersema et al., 2003; Grimmer et al., 2000). Although a certain level of stress applied to the body will strengthen the musculoskeletal system during growth, excessive stress may result in injury on child’s body. It is difficult to determine what level of stress and how much exposure is tolerable for each child before injury occurs because of individual variation. Researchers have demonstrated that if a backpack load exceeds 10% of a child’s BW it will increase energy consumption, trunk forward lean, and decrease lung volumes and as a result, the shoulders and spine are more susceptible to injury as they are in direct contact with the backpack (Sheir-Neiss et al., 2003). Furthermore, the spine and body structure of children/adolescents are different from the spinal structure of adults, as the development of the children’s spine will not reach full growth (ossification of vertebrae) until 24 years of age (Chansirinukor et al., 2001; Grimmer et al., 2000). In addition, children experience several growth periods, especially during their school-age (5-18 years) but the highest rate of the growth occurs during puberty (10-12 years of age for girls and 13-15 years of age for boys) (Lebiedowska et al., 2000; Brackley et al., 2004); therefore a great care should be emphasized during these years as Pascoe et al. (1997) stated the use of a heavy backpack will result in excessive stress on the spine and surrounding muscles and different spinal conditions such as functional scoliosis may be exacerbated as a result.

As stated before, heavy loading of the spine during growth may induce vertebral stress, resulting in problem such as scoliosis, kyphosis and lordosis because of poor posture resulted from a backpack load (Lai et al., 2001; Chow et al., 2007); external forces may also affect the development of normal skeletal alignment which will result in vertebral abnormality and compensatory mechanism which alter postures and muscle activities (Chansirinukor et al., 2001; Goodgold et al., 2002).

The injuries associated with backpack use reported in children/adolescents in addition to back pain and shoulder pain include muscle soreness and rucksack palsy. Pascoe et al. (1997) reported that around 24% of students suffered from numbness in their arms and shoulder pain which are all symptoms of rucksack palsy. This problem occurs because of poor shoulder padding of the backpack straps and too narrow straps, thus producing unequal and large pressure across the shoulder, including direct pressure on the top of the brachial plexus structure (Figure 2-1) thus pressing the nerves against the underlying rib cage or collar bone (Pascoe et al., 1997).

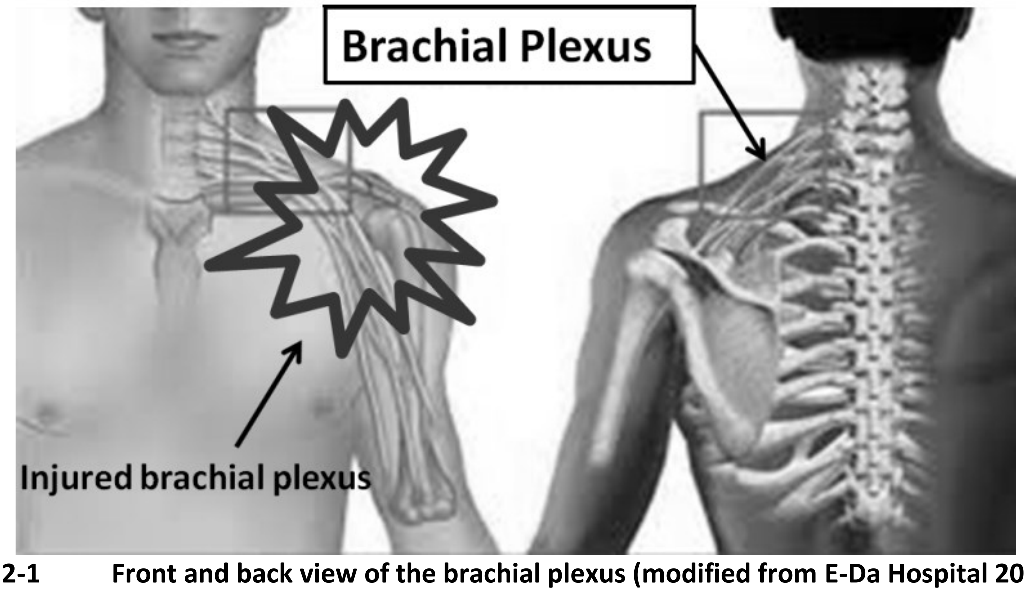

Figure 2-1 Front and back view of the brachial plexus (modified from E-Da Hospital 2012)

2.4 The impact of backpack loads on the posture of adolescents

2.4.1 Biomechanical response to the backpack loads

Carrying a loaded backpack shifts the centre of gravity (COG) toward the rear of the base of support; therefore, this will result in postural change in static and dynamic situations to maintain balance and control the movement. The combination of these factors (postural change and increased backpack load) will alter the gait patterns. Goh et al. (1998) reported that the increase of backpack load is not equivalent or linear to the increased forces experienced by body; therefore the postural adaptations do not follow a linear response (Goh et al., 1998). This is very concerning for children/adolescents between the age of 10 and 15 years (the greatest rate of growth) as there is no indication of how their posture will adapt to the excessive backpack load.

Previous studies have investigated the effect of carrying a loaded backpack on trunk forward lean (TFL), craniovertebral angle (CVA), and gait parameters which are explained briefly (Figure 2-2).

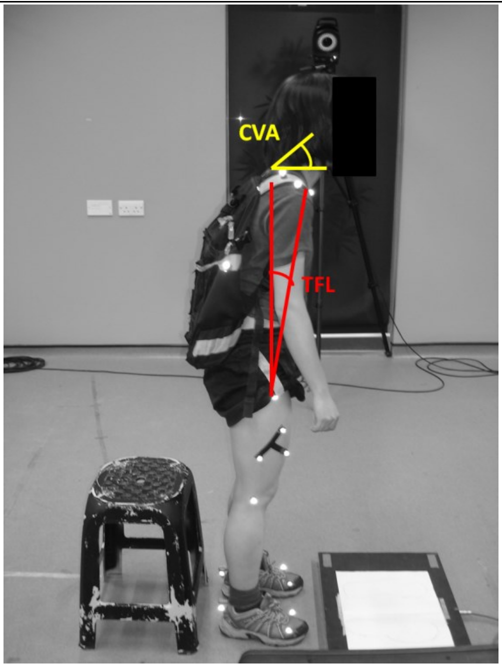

Figure 2-2 Illustration of the positions of the trunk forward lean (TFL) and craniovertebral angle (Motion Analysis Laboratory, Imperial College London)

2.4.1.1 Trunk forward lean (TFL)

The kinematic responses to carrying a loaded backpack while walking or standing will result in postural responses that require an interaction and adjustments of the trunk and limbs. Trunk forward lean is a clear change in postural alignment, postural stability and gait. TFL is defined as the angle between the vertical line and a line produced by connecting the greater trochanter and acromion process (Figure 2-2). This postural change is associated with increased forces at the lumbosacral joint, which may contribute to low back injuries (Goh et al., 1998). Using biomechanical modeling, Goh et al. (1998) compared the lumbosacral forces obtained from backpack loads of 15% BW and 30% BW to an unloaded backpack in young adult men. The results of this study showed that the peak lumbosacral force increased by 26.7% from the unloaded condition (absolute values 1.9 BW) (Goh et al., 1998).

In biomechanical studies in children, it was shown that as the backpack load increases the TFL also increases. The range of loads varied from 0% to 25% BW but the TFL changes occurred with loads of 15% BW and greater (Hong et al., 2000; Lamar et al., 2000; Li et al., 2001). Hong et al. (2000) investigated the effect of varying loaded backpacks on children's gait; the result showed that a 20% BW load significantly increased the trunk forward lean during gait. Also Chansirinukor et al. (2001) showed that a backpack weighing 15% BW can alter the adolescents' posture by increasing the trunk forward lean. As well as the weight of the backpack, the demands of the task being performed can affect the TFL. Goodgold et al. (2002) performed a pilot study with only two subjects to investigate the effect of task on the TFL. They showed that the TFL would be greater for running compared to walking.

2.4.1.2 Craniovertebral angle (CVA)

Another postural compensation mechanism is CVA which is the angle between the head and neck posture; tilting the head forward decreases the CVA. Chansirinukor et al. (2001) investigated the influence of backpack load, the position of the backpack on trunk, and the amount of the time spent carrying the backpack on the student's cervical spine and shoulder posture. They reported that the CVA measurement decreases while carrying the backpack which indicates that the head is tilted forward (Chansirinukor et al., 2001). The finding of this study was supported by Pascoe et al. (1997) who suggested that the postural responses of adolescents are sensitive to loads of 17% BW (Pascoe et al., 1997; Chansirinukor et al., 2001). Chansirinukor showed that the CVA measurement for the student carrying their backpack decreased after 5 minutes of walking and that there were minimal effects on the neck and head posture as a result of student carrying the backpack over two shoulder straps compared to one. A study conducted by Hong et al. (2001) revealed that no changes occurred in CVA measurements and they concluded that children compensated for the weight of their backpack through trunk flexion. This contradiction may be explained by noting the age difference in the children that participated in these studies. The subjects in the study of Hong et al. (2001) were 6 years old which were much younger than the subjects in Pasco et al. (1997) and Chansirinukor et al. (2001) which were 11-13 and 13-16 years of age, respectively. Therefore, this might be an indication of how growth and motor development during puberty could have an impact on biomechanical responses due to the heavy backpack load.

2.4.1.3 Changes in gait

A prominent change in kinematics in response to carrying a heavy backpack is observed in gait changes. Such changes result from adjustments in stance and centre balance to compensate and minimize the effect of carrying the load. However the details of these changes are inconsistently presented in the literature in part reflecting the assessment of gait itself which has varied between treadmill assessments and normal over ground walking. The examination of children's gait with varying backpack loads revealed that the swing duration decreased and double support time increased when carrying a backpack loaded with 20% BW during treadmill walking (Hong et al., 2000). Singh et al. (2009) investigated the impact of the backpack load carriage and its vertical position on the back with respect to temporal-spatial and kinematic parameters associated with gait and postural stability (17 participants, mean age of 9.65 years). No significant differences were found between the two backpack position configurations for the trunk forward lean in both static and gait measurements (upper configuration: positioning the backpack load superior to eighth and ninth thorax vertebrae, and lower configuration: positioning the backpack load inferior to T8 and T9). The results also showed a decreased gait velocity and cadence, and increased double support time for 9 year old children while carrying a backpack load of 20% BW (for both configurations during treadmill walking), these findings on spatiotemporal parameters could be an indication of a compensatory mechanism by children to minimise the instability during gait or may result from a mechanical strain on the musculoskeletal system (Singh et al., 2009). In contrast no significant differences were reported in stride or temporal parameters for children between 9 and 10 years old with a backpack weight of up to 20% BW (over ground walking for 2 km) (Hong et al., 2003). A further over ground study of gait showed a decreased stride length, increased double support time and increased stride frequency when students walked while carrying 17% BW in a two straps backpack (the distance walked was not recorded) when compared to no load (Pascoe et al., 1997).

The trunk inclination angle has been also used during gait to measure the effect of the backpack load on changes in posture. A study conducted by Abdrahman et al. (2009) using two boys recruited from a local primary school in Malaysia assessed gait under four different load conditions: without the backpack, backpack with 10% BW load, 15% BW load and 20% BW load (carried on both shoulders). They reported that the trunk inclination angle increases more than 5 degrees with loads of 15% and 20% BW compared to that of 0% and 10% BW (Abdrahman et al., 2009).

Changes in trunk posture were also reported by Li et al. (2003) in 15 boys (10 years old). The participants completed four walking trials on a treadmill: a backpack load of 0%, 10%, 15% and 20% of BW while the backpacks were positioned at waist level, with two straps. The results showed that trunk inclination increased as the load increased but no significant differences were found in trunk inclination angle between any loads over 10% BW during the first minute of the trials (Li et al., 2003).

Seven et al. (2008) investigated the effect of a loaded backpack on the kinematics and kinetics of the sit to stand motion of fifteen children (8 boys and 7 girls) with a mean age of 9 years. A motion analysis system consisting of 6 infrared cameras was used to measure the subjects with no backpack load and with backpack loads of 10% and 20% BW. The results indicate that the children made some changes compared to their unloaded pattern whilst carrying a high load. These included main kinematic and kinetic adjustments which were increased trunk flexion, greater ankle dorsiflexion and increased knee extension moment (Seven et al., 2008). In this study there was no comparison between the compensatory mechanism of the two genders and the effect of the loaded backpack was mainly investigated at the knee and ankle joints. A similar study was conducted by Goodgold et al. (2002) to investigate the effect of increased backpack load as well as task demands on the posture of two school children (age 9 and 11 years). They attached 20 reflective markers on 20 anatomical landmarks and videotaped the subjects under nine experimental conditions, including three level of backpack load (0%, 8.5% and 17% BW) and three levels of task demands (stand, walk and run). They reported that the trunk forward lean increased with increases in backpack load and task demand but there was no report on pelvic movement and they only investigated two subjects.

One study investigated the influence of carrying a loaded backpack on pelvic tilt, rotation and obliquity in female college students with mean age of 22 years (Smith et al., 2006). Three conditions were used to analyse the gait including: walking without a backpack, carrying a backpack unilaterally, and carrying a backpack over both shoulders with the backpack load of 15% BW. Carrying the backpack bilaterally showed the greatest angular pelvic tilt compared to unilateral carriage or walking without a backpack. Even though the angles of pelvic tilt or rotation were not changed across the conditions, the range of motion of the pelvic obliquity and rotation was significantly decreased when walking with a backpack. But this study only investigated the effect of loaded backpack on college students (18 to 30 years of age) who may use different compensatory mechanism than the adolescents.

2.4.2 Postural control response to backpack loads

Biomechanically, the human body can achieve a balanced state in the absence of external forces and achieve equilibrium in quiet stance using passive muscle tension and the ground reaction force vectors. Wearing a loaded backpack challenges the biomechanical equilibrium and the postural control of the trunk. Carrying a load of more than 15% BW for adolescents challenges their ability to maintain an upright standing posture by changing the cervical (decreasing CVA), shoulder (rounded and tilted forward) and trunk (forward lean) postures (Chansirinukor et al., 2001).

An individual’s standing posture will change when a loaded backpack is worn and cause the individual’s trunk to shift anteriorly in order to bring the new centre of mass (COM) over the base of support. If the backpack is carried using both straps then the individual’s posture is shifted anterior/posteriorly rather than medio/laterally by leaning forward at the head, trunk, hips and ankles. If the load is carried only by one shoulder strap, then a lateral trunk shift is used to achieve a stable position (Pascoe et al., 1997). This compensatory shift response which involves the elevation of the carrying shoulder and deviation of the spine away from the backpack may lead to misalignment of the spine (functional scoliosis) (Pascoe et al., 1997).

Another important objective component of postural stability is postural sway. Postural sway is measured by the determination of the centre of pressure (CoP) during standing and recording the movement of the CoP during fixed time period. Usually a force plate is used to measure CoP and consequently postural sway. As an individual stands on the force plate, the transducers that are mounted on corners of the force plate will measure the forces on the force plate, and CoP can be calculated. The CoP is the location of the vertical ground reaction force on the force plate and it is equal and opposite of the all forces acting downward (Figure 2-3).

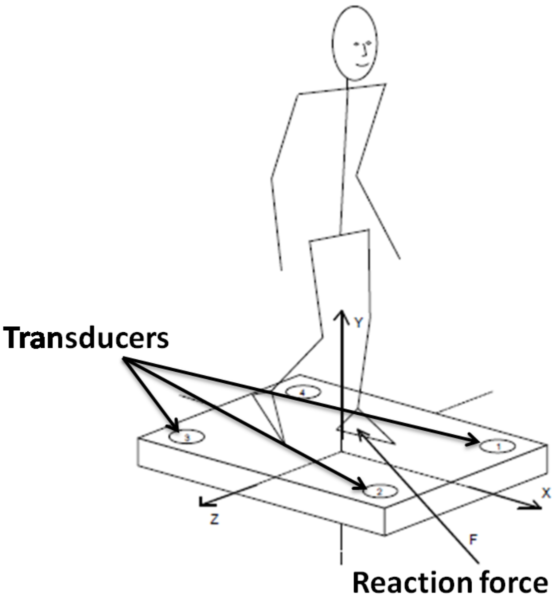

Figure 2-3 Illustration of the force plate and four transducers plus the reaction force applied to the force plate, more detail is given in Chapter 7 (modified from Health Uottawa)

During quiet standing (i.e. subject standing still) it is possible to track the movement of the CoP by calculating the total distance the CoP travels (postural sway length) and the total area covered by the CoP (postural sway area). Both are considered as measures of postural stability. Chow et al. (2006) conducted an experiment to investigate the standing posture of two groups of 20 healthy schoolgirls (10-15 years) and 26 girls (11-14 years) with mild adolescent idiopathic scoliosis (AIS). Both groups were asked to stand still for 90 seconds while carrying a backpack load of 7.5%, 10%, 12.5%, 15% BW and with no backpack. A standardized dual strap backpack was used with the COG of the backpack located between the 11th and 12th thoracic vertebrae of each subject. The mean angles between the pelvis, trunk and head in space were recorded using a motion analysis system and the CoP was recorded using the force plate. They found that carrying a loaded backpack causes similar sagittal plane changes in posture and balance in both groups. Also, it was shown that increased backpack load causes increased antero-posterior range of CoP motion and sway distance. But no changes in medio-lateral position of the CoP with respect to the pelvis were seen as the backpack load increased (Chow et al., 2006). However, this study used a purposed designed backpack in which the COM of the backpack was located close to the body; a typical school backpack is located further away from the back and therefore the location of the subject's and backpack's COM is more posterior to that in the study of Chow et al. (2006).

Another factor that affects postural stability is the position of the load which has been shown to affect posture, movement and energy expenditure. The majority of backpacks used by children have adjustable straps to allow varied placement of the backpack on the spine. Children choose the placement of the backpack according to their personal comfort, ease in putting on and removing the backpack, or even fashion and peer acceptance (Goodgold et al., 2002). The response of adolescents' standing posture in the sagittal plane to different loads and position of the school backpack was investigated by Grimmer et al. (2002). A total of 250 students, age between 12 to 18 years, were randomly selected from five different schools in Australia, and they completed nine experimental conditions which consisted of a loaded backpack of 3%, 5% and 10% BW, while carrying it positioned with the centre of the backpack located at the upper (T7), middle (T12), and lower spinal (L3) positions. Under these experimental conditions and unloaded standing posture, sagittal plane photographs were taken. The results showed that carrying the backpack centered at level of third lumbar vertebra resulted in the least postural displacement and required minimal postural adjustment to maintain. Therefore it was suggested that the backpack loads should be placed lower on the spine in order to minimize children's postural alterations.

2.4.3 Physiological response to backpack loads

As well as association of backpack load to measurable kinematic responses (gait, posture and balance), physiological responses including cardiovascular, pulmonary, metabolic and nerve function changes and changes in lung volume are observed in response to carrying a loaded backpack.

As discussed before, there is a clear relationship between the change of posture during carrying a backpack and changes of trunk position and motion. Therefore as an individual carries a loaded backpack, the forward lean of the trunk increases, thus limiting the range of motion of trunk available and increasing breathing frequency (Li et al., 2003).

The effect of various backpack loads on lung volume and function was investigated by Lai et al. (2001). They measured forced expiratory volume (FEV), force vital capacity (FVC), and peak expiratory flow rate (PEF) with 0%, 10%, 20%, and 30% BW in 43 children (9-11 years old). They have also measured the effect of the loaded backpack on the shoulder girdle by measuring the kyphotic posture before and after using the loaded backpack. They found significant decreases in the FEV and FVC for 20% and 30% BW. Also they showed that kyphotic posture (rounded shoulder and back) produced an equivalent decrease in lung function when compared to carrying a minimum backpack load of 10% BW. Li et al. (2003) also conducted a study to examine the effect of carrying a loaded backpack on respiratory changes in 10 years old boys. The results of this study indicated that a load of 10% BW did not significantly affect the trunk posture and respiratory function but when the backpack load reached 20% BW a significant increase was reported for both trunk posture and the respiration. Therefore these results suggested that the respiratory function of children is not impacted by 10% BW (Lai et al., 2001).

Hong et al. (2000) measured the heart rate before, during and after 5 minutes of treadmill walking (over 20 min period) in 15 boys (mean of 10.3 years of age) using a cardiopulmonary function system. The result showed that the heart rate measured after 20 min of walking with 20% BW load condition was 125 bpm, which is 60% higher than the resting heart rate of children at this age. The blood pressure was measured prior to and immediately after the walking test and at 3 and 5 min after finishing the test. Walking for 20 min significantly increased the blood pressure for all loads but the recovery in blood pressure was significantly different among different loads. After 3 minutes of recovery the blood pressure reached the baseline (blood pressure recorded at rest) when carrying 0% and 10% BW. However, the blood pressure was still higher than the baseline even after 5 minutes of recovery when carrying loads of 15% and 20% BW. They also reported that 5 minutes of walking led to a significant increase in heart rate in comparison to pre-exercise heart rate (Hong et al., 2000).

Another study that examined the respiratory conditions in 15 boys aged 10 years was conducted by Li et al. (2003) in which the participants walked on a treadmill for 20 minutes while wearing a face mask that was attached to a cardiopulmonary function system to measure the respiratory condition. This study showed that walking with 20% BW load induced higher thoracic respiratory muscle activity than other loads (10% and 15% BW). Another recent study by Chow et al. (2009) assessed the effects of backpack load placement on pulmonary capacities in 22 normal schoolchildren (mean age of 12 years). FVC and FEV were measured during free standing and when carrying a backpack of 15% BW with its centre of gravity positioned at T7, T12 and L3; the results of the study showed that the load had a significant effect on FVC and FEV while there were no significant effects of load placement on the pulmonary function of school children (Chow et al., 2009). In contrast, Stuempfle et al. (2004) found that the oxygen consumption was significantly lower in the high position of the backpack compared to the low position. As the position of the load changed from the high to low position there were no significant changes in heart rate and respiratory rate. Therefore it was recommended that locating heavy items high in the backpack may be the most energy efficient method of carrying a load on the back (Stuempfle et al., 2004).

2.5 Contradiction in previous studies

As discussed in the previous sections, positioning backpack load on the spine is another factor that affects the postural stability, gait parameters and physiological responses (Stuempfle et al., 2004; Grimmer et al., 2002; Singh et al., 2009). However, findings from these studies contradict with the previous assessment on the positioning of backpack load. Singh et al. (2009) investigated the impact of vertical position of backpack load on the spine during walking on an instrumented treadmill (Figure 2-4). They reported that placing the load low on the back affected the trunk forward lean more than placing it high on the back while carrying a load of 20% BW during gait (participants: 9.65 ± 1.58 years). However, they discussed that the differences between the two configurations were not significant enough to conclude anything with certainty.

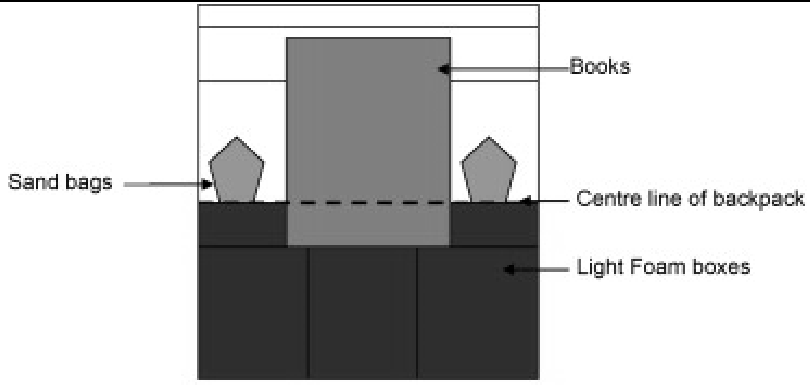

Figure 2-4 Adjustment of load in the backpack for an upper configuration (Singh et al. 2009)

On the other hand, Grimmer et al (2002) reported that positioning the backpack high on the spine (Centre of backpack at T7) produced largest postural response at all anatomical points including the neck and shoulder (participants: 250 students from five high school year levels). However, this study was only based on the static posture with maximum backpack load of 10% BW. There was no indication on how long the participants wore the backpack during each condition and they used two-dimensional photography to measure the sagittal standing posture (Figure 2-5), while Singh et al. (2009) used an optical motion analysis system and force plate and asked their subjects to walk for 6 minutes before recording the data for each condition.

Figure 2-5 Illustration of backpack position in the study conducted by Grimmer et al. (2002). Backpack positioned at high (T7), middle (T12) and low (L3), from left to right (adopted from Grimmer et al. 2002)

Stuempfle et al. (2004), however, only investigated the effect of backpack load position on physiological and perceptual variables of female college students (18-22 years of age) and they concluded that after 10 minutes of walking oxygen consumption and rating of perceived exertion were significantly lower when the load was carried in the high position (T1-T6) compared to the low position (L1-L5; Figure 2-6).

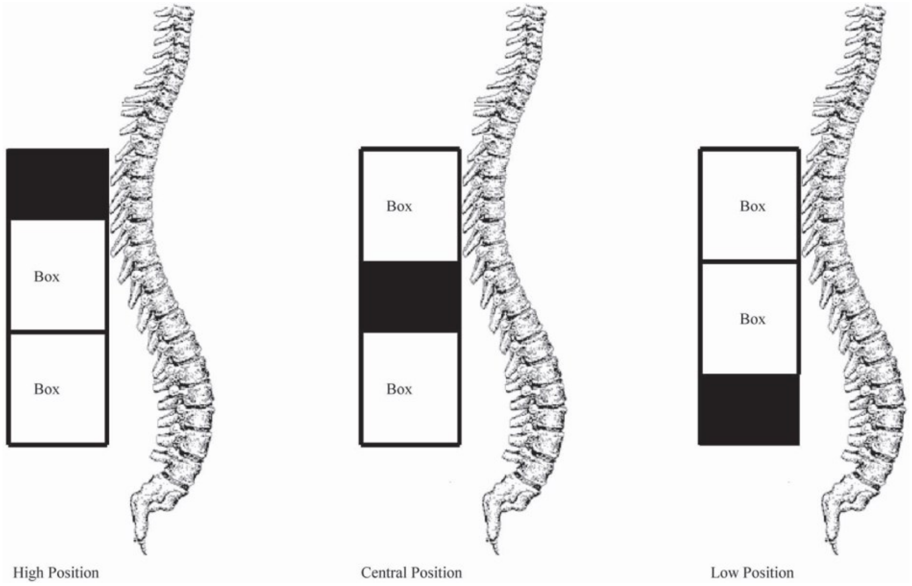

Figure 2-6 Illustration of load positions in the study conducted by Stuempfle et al. (2004). The black boxes represent the load positions of 25% BW. From left to right, the load is positioned at high (T1-6), central (7-12), or low (L1-5) (adopted from Stuempfle et al. 2004).

With regards to the vertical position of backpack load, there could be different reasons for the above contradictions. These include: age of participants, amount of backpack load, duration of backpack wearing, type of the activity (static or dynamic task), type of the instruments used to collect data, type of the backpack used (framed, unframed, or ergonomic), and finally the distribution of the load inside the backpacks.

2.6 Limitation of the current studies

In the previous sections a summary of the literatures was presented. Even though most of the prior work has shown the significant effects of carrying a heavy backpack, still there are some significant gaps and limitations.

There are several studies that have investigated the effect of the loaded backpack by creating a backpack similar to those used in hiking or in the military which have either an internal or external framed support system (Kirk et al., 1992; Legg et al., 1985; Pascoe et al., 1997). However few studies have analyzed the biomechanical compensations that occur during gait or in static or dynamic trials of activities of daily living using unframed backpacks similar to those carried by most school children; the studies conducted by Chow et al. (2005) utilized a dummy backpack of standard design which still does not represent the real backpacks that are currently used by adolescents (Figure 2-7).

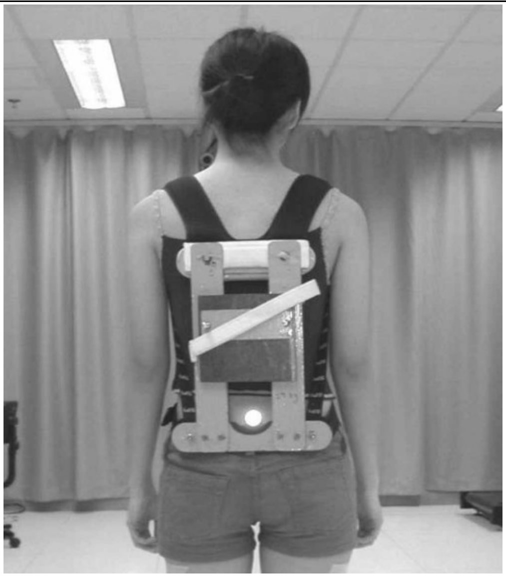

Figure 2-7 The standardized dummy backpack that used by Chow et al. (2005) to measure the effect of loaded backpack

No studies have investigated the effect of ergonomic loaded backpacks on posture and the kinematics of the joints and compared these to less ergonomic backpacks.

Only one study investigated the effect of loaded backpacks on pelvic kinematics and discussed the importance of compensatory pelvic motions due to increased load which leads to alteration in gait and additional movements at superior levels of the spine and may cause back pain (Smith et al., 2006). This study investigated pelvic kinematics in college students of 18 to 30 years of age and the findings of this study might not be transferable to adolescents. Another limitation that was noticed in this study was that the backpack caused displacement of the sacral marker that may contribute to inaccurate results.

As it was shown that many school children complain about the back pain associated with carrying heavy backpacks, it is important to comprehend how the pelvic movement is altered whilst carrying a loaded backpack.

To achieve this, it is important to understand the pelvic kinematics and available measurement techniques to measure and track its movement precisely before analyzing the effect of a loaded backpack on the pelvis amongst adolescents; therefore in the next chapter (Chapter 3) a literature review of pelvic kinematics and its measurement techniques will be presented.

2.7 Summary

Backpacks are used by the majority of children worldwide and it has been suggested that carrying a backpack loaded with 10% to 15% BW is detrimental. However, the weight of the backpack is not the only factor that causes musculoskeletal disorders, tissue injury or back pain; other important factors include the distance the load is to be carried, the design of the backpack, the child's physical fitness and their maturation. Studies from different countries showed that carrying a heavy backpack might cause deformities in the musculoskeletal system. By understanding these factors we may enlighten parents and children about safer backpack use and prevent backpack related musculoskeletal injuries.

Chapter 3

Pelvic kinematics: a review of the literature

Aim This chapter represents an appraisal of the current literature on the assessment of pelvic kinematics and was undertaken to inform the subsequent methodological approach adopted for the proposed clinical studies.

3.1 Introduction

The pelvic girdle, also known as the pelvis, forms the base of the trunk and links the lower limbs to the vertebral column. As a result, knowledge of both the anatomy and biomechanics of the pelvis is vital and may provide essential information to assist clinicians and engineers in the prevention and diagnosis of clinical disorders and gait abnormalities.

The pelvis presents a challenge to current measurement techniques widely used in biomechanical analysis due to its shape, the mobile nature of the skin and the diversity of body shapes in the population. For this reason, a variety of methods has been developed to measure pelvic kinematics; these methods addressed the difficulties described above, but the complexity of some of these methods can limit their use in clinical assessment.

The literature review presented in this chapter will provide a brief introduction to pelvic anatomy and function with the main focus being the challenges facing pelvic motion measurement techniques and the currently available solutions for assessing pelvic motion.

3.2 Pelvic anatomy and function

3.2.1 Pelvic bone and joints

In the skeleton, the bony pelvis, also called the pelvic girdle, is located between the spinal column and the lower extremities and plays a crucial role in the load transfer mechanism from trunk to the legs and vice versa. It consists of three bones: two hip bones (pelvic bones) and a sacrum.

The Ilium, Ischium and Pubis are fused together during puberty and are known as the hip bone or innominate bone (Figure 3-1). This hip bone interacts with the rest of the skeleton through three joints: (1) sacroiliac joint (SIJ), which connects the hip bone posteriorly to the sacrum; (2) the pubic symphysis, which connects the two hip bones anteriorly; and (3) the hip joint, which connects the hip bone to the leg.

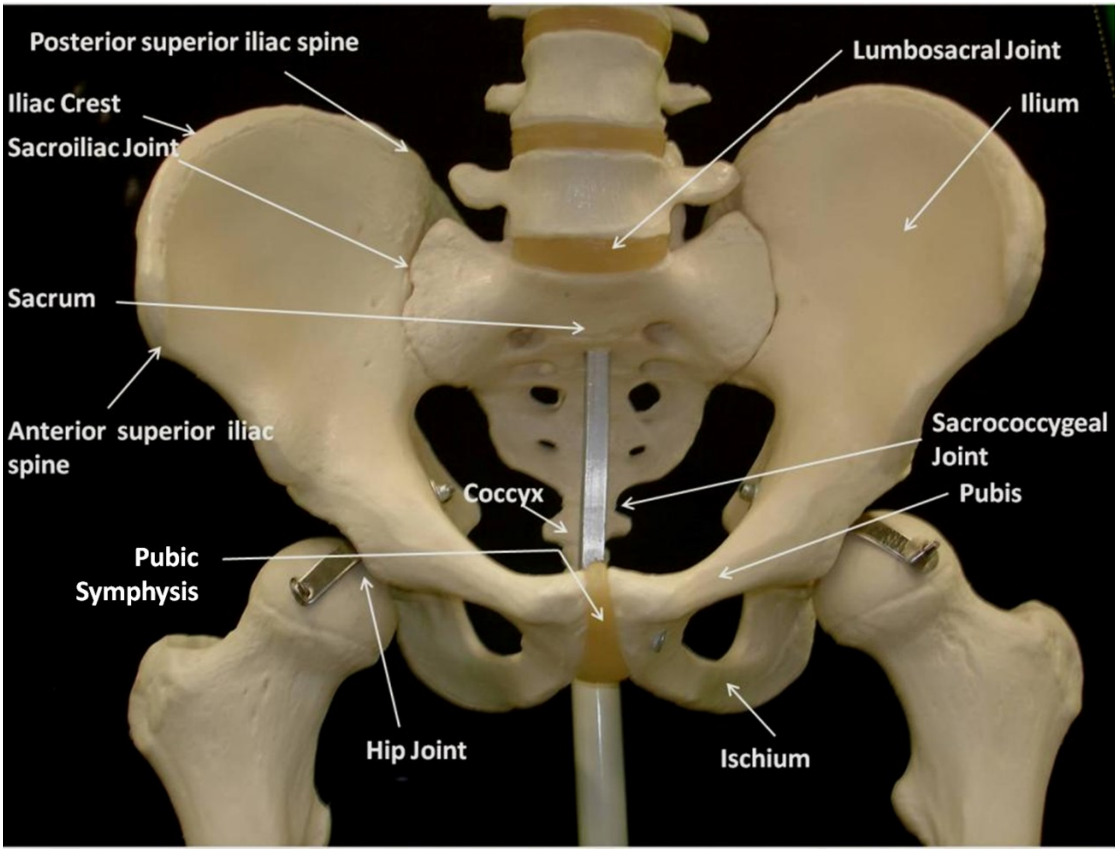

Figure 3-1 Anterior view of the pelvis

The sacrum connects the spine to the pelvis at the lumbosacral joint, and connects the hip bones posteriorly at SIJ to form a closed chain known as the pelvic ring. In order to enhance the stability of the chain as well as to provide muscular connections, extensive fibrous connection exists between the sacrum and pelvic bones. As a consequence of the tightness of the fibrous connections and the specific architecture of the SIJ, mobility in the SIJ normally is minimal if at all (Vleeming et al., 1997). The motion within the pelvis as well as the motion of the pelvis as a whole is discussed below.

3.2.2 Pelvic movement and range of motion

As for any rigid body, the pelvis has six degrees of freedom, rotations about and translation along the X, Y and Z axes as shown in Figure 3-2. In this thesis only the rotational movement of the pelvis will be discussed.

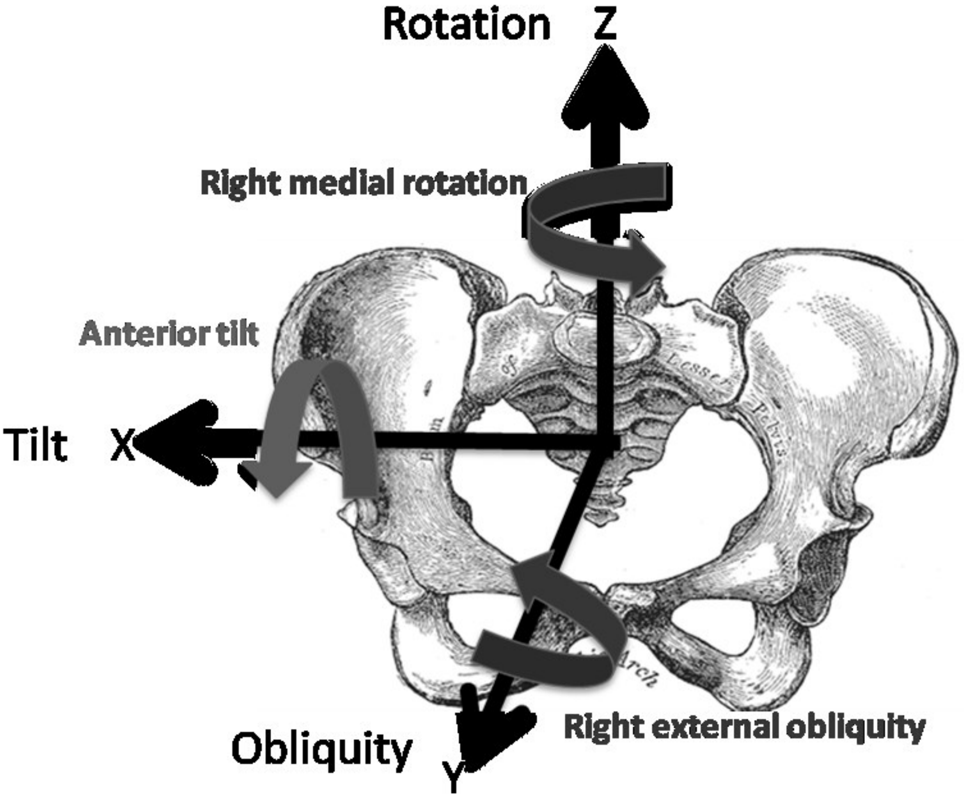

Figure 3-2 Pelvic rotation occurs in all three planes. Arrows around the X, Y, and Z axes represent the anterior/posterior pelvic tilt, right internal/external obliquity and right lateral/medial rotation, respectively. The X, Y, and Z axes are perpendicular to the sagittal, frontal, and transverse planes, respectively (modified from Wikipedia, 2012).

Flexion/extension movements usually occur in the sagittal plane (about the X axis) which is also known as anterior/posterior pelvic tilt. Anterior pelvic tilt, from the position of Figure 3-3a to that in Figure 3-3b, involves increased inclination in the sagittal plane about the X axis. Therefore this results in the lower part of the pelvic girdle, pubic symphysis, to turn inferiorly and the posterior surface of the sacrum to turn superiorly. Posterior pelvic tilt, from the position in Figure 3-3a to that in Figure 3-3c, involves decreased inclination in the sagittal plane about the X axis. This requires the pubic symphysis to move superiorly and the posterior surface of the sacrum to turn inferiorly.

Pelvic abduction/adduction occurs in the frontal plane (around the Y axis) which is also known as pelvic obliquity. Pelvic obliquity occurs when one iliac crest is moved inferiorly while the other one is moved superiorly. Thus right internal obliquity is when the right iliac crest is moved superiorly and the left iliac crest moves inferiorly (Figure 3-3d).

The pelvis can also rotate medially and laterally in the transverse plane about a vertical axis (around the Z axis) which is referred to as pelvic rotation. The movement is named after the direction towards which the front of the pelvis turns, which means that when the right part of the pelvis moves forward this is called right internal rotation.

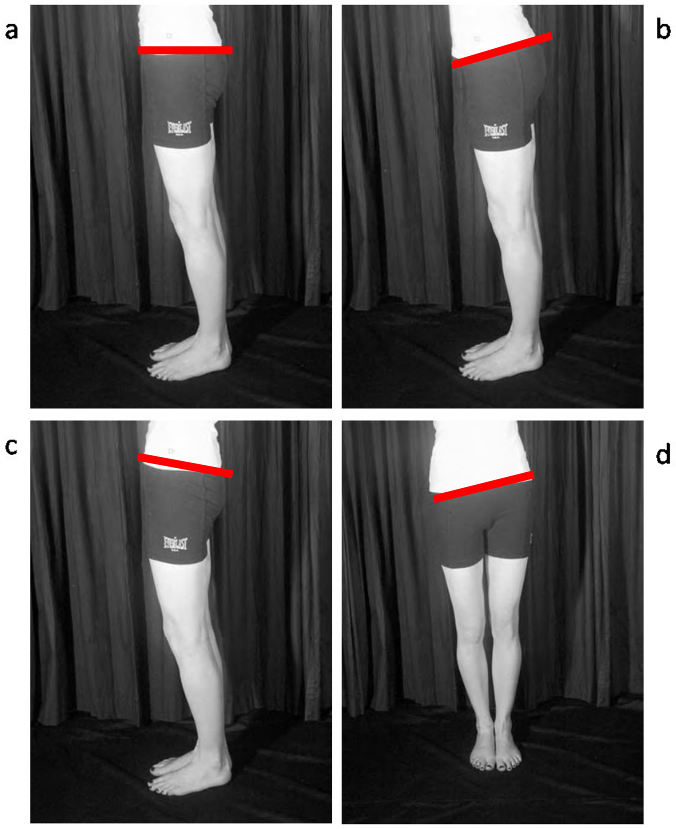

Figure 3-3 Pelvic girdle movement: a) neutral position of pelvis; (b) anterior pelvic tilt; (c) posterior pelvic tilt; (d) pelvic obliquity (modified from Richards, 2008)

The importance of the motion of the pelvis was first documented by Saunders et al. in 1953 who identified pelvic tilt and rotation as major determinants in normal and pathological gait (Saunders et al., 1953; Salazar-Torres et al., 2011). Richards (2008) examined the vital role of pelvic obliquity during normal walking and suggested that it serves two purposes: to allow shock absorption, and to allow limb length adjustments.

Furthermore, the importance of SIJ as the key element in the pelvis was noted (Vleeming et al., 1997). It has been suggested that as the movements in the SIJ are very little that the external examination such as static and dynamic palpation of motion and position of SIJ is virtually impossible (Sturesson et al., 2000). As the SIJ is wedge shaped, both anteriorly and posteriorly, it has not been established if there is a fixed axis about which the joint rotates. The problem is very complex in that the SIJ motion is affected by motion in the lumbar spine, hip joint, and pubis symphysis (Vleeming et al., 1997). It has been shown that any pressure on the sacrum is transformed into forces which press the sacrum between both pelvic bones and pull the pelvic bones in towards the sacrum. Therefore the interosseous sacroiliac ligaments (Figure 3-4) which run inferiorly in a medial direction from the hip bone to the sacrum are under tension.

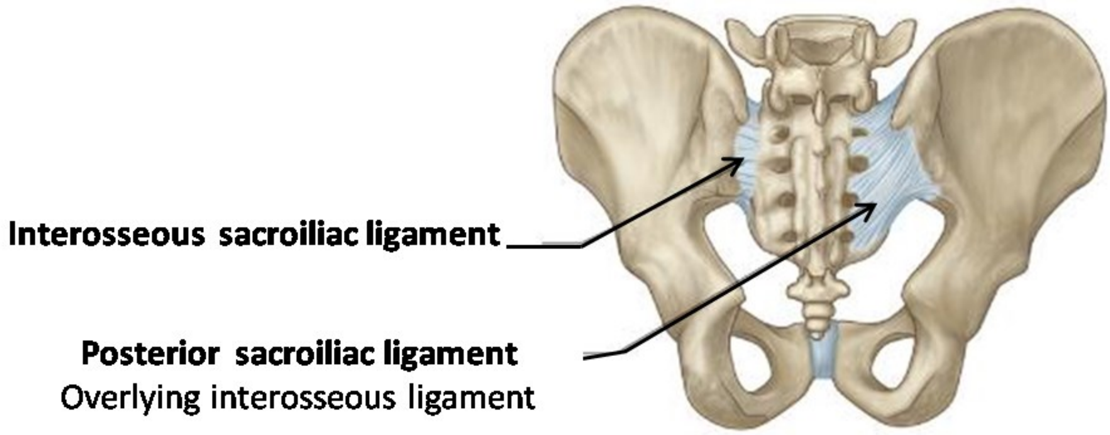

Figure 3-4 The interosseous sacroiliac ligaments stabilise the sacroiliac joint when any pressure is applied to the sacrum (modified from Therapy Protocol, 2012)

The line of direction of this force passes anterior to the sacroiliac joint and therefore acts with a moment on the sacrum. As a result of this moment, the upper part of the sacrum tends to rotate anteriorly (sacrum nutation) and its lower part to rotate posteriorly. However, this rotational movement is prevented by the stiff sacrotuberous and sacrospinous ligaments as shown in Figure 3-5 (Vleeming et al., 1997) . A literature review conducted by Goode et al. (2008) investigated the studies that measured three-dimensional movements of the SIJ using Roentgen Stereophotogrammetric Analysis (RSA). The RSA is a very accurate and well documented method of detecting small movements in joints. An RSA procedure used in detection of motion of SIJ was accomplished by percutaneously inserting small tantalum balls into motion segments of the pelvis, followed by an RSA examination within two weeks after implantation (Sturesson et al. 1989).

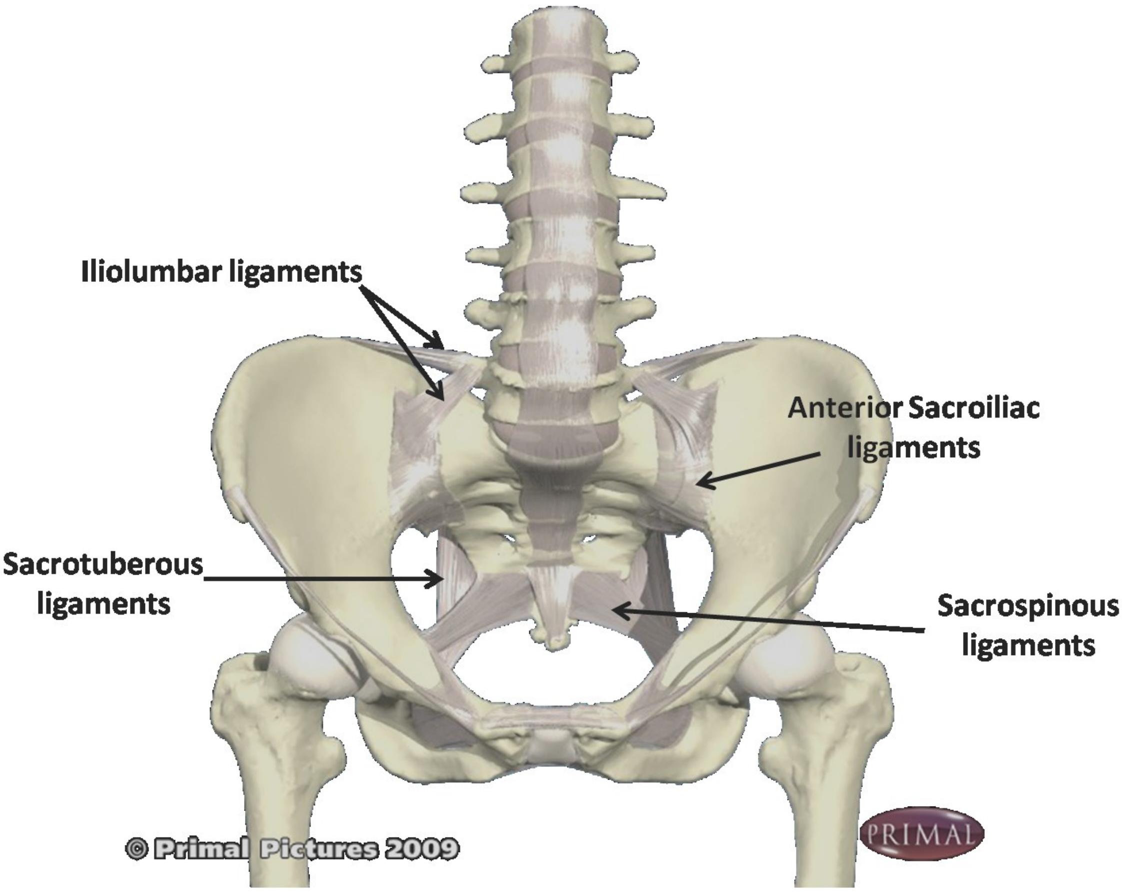

Figure 3-5 Sacrotuberous and sacrospinous ligaments prevent the sacrum from rotational movement (modified from Anatomy TV 2012)

In the study conducted by Sturesson et al. (1989), the posture change from standing normally to hyperextension produced a motion of slightly more than 2° on average, with a maximum of 4°. Male subjects were slightly less mobile than females but there were no changes in mobility with advancing age. Further studies suggested that SIJ has very little movement of 2° on average in non-weight bearing (Sturesson et al., 1989; Jacob et al., 1995) and even less in weight bearing (average of 0.2°) (Sturesson et al., 2000).

These studies suggest that the rotational and translational movements available at the SIJ are limited. Table 3-1 outlines the SIJ rotation about three different axes of a Cartesian coordinate frame based on initiated movements of the lower limb. A systematic review of the literature by Goode et al. (2008) scored the quality of these reported values which varied from a score of 13 out of 13 (Jacob et al. 1995) to 10 out of 13 (Smidt et al., 1997). Based on the currently available literature, motion of the SIJ is limited to small amounts of rotations and translations and still continued research is needed as previous studies have not come to a consensus on the type and amount of movement between the sacrum and pelvic bones.

Authors	**In-vivo/ In-vitro**	**Amount of movement (range or Standard deviation)**			**Instrument**	**Standard error of instrument**
		X (range / SD)	**Y (range / SD)**	**Z (range / SD)**		
1. Smidt et al. (1997)	In-vitro	2.0° (1.0 to 4.0)	7.0° (4.0 to 11)	2.0° (1.0 to 4.0)	CT Scan	1.0°
2. Smidt et al. (1997)	In-vitro	4.0° (-4.0to 3.0)	5.0° (1.0 to 11)	4.0° (1.0 to 7.0)	CT Scan	1.0°
3. Jacob et al. (1995)	In-vivo	0.97° SD(0.82)	0.5° SD(0.39)	0.77° SD(0.68)	Cam K-wires	0.34°
4. Sturesson et al. (2000)	In-vivo	-0.2° (1.0 to 0.5)	0.2° (-0.3to 0.9)	0.2° (-0.7to 0.8)	RSA	0.3° (X) 0.1° (Y) 0.4° (Z)

Table 3-1 (1) SIJ movement during double hip flexion to double hip extension angular motion, (2) SIJ movement during reciprocal Hip flexion/extension, (3,4) SIJ measurements during standing erect on both feet to one legged stance.

As a result, in most of the kinematic studies the pelvis is considered as a single rigid body. In the next section, the pelvic kinematics and different measurement techniques will be discussed in detail.

3.3 Techniques in measuring pelvic kinematics

A number of techniques have been developed to measure lower limb kinematics varying from imaging techniques, cinematography, and motion analysis systems, to cadaver testing, bone pins, electrogoniometry and accelerometry. Each method provides valuable information but each has limitations. In 1991, it was pointed out that cadaveric studies are limited by the removal of musculature and therefore do not accurately reflect motion in the living even though it can provide baseline data for the joints (Bogduk et al., 1991).

In this section the most commonly used techniques are presented and their accuracy and suitably are discussed.

3.3.1 Invasive techniques

Bone pins

The direct insertion of pins to relevant bones to obtain kinematics measurements have been used in number of motion analysis studies of the lower limb (Fuller et al., 1997; Neptune et al., 1995; Reinschmidt et al. 1997; Cappozzo et al., 1996; Lafortune et al., 1992). Bone pins also were inserted in the pelvis to obtain accurate in-vivo measurements of pelvic kinematics during gait as well for the measurement of the hip joint centre as shown in Figure 3-6 (Levens et al., 1948; Neptune et al., 1995).

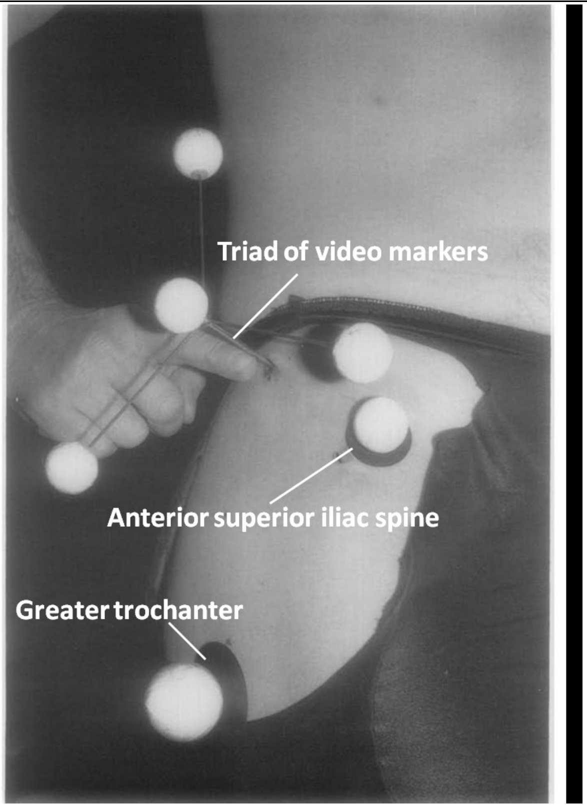

Figure 3-6 Triad of reflective markers attached to intracortical pin inserted in the iliac crest. Additional spherical reflective markers are placed over anterior superior iliac spine (ASIS) and superior aspect of the greater trochanter (modified from Neptune et al., 1995).

While this approach generates a valid presentation of the motion of the skeleton, there are some limitations to this method. These include: (1) alteration of the movement due to the pain during the procedure; (2) the risk of infection; (3) loosening of the pins during the experiments; (4) loss of statistical power and misinterpretation of important results in clinical studies due to small subject groups, and (5) movement of the inserted pins due to the muscle contraction and skin force (Fuller et al., 1997).

Radiographic imaging

Radiographic imaging techniques are often used clinically in the diagnosis and assessment of hip joint, spine and pelvic pathologies. As this is a direct measurement method, the results of radiographic imaging techniques have mostly been used as a reference method in evaluating other methods, particularly for the spine (Pearcy, 1985). In recent years, radiographic imaging techniques have been used to measure pelvic mobility as well as kinematics of the pelvic-lumbar complex preoperatively and postoperatively during maximal squatting (Perret et al., 2001; Lamontagne et al., 2011). However, the exposure to ionizing radiation doesn't always justify the use of this technique over non-invasive techniques.

3.3.2 Non-invasive techniques

Mechanical motion tracking system

Mechanical systems directly measure joint angles while attached to the body. Such systems only measure the relative movement of the segments and not the position of the subject in space. One such a device is digital inclinometer. Measuring pelvic tilt angle using an inclinometer device does not take place in real-time, therefore making it difficult for real-time monitoring during gait or activities of daily living, thus limiting its use to a static environment. Further, as shown in Figure 3-7, this device can only measure pelvic motion in the sagittal plane.

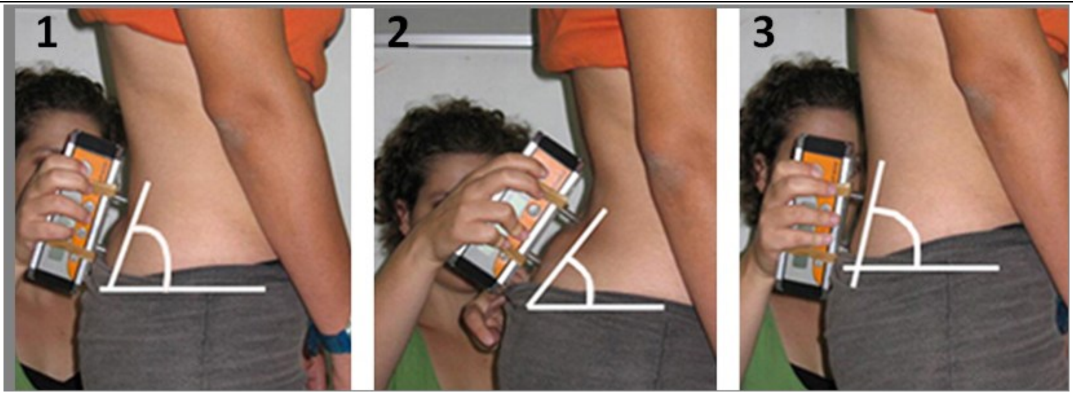

Figure 3-7 Utilizing digital inclinometer for measuring sacral inclination (1) Neutral position, (2) Anterior pelvic tilt and (3) Posterior pelvic tilt (Prushansky et al., 2008)

As this device only provides static pelvic posture, other devices have been developed such as electrogoniometers (Richards, 2008), accelerometers (Isniza et al., 2011), strain gauges

(Donatell et al., 2005) and gyroscopes (Lee et al., 2003), primarily for the measurement of spinal motion. Most of the mentioned devices allow a direct and immediate signal output which can provide real-time visualization and biofeedback. They tend to be relatively low cost; however, there are many potential sources of error when assessing human motion including skin errors which involves displacement of sensors on the body surface as a result of soft tissues around a joint.

Electromagnetic and optical motion tracking systems

Electromagnetic and optical tracking systems are the most frequently used motion tracking systems in biomechanics research. These systems are used to track three-dimensional movement of a body segment under different conditions ranging from activities of daily living to sports biomechanics (Roca et al., 2006; Bull et al., 2000; Bull et al., 1998)

In electromagnetic systems (Figure 3-8), the sensors and transmitter are cabled to an electronic control unit that quantifies their location within the generated magnetic field. Since each sensor measures six degree-of-freedom (DoF), useful results can be obtained with only one-third of the number of markers required in optical systems.

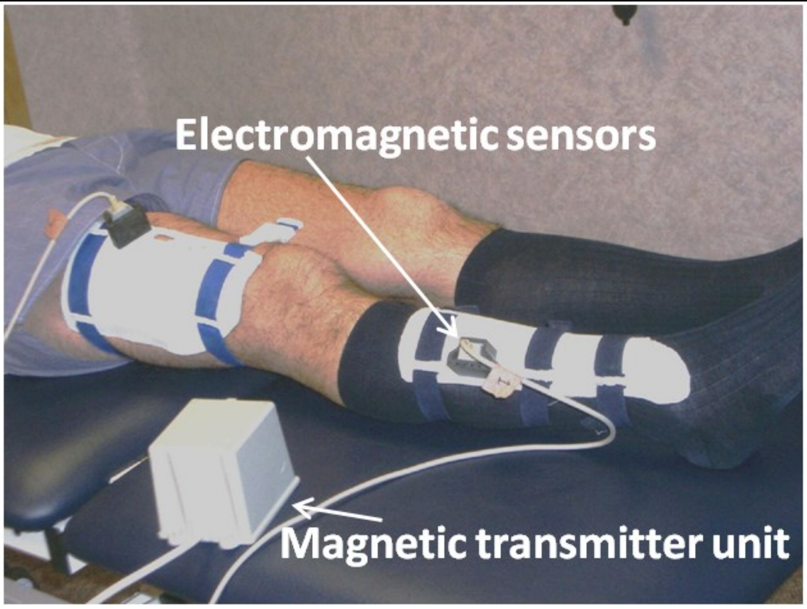

Figure 3-8 A single sensor is used for each segment to measure the rotational and translational degree-of-freedom in electromagnetic motion tracking system, (modified from Amis et al., 2008).

There are two types of electromagnetic systems: using AC current or pulsed DC waveforms. The AC version is more accurate, faster with a better signal to noise ratio and less affected by fluctuation in the power supply. However, the pulsed DC technology used by Flock of Birds (Ascension Technology Corporation, Burlington, USA) is 5 times less susceptible to metal distortion than its AC counterpart (Chung, 2008). The Flock of Birds electromagnetic system (Figure 3-9) has been used to record spinal motion and the movement of the lower body (Bull et al., 1998; Bull et al., 2000). In the study conducted by Bull et al. (2000), it has been suggested that it is possible to accurately measure the motion of lumbosacral spine using an electromagnetic tracking system in a metal-free environments. It has also been shown that this system has a good accuracy values in metal free environment with root-mean-square-errors (RMSE) of 1-3 mm and 0.5° (Bull et al., 1998).

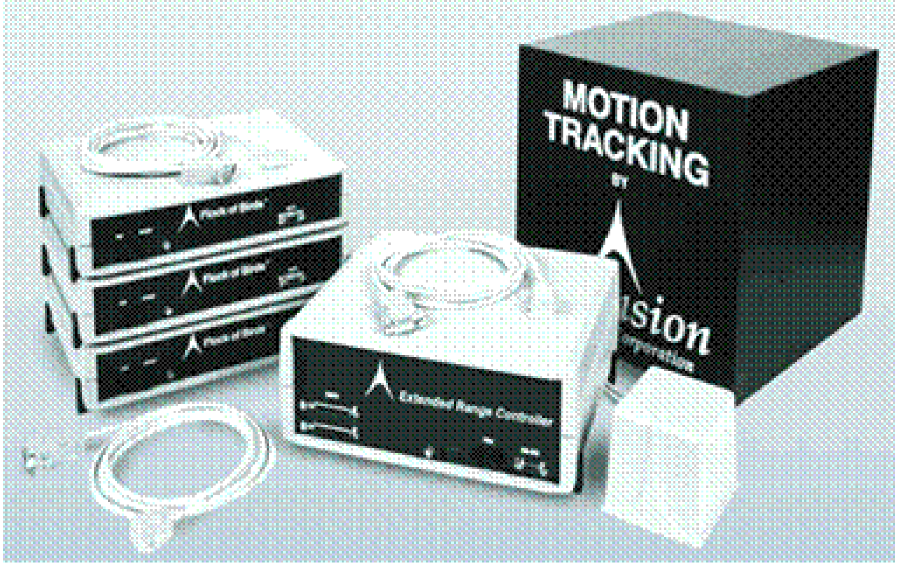

Figure 3-9 Flock of Birds Magnetics Motion Capture delivers magnetic fast even in metallic environment, (obtained from Souvr.com, 2009)

This system suffers from certain disadvantages, such as: the wiring from the sensors tends to limit the subject's movement, the capture volume is very small and is susceptible to magnetic interference, and the sensor response is nonlinear, especially toward the extremes of the capture area.

Optical motion tracking systems requires the use of minimum 3 markers per body segment and it provides a positional data from each marker (Figure 3-10). The system measures the positional data of the markers using multiple infra-red or near infra-red cameras simultaneously and it is possible to compute the joint rotations from clusters of markers. It also has a higher accuracy than the electromagnetic systems with RMSE of 0.1-0.4 mm (Wiles et al., 2004).

Figure 3-10 Optical motion tracking system. The positional data of markers attached to the skin are obtained using a number of infrared cameras (Motion Analysis Laboratory at Imperial College London)

This method has been used widely in biomechanical research as well as sport science and it is more suitable for fast dynamic movement than the electromagnetic systems (Roca et al., 2006). However, this system is sensitive to light conditions and any obstacle between the markers and the camera can degrade the system's performance and will result in loss of information.

These systems still produce accurate and reliable data for markers and sensors that are placed on a thin layer of soft tissue firmly attached to the underlying bone (such as the anterio-medial surface of the tibia), on the other hand, where the soft tissue are thick (such as at the hip) or mobile relative to the underlying boney landmarks (such as the scapula) then markers and sensors will tend to reflect the skin movement rather than the skeleton (Lundberg, 1996). For these reasons, these systems are sometimes used in conjunction with other measuring techniques such as non-invasive imaging.

Non-invasive imaging

Open magnetic resonance imaging (MRI) has been used to reconstruct images of the lumbar spine and sacrum to quantify the relative motion between the electromagnetic sensors and the underlying bones (Bull et al., 2000). This study demonstrated the possibility of accurately (average error of ±1.0°) recording the motion of the lumbar-sacral spine using an electromagnetic motion tracking system and also provided useful and important information on the motion of the body segments and the overlying skin during rowing. There are some disadvantages related to this technique, such as poor image quality and the static nature of the technique. Although the open MR imaging does not restrict the subject to a supine position, this technique is very costly.

Other measurement techniques

As well as photogrammetric and MRI techniques, the use of ultrasonic tracking has received attention (Vogt et al., 2003). In one approach, ultrasonic recorders are used to track the movement of ultrasonic markers (Figure 3-11). This will, most likely, suffer from the risk of sound transition disturbances (Lundberg, 1996), and thus further validation of this technique in research is needed.

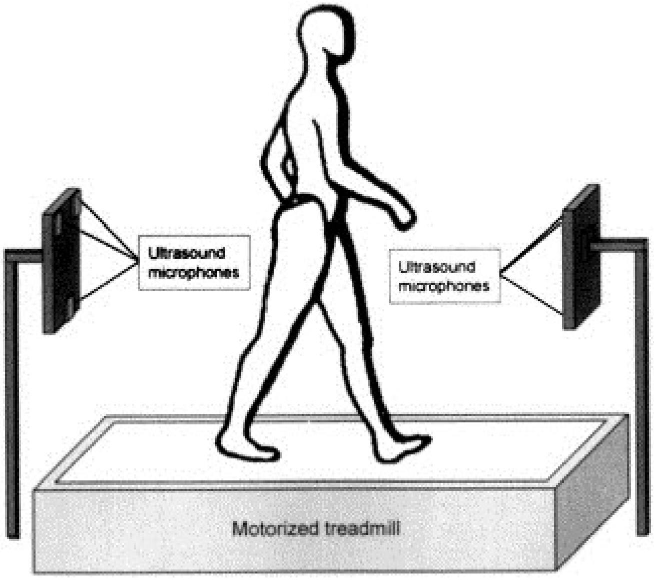

Figure 3-11 Measurement set up for tracking the ultrasound body surface markers during treadmill ambulation. The two ultrasonic microphones are positioned anterior and posterior to the pelvis in walking area to track the movement of the body segment (Vogt et al., 2003).

3.4 Challenges in measuring pelvic motion

Currently, one of the most commonly used measurement techniques to measure pelvic kinematics non-invasively is optical tracking. This approach also has some limitations associated with marker locations and soft tissue artifact (STA). These will be discussed in detail below together with a description of compensatory methods for STA.

3.4.1 Marker location

The choice of marker location to define the segments in optical tracking is not consistent between studies. The simplest marker set is fixing markers on skin over a bony anatomical landmark and then the position of the segment is defined by the straight line between the two markers. This method requires fewer markers but does not allow the calculation of full three-dimensional rotations of the body segment (Figure 3-12).

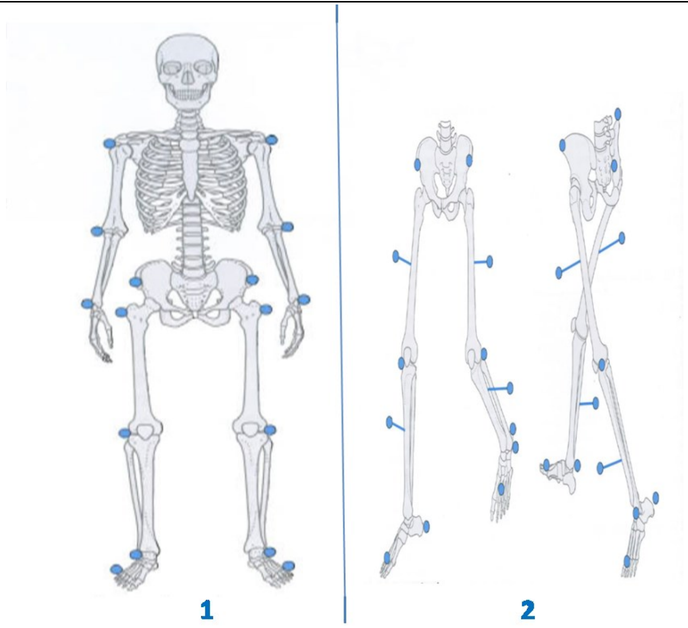

Figure 3-12 1) The simple marker set. The anatomical landmarks used are: head of fifth metatarsal, lateral malleolus, lateral condyle (femur), greater trochanter, anterior superior iliac spine, acromion process, lateral condyle (humerus) and styloid process 2) Helen Hayes marker set. The anatomical landmarks used are: head of second metatarsal, lateral malleoli, heel, tibial wand, femoral epicondyle, femoral wand, greater trochanter, anterior superior iliac spine, acromion process, lateral condyle (humerus) and styloid process, modified from Richards (2008)

The Helen Hayes (HH) marker set is well accepted as a relatively simple set of markers which was developed by Kadaba et al. (1990). The basic HH marker set consists of 15 lower body markers (Figure 3-12) and the thigh and the shank each have a 10 cm wand attached for measuring the three-dimensional motion of the lower limbs (Kadaba et al., 1990). Although the HH marker set allows the measurement of joint and segment rotations, it is still prone to STA. There are two types of errors associated with the marker sets and affect the joint and segment rotations measures which are absolute and relative errors. The absolute error refers to the movement of markers with respect to the underlying bony landmarks which violates the rigid body assumption and the relative error represents the relative movement between two or more markers that are fixed on the same body segment. The simplicity of the HH marker set does not negate the fact that it suffers from both types of errors, in particular around the pelvis. In order to reduce these soft tissue artefacts different marker sets have been proposed. To compensate for such errors, a pelvic clip was introduced as a new marker set for the pelvis as shown in Figure 3-13 (Ameyaw, 2006). While the pelvic clip reduced the soft tissue artefact and followed the pelvis movement well, it introduced undesirable inertial effects and reduced the movement of the pelvis in such activities that require a maximum range of motion.

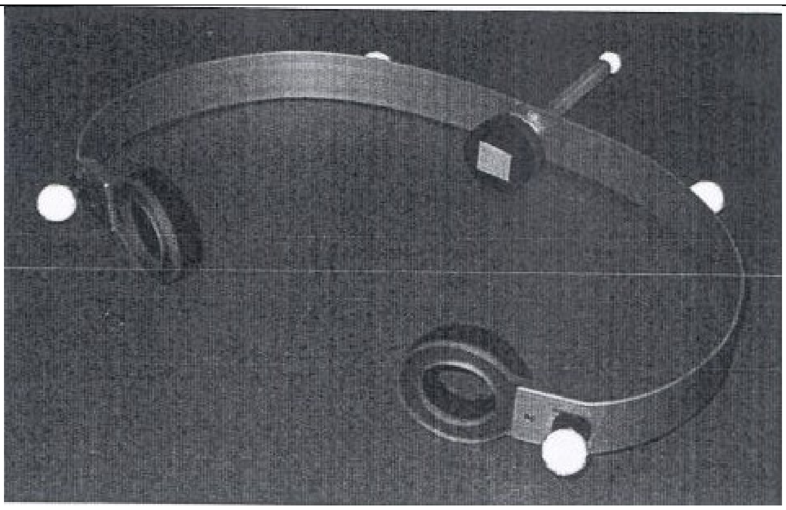

Figure 3-13 Pelvic clip with three points of contact (left and right ASIS and sacrum) were introduced to minimize relative and absolute errors (Ameyaw, 2006)

To tackle this issue, the HH marker set was modified by adding new technical markers. In the pelvis, these markers were positioned individually on iliac crest or as a cluster of four markers on the iliac crest or sacrum (Figure 3-14) in which the added markers were defined as a technical coordinate system and their positions were defined with respect to the anatomical landmarks. Another proposed markers set for the pelvis is a triad of three markers directly placed on the posterior aspect of the pelvis (Frigo et al., 1998). This method was used to define directly the pelvic anatomical coordinate frame. Pohl and Lloyd et al. (2010) similarly followed the same technique; however, they used a rigid triad of markers to quantify pelvic kinematics with the addition of two markers on the iliac crest (Figure 3-14), noting that this may not be the most reliable method to define the anatomical coordinate of the pelvis as none of the markers were placed on the anatomical landmarks of the pelvis.

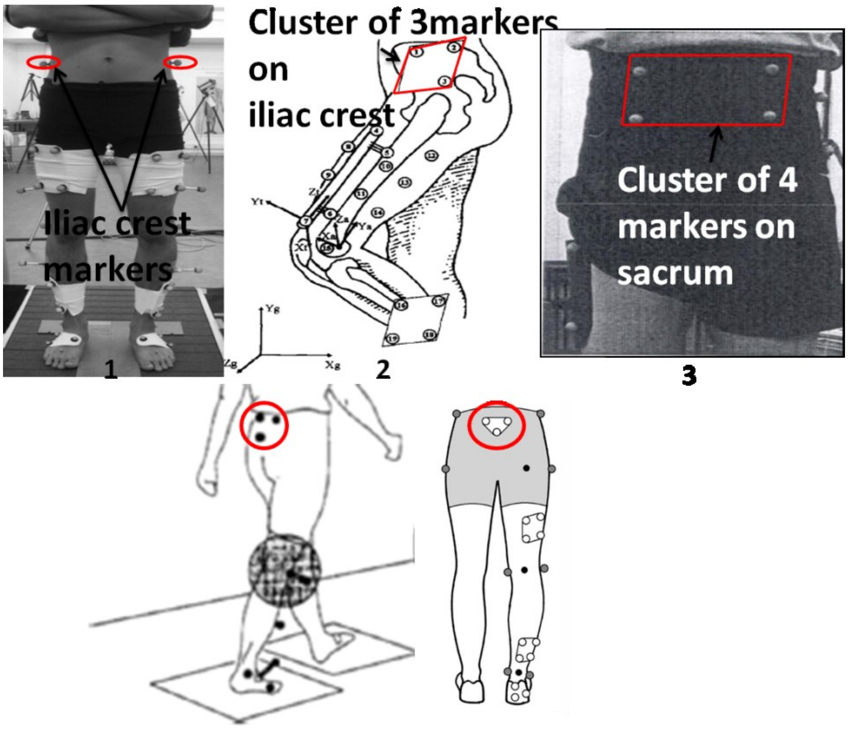

Figure 3-14 **Location of markers for modified HH. 1) Markers located on iliac crest are known as technical markers which were used to measure pelvic kinematic (Collins et al., 2009) 2) Cluster of 3 markers were used on iliac crest as a technical marker to measure pelvic kinematics (Cappello et al., 1997) 3) Cluster of 4 markers attached on sacrum were used to measure pelvic kinematics (Benedetti et al., 1998) 4) triad of three markers located on LPSIS, RPSIS and lower prominence of sacrum (Frigo et al., 1998) 5) rigid triad of markers located on the posterior aspect of the pelvis (Pohl et al., 2010)**

Another method that proposed to reduce errors was the calibrated anatomical system technique (CAST) proposed by Cappozzo et al. (1995) in which the position of certain anatomical landmarks will be defined relative to the technical markers on the same segment using a pointer of known dimensions (Figure 3-15).

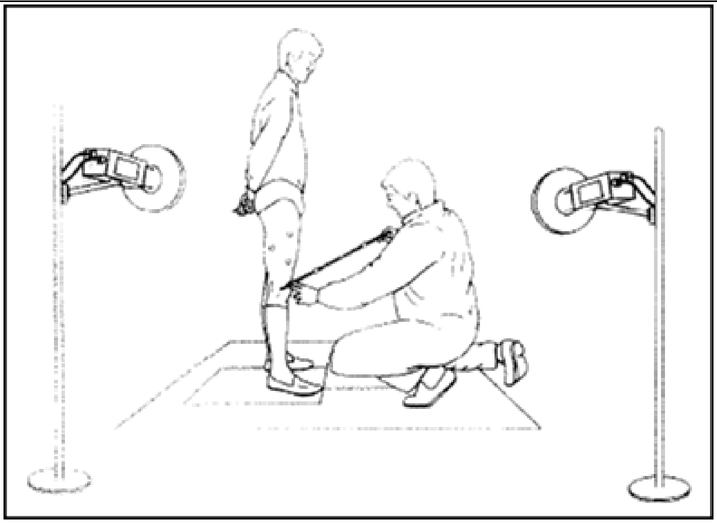

Figure 3-15 Calibrated anatomical system technique (CAST) used to calibrate femur anatomical landmarks (Cappozzo et al., 1995)

These anatomical landmarks are either not practical for use in dynamic experiments or can introduce high skin errors such as skin movement and occlusion of anterior superior iliac spines (ASIS) markers in the pelvis. One of the advantages of this method is the reduction of marker occlusion during dynamic trials and also minimizing the absolute and relative errors. Combination of both the technical marker set and the CAST technique can be useful as Cappello et al. (1997) have shown the advantages of using a cluster of markers in either rigid or deformable frames; these advantages include easier mounting, reduced number of cameras, and optimal selection of the cluster location.

3.4.2 Coordinate system and joint angles

One of the main objectives in human motion analysis is the description of segment/joint kinematics. There are different ways to define segments and joints but the starting principle is the definition of space; any point in space can be described by three orthogonal axes which are together called the global coordinate system (GCS). GCS is adequate if one only wants to describe single points in space but objects typically consist of many points and it will be very complicated to define each point relative to the GCS. If an object is considered as a rigid body then a straightforward calculation can be used to define the rigid body position relative to the GCS. For a rigid body, a local coordinate system (LCS) can be defined fixed to any reference point on that rigid body. The human body can then be treated as a series of rigid bodies or segments in which specific anatomical landmarks are used to define the LCS.

In an optical motion analysis system, marker sets are used to define and track the LCS of each segment relative to the GCS. In order to calculate the position and orientation of each segment, a minimum of three non-collinear markers on each segment are needed. However, for motion to be anatomically recognizable, the markers should be positioned on well-defined anatomical landmarks, or should be consistently related to these landmarks. Various marker sets have been defined and are currently used in order to achieve a balance between the ideal modeling of the segment movement and various practical issues. There are set of practical concerns for choosing the markers location such as (Cappozzo et al., 1995):

- each marker must be detected by enough cameras to allow further three-dimensional computation,
- to allow definition of a plane and minimize interferences, the markers must be placed non-linearly and far apart,
- the marker attachment must be quick and simple, and
- the movement between the markers and underlying bones must be as little as possible.

The LCS should also be expressed relative to the three anatomical planes: sagittal, frontal and transverse. Although various approaches have been presented to define the LCS and a joint coordinate system (JCS) at each joint, only a few of these are well understood (Wu et al., 2002; Cappozzo et al., 1995).

In order to define the position and orientation of one LCS to the other, thus defining a JCS, or to the GCS, different methods have been used: rotation matrix, Euler/Cardan angles, or helical axis method. It has been shown that Euler/Cardan angles are the most convenient way to describe the segment or joint rotations (Chau, 1980; Davis et al., 1991; Kadaba et al., 1990; Cole et al., 1993). Cole et al. (1993) further explained that the Euler/Cardan angles are a set of three independent angles obtained by an order sequence of rotations about the axes of coordinate system. The most commonly used definition of pelvic angles in conventional gait analysis and commercial gait analysis software packages is in the sequence tilt, obliquity, and rotation (e.g. Vicon Clinical Manager: Oxford metrics, UK, Coda: Charnwood Dynamics, UK, Elite: BTS, Italy, Motus 2000: Peak Performance Technologies, USA).

3.4.3 Skin and soft tissue artefacts

One of the main objectives of motion analysis system is to measure the segment and joint kinematics using trajectories of markers placed on the skin. These trajectories are used to measure the position of the underlying bony segment with the assumption that markers and bony segments are rigidly connected.

It is well known that markers move with respect to the underlying bone, the movement of which is mostly associated with interposition of both passive and active soft tissues (Cappozzo et al., 1995; Stagni et al., 2009). Two different sources of errors originate from this interposition; these are STA and anatomical landmark displacement.

In clinical motion analysis, STA is recognized as the most critical source of error (Andriacchi et al., 2000). As the STA originates from the same motion as the segment and has the same frequency content as that of the underlying bone, the exact magnitude of STA in kinematics calculation has been difficult to determine (Cappozzo et al., 1996; Leardini et al., 2005). However, a variety of techniques such as bone pins (Fuller et al., 1997; Reinschmidt et al., 1997), external fixators (Angeloni et al., 1992; Cappozzo et al., 1996), percutaneous trackers and roentgen photogrammetry have been used to quantify the motion of skin relative to the underlying bone. These studies have shown that the influence of skin artefact is directly associated with the physical characteristic of individuals (i.e. overweight, obese and normal), the nature and the speed of the movement performed and also the marker placement (Cappozzo et al., 1996; Leardini et al., 2005). Some analytical techniques have been proposed to minimize the STA, such as the use of technical marker sets with a predefined relationship to the anatomical marker set as defined in Section 3.4.1 (Cappello et al., 1997; Cappello et al., 2006; Cappozzo et al., 1995), least squares calculation techniques (Cappozzo et al., 1996; Holden et al., 1997; Reinschmidt et al., 1997), point cluster technique (Cappello et al., 2006), multiple anatomical landmark calibration (Cappello et al., 1997; Cappello et al., 2006; Stagni et al., 2009), local and global skeleton fitting techniques (Silaghi et al., 1998), double anatomical calibration and global optimisation (Stagni et al., 2009). Most of the proposed techniques are general and do not take into account the great variability between subjects or differences between motor tasks (such as global optimisation technique) or in some cases require a significant number of additional markers (such as point cluster techniques).

Although most of the techniques have been developed for the lower limb, only a few studies have investigated skin deformation over the pelvic region. These have shown that markers that are located on the anterior superior iliac spine (ASIS) are more prone to STA than the posterior superior iliac spine (PSIS) markers (Rozumalski et al., 2007). In Section 3.4.4, different methods are described to tackle and reduce issues of marker location and STA around the pelvis.

3.4.4 Current techniques to tackle issues in pelvic motion

3.4.4.1 Reconstruction and alternative markers methods

McClelland et al. (2010) described possible modifications to the modeling procedure that do not rely on consistent visualisation of ASIS markers. They compared four different modeling procedures, these procedures were: 1) moving the ASIS markers to a more lateral position on the iliac crest as shown in Section 3.4.1; 2) calculate the pelvic kinematics when a single ASIS marker is occluded, by calculating its position in relation to the two additional marker on iliac crest and the other remaining ASIS marker; 3) calculating the pelvic kinematics when both ASIS markers are occluded only for a short time in dynamic trials, therefore the positions of the ASIS were defined in relation to the sacrum and the two additional markers on the iliac crest; 4) calculating the position of ASIS markers based on their real position in a static trial, therefore virtual markers can be used to calculate pelvic kinematics in dynamic trials. These reconstruction approaches rely on the assumption that the pelvis is rigid, so soft tissue artefacts do not introduce errors to the reconstructed ASIS. These authors showed that these alternative modeling processes propagate errors in different planes of movement; therefore it is necessary to understand this error before implementing these procedures. Using these above techniques require at least three markers to reconstruct the position of missing markers.

3.4.4.2 Technical markers

The study conducted by Collins et al. (2009), has compared the HH marker set to a six DOF marker set. They used markers on iliac crest in addition to the anatomical set (PSIS, ASIS). Even though the 6DOF marker set overcomes some theoretical limitation of the HH marker set, it does not improve the STA problem and the landmark identification due to the fact that the iliac crest is a site for fat deposition and a substantial amount of fat and skin tissue can be present in overweight and obese subjects. As the reliability of using the iliac crest markers as technical markers have not been evaluated, Fukuchi et al. (2010) proposed the use of the left and right hip joint centre (HJC) together with PSIS markers as alternative technical markers. It was suggested that using the HJCs as technical markers may reduce the number of markers around the pelvis, but calculation of HJC from a thigh cluster using different techniques may propagate errors as there is still a debate about how to accurately calculate the position of HJCs using non-invasive techniques (Gamage et al., 2002; Halvorsen et al., 1999; Ehrig et al., 2006; Halvorsen, 2003).

3.4.4.3 Pelvic cluster

As discussed in Section 3.4.1, another proposed method to measure pelvic kinematics is to use a cluster of markers (Pearcy et al., 1987; Vogt et al., 2003; Benedetti et al., 1998). Pearcy et al. (1987) used a calibrated television/computer system to measure spinal movement using reflective markers on rigs attached to the back, and they demonstrated the pattern of movement obtained from the cluster was similar to the previously reported patterns of spinal movement measured radiographically. Benedetti et al. (1998) measured the movement of the pelvis using a rigid plate consisting of four retroreflective markers which were attached to the side of the pelvis. They also used the CAST method (Section 3.4.1) in order to define the movement of the cluster relative to the anatomical markers. They reported that the kinematics data obtained were in good agreement with previous studies and they also showed that plate-mounted markers were suitable for assessing normal gait. In 2003, Vogt and colleagues used three external ultrasound markers attached to a small lightweight T-plate (9cm×9cm) which was directly attached to the subject’s skin on the posterior midline of the sacrum. The plate mounted on the sacrum was then used to measure pelvic kinematics while the subjects walked on the motorized treadmill. This study concluded that for routine gait analysis, this system is convenient and adequate for monitoring the rotational pelvic motion.

3.4.4.4 Change of camera setup

The number and position of the cameras in data collection can also be altered in order to minimize marker occlusion. Placing the cameras in such a way that they face towards the pelvic region with different elevations, particularly around the waist, might be a simple method. But it may not be cost effective as each camera costs between £10,000 and £12,000, thus frequently limiting the number of cameras that are used.

Across the literature there seems to be consensus that one of the main limitations in kinematic analysis is related to the movement between the markers and underlying bones which comes back to the initial assumption that human body segments are rigid. This is a reasonable assumption for bone but between the bone and external markers there are considerable non-rigid tissues (muscles, tendons, ligaments, soft tissue and skin). Any new marker set that tries to tackle the technical and practical limitations of the previously used marker set such as the HH set must show sufficient improvement to overcome the legacy of the long-term use of that marker set. Therefore, the aim of the next chapter is to propose a new marker set for the pelvis as there is a lack of research on how to improve tracking the pelvic movement, particularly for overweight and obese subjects for whom STA is a more considerable issue than for low body mass individuals. To achieve this objective a preliminary study was completed to identify the main issues surrounding the design of marker set and the use of motion analysis.

3.5 Summary

A number of measurement techniques have been developed to measure the movements of the pelvis. The insertions of bone pins provide adequate measurement of lower limb and pelvis but the method is invasive and also suffers from small group sizes due to ethical considerations. Some accurate radiographic imaging techniques are considered invasive due to exposure to ionizing radiation. Non-ionising radiation imaging techniques can be used, but these are associated with poor reconstruction quality, as well as movement restriction. Other non-invasive techniques such as electromagnetic motion tracking and optical motion tracking are affected by skin movement artefact which is particularly relevant for the measurements of pelvic movement. Different types of compensation methods have been proposed to minimize the soft tissue artefact and it has been shown that the soft tissue artefact can be minimized to an acceptable level by modifying the HH marker set as well as adding technical markers. There is still a lack of research on how to optimize the marker set around the pelvis to tackle the limitations shown here. Therefore, in the following chapter a new pelvic marker set is developed and tested.

Chapter 4

Pelvic tracker development

Aim The aim of this chapter is to develop a novel approach for measuring pelvic kinematics, including the development of a kinematic model and investigating the sensitivity of the model to the anatomical landmark calibration.

4.1 Introduction

As described in Chapter 3, measuring the three-dimensional (3-D) movement of the pelvis is important in the diagnosis and treatment of gait abnormalities. However, a major limitation in all skin-based measurement techniques arises from soft tissue artefacts and landmark identification primarily due to the varying quantity of soft tissues covering the pelvis which lead to marker movement relative to the underlying skeleton, poor landmark definition and inaccuracies.

In optical motion analysis systems, kinematic analysis is often based on markers located according to a standard marker set. Chapter 3 demonstrated that a variety of marker sets have been proposed to minimize and compensate for the skin movement around the pelvis (Section 3.4.2), but the majority in use are based on a variation of the HH marker set (Kadaba et al. 1990). The HH marker set was developed for low resolution imaging systems which necessitated fewer individual markers, as far apart as possible (Della Croce et al. 2005). In addition, the thigh segment definition is reliant on the estimation of the HJC which in turn is estimated from pelvic markers again introducing the potential for errors in joint angle calculation. Given the difficulty of measuring the position of the RASIS and LASIS markers due to occlusion by the arms and soft tissue, alternative methods should be developed to measure pelvic motion.

Therefore, based on the review in Chapter 3, in this chapter a new marker set for the pelvis is proposed and an associated kinematic model is presented. The sensitivity of this model was investigated following the one parameter-at-a-time principle whereby the effect of each parameter is assessed independently. The model sensitivity to the orientation of the pelvis during single anatomical landmark calibration, double anatomical landmark calibration and the size of calibrating pointer is investigated by calculating the average range of motion (ROM) and maximum pelvic tilt, obliquity and rotation, standard deviations (SD) and coefficient of multiple correlation (CMC).

4.2 Challenge and aim

Section 3.4 highlighted the need for a non-invasive method for assessing pelvic motion that was reliable over a range of movements and activities.

The aim of this chapter is to design and develop a new technical marker set to measure pelvic kinematics in clinical studies as well as improving the practical and theoretical characteristics of measuring pelvic motion. The new method should be able to measure full ranges of motion as well as movement during activities of daily living.

In this chapter, the development of the new method and the kinematic model of the pelvis are presented.

4.3 Design specifications

For the new technical marker set to be suitable for use in future clinical studies, it will need to meet the following criteria as outlined by Cappozzo et al. (1995).

1. Non-invasive
2. Measure the pelvic movement to a reasonable accuracy (should be repeatable both inter- and intra-individually) for the full range of motion as well as activities of daily living
3. Positioned optimally to minimize skin-to-bone displacement
4. Simple to use and easy to mount markers
5. Easy to use in routine laboratories set up
6. Small number of markers
7. Eliminate ASIS occlusion
8. Protect the subjects’ modesty
9. Adaptable and practical for different body shapes
10. Time- and cost-effective

4.4 A new marker cluster

A number of techniques for minimizing soft tissue artefacts and compensating for their effects have been proposed (Section 3.4). These techniques depend upon the marker configurations. Markers may be singular to represent a segment or in the form of clusters which are positioned on the segment itself. Much work has been carried out to determine the optimal configuration of marker clusters and it is now widely accepted that a rigid base with a cluster of three to four markers are a good solution (Cappello et al., 1997), because of easier mounting on subjects and optimal selection of cluster location to minimize skin movement artefacts. For this study a custom-designed cluster was developed using a plastic base (10mm×10mm) and three reflective markers (14 mm in diameter) which were attached to the end of three plastic rods fixed to the base. One of the rods is mounted vertically and the other two are mounted at 30° inclination from the vertical axis (Figure 4-1).

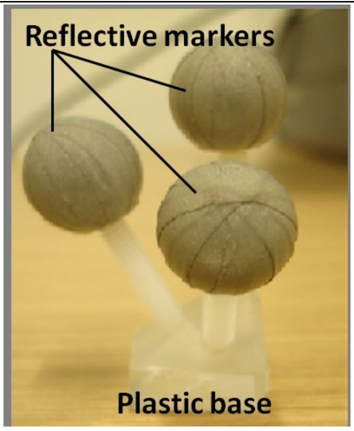

Figure 4-1 Light weight cluster. The cluster is made of a plastic base which holds three reflective markers 14 mm in diameter.

One of the limitations of skin-mounted markers for measuring kinematics is the error introduced by skin motion or inadequate fixation of the markers to the skin. In spinal kinematics, the fact that the fascia over spinous processes is firmly fixed to the bone suggest that the skin movement will reflect the movement of the underlying bone more closely than in many other regions (Vogt et al., 2003). The same fact is also applied to the sacrum (as shown in Chapter 3); the thickness of soft tissue over the sacrum has been measured using ultrasound and it was reported that for normal elderly subjects the average thickness was 13.7 mm (Clark et al., 1989) while the thickness of soft tissue around the ASIS were measured between 17 mm to 28 mm (Lalonde et al., 2003) depending on the body mass index and body shape. Further, a study conducted by Bull and McGregor (2000) demonstrated that it is possible to measure the motion of lumbo-sacral spine using a sensor attached to the sacrum with an average error of ±1.0° and provide useful information on the motion of the body segment during rowing. Consequently it was felt appropriate in this study to attach a cluster to the sacrum which from hereon in will be referred to as the 'sacral cluster'.

4.5 Study I: Defining a pelvic kinematic model using a sacral cluster

4.5.1 Aim and objectives

In the previous section a new set of technical markers was developed. The aim of this section is to develop a kinematic model using the new technical markers to facilitate the measurement of pelvic kinematics. In order to reconstruct the 3-D kinematics of the pelvis during the execution of a motor task it is necessary to obtain information on the pelvis position and orientation by defining a local coordinate frame, relative to the global or laboratory frame of reference. In this section, all the steps of model development, characteristics of the participant group, data collection, modeling process and data analysis are presented.

4.5.2 Materials and methods

4.5.2.1 Equipment and lab set up

In this study, an optical motion tracking system (Vicon, Oxford, UK) which consists of 9 high speed MX-13+ cameras running at acquisition rate of 200 frames/second was used to capture the 3-D trajectories of passive reflective markers. The MX cameras emit infra-red light which is reflected by the markers. The cameras were positioned in such a way that ensures at least three cameras are always tracking the positional data for each marker. Prior to data collection the calibration of all the cameras were completed and an accuracy of ±0.2 mm was always obtained; the accuracy of the data produced by motion analysis system depends on the accuracy of the calibration procedure (Figure 4-2).

Figure 4-2 The capturing volume and the orientation and position of the cameras were calibrated by waving the calibration Wand before the experiment.

4.5.2.2 Subject preparation

Reflective markers which are spheres of 14 mm in diameter on plastic base were attached to the bony landmarks on the pelvis and the lower limbs using double sided tape. To develop a kinematic model using the sacral cluster, a skeleton model was used as it was easier to mount the markers (Figure 4-3).

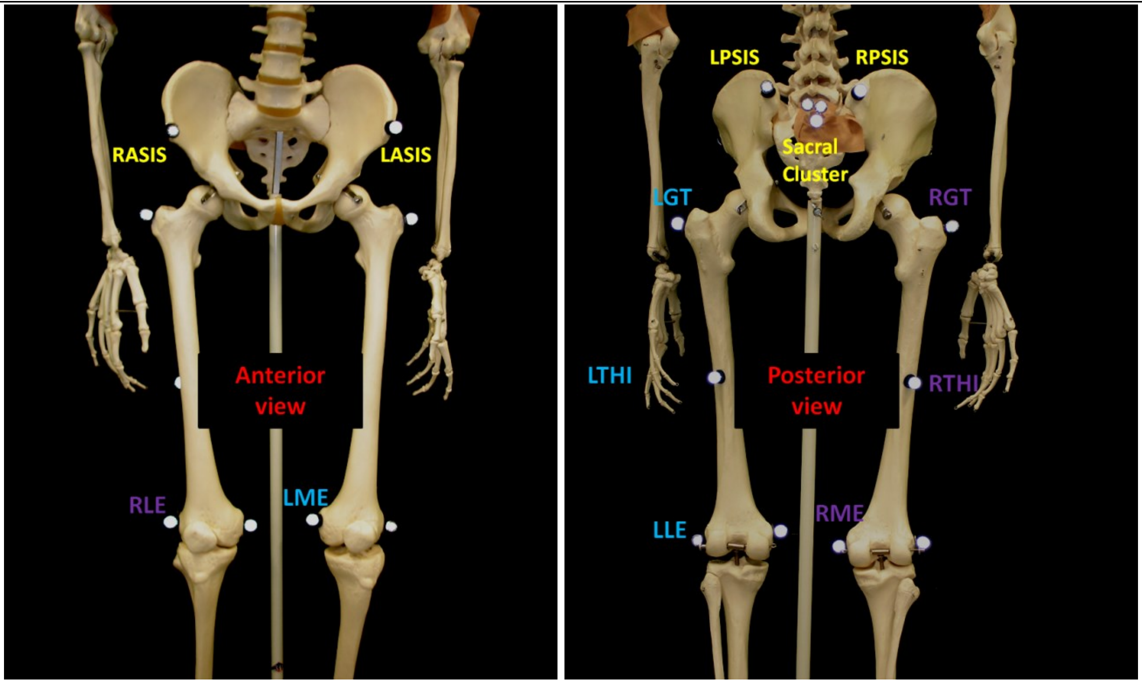

Figure 4-3 Anterior and posterior location of retro-reflective markers on the skeleton. Marker positions are listed and explained in Table 4-1

Figure 4-3 and Table 4-1 give a description of the landmarks that were used to define anatomical coordinate frames (ACF); these landmarks were identified by manual palpation. While some of the markers were used directly to define the ACF as recommended by the International Society of Biomechanics (Wu et al., 2002), other internal anatomical landmarks such as HJC derived using mathematical models.

Segment	Description	Landmark/marker
Pelvis	Anterior superior iliac spine	L/R ASIS
	Posterior superior iliac spine	L/R PSIS
	Hip joint center	HJC
	Sacrum	Sacral cluster
Femur	Top of greater trochanter	GT
	Lateral epicondyle	LE
	Medial epicondyle	ME
	Posterior surface of the femur	L/R THI

Table 4-1 Anatomical landmarks used in pelvis and femur tracking; the HJC marker is not present during dynamic trials as it is estimated via mathematical modelling. L/R represents Left/Right.

The HJC is not an accessible anatomical landmark but was needed in order to define the coordinate frame for the femur (Cappozzo et al. 1995); it was therefore estimated using a least-square algorithm developed by Gamage and Lasenby (2002) which is discussed in Section 4.5.2.4.

4.5.2.3 Experimental protocol

The experimental protocol was created to satisfy the objectives in Section 4.5.1, which were to develop a kinematic model based on the sacral cluster.

The protocol was as follows:

1. A static trial to digitise the position of LASIS marker using the CAST technique (Cappozzo et al., 1995)

This trial was used to calibrate the LASIS while the skeleton was static. The tip of the pointer was positioned by the observer on the LASIS as shown in Figure 4-4. The post-processing and analysis of this trial will be explained in detail in Section 4.5.2.4.

2. A static trial to digitise the position of RASIS marker (Figure 4-4) using the CAST technique (Cappozzo et al., 1995)

This trial was also used to calibrate the position of RASIS using the tip of pointer as described in step 1.

3. A static trial of marker setup

This was done with the skeleton standing in the middle of the capture volume. The positions of anatomical landmarks were recorded for 3 seconds and this trial was later used as a template for labeling the markers.

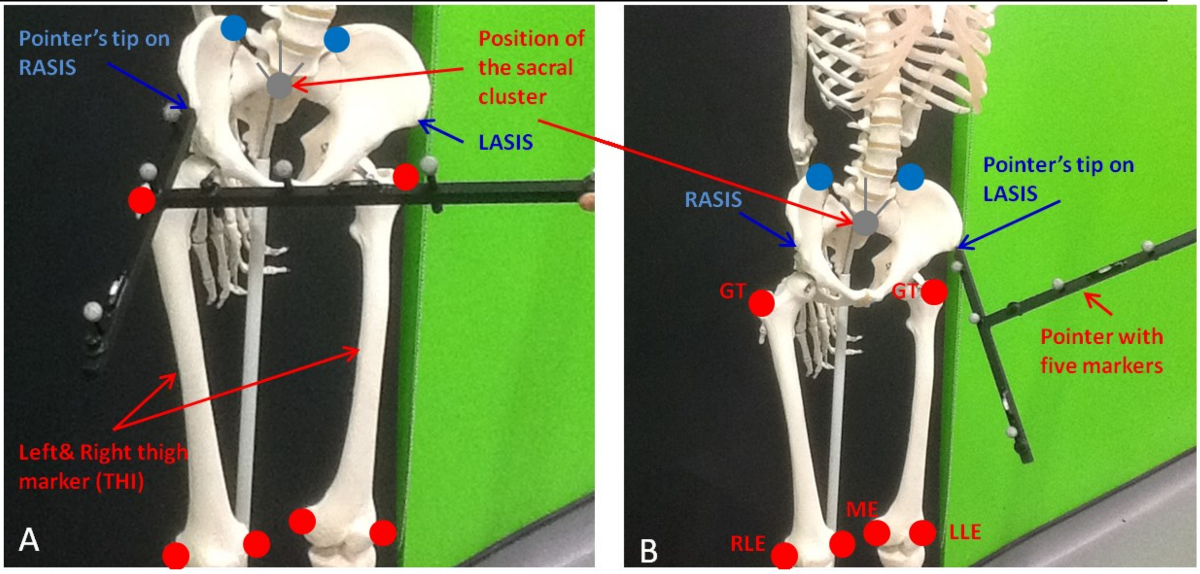

Figure 4-4 Digitisation of the anatomical landmarks, A) RASIS position was calibrated using a pointer of known distance in static trial; B) The position of the LASIS was also calibrated using the tip of a pointer. The red circles represent the location of marker attachment on the femur, and the blue circles represent the boney landmarks on the pelvis. Also the sacral cluster is shown by gray colour.

4. A dynamic trial to define the HJC

To estimate the HJC, a functional method was used (Section 4.5.2.4). The femur of the skeleton was moved in a random non cyclical manner while the pelvis was stationary. The movement consisted of flexion/extension, abduction/adduction, and circumduction. This trial lasted for 30 seconds to ensure that sufficient data was collected for the estimation of the centre of rotation.

5. A dynamic trial to calculate the femur kinematics while the pelvis was fixed

This trial was conducted to estimate the value of femoral rotation while the pelvis was stationary and to examine the outcome of the model and compare it to the controlled input values. Therefore, the femur was flexed, extended, abducted, and adducted by 25°, 35°, 25° and 10°, respectively. These values were calculated using trigonometric rules as shown in Figure 4-5.

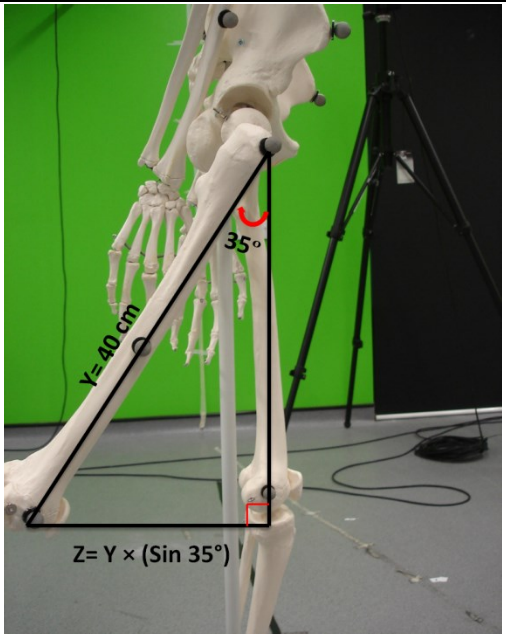

Figure 4-5 Trigonometric rules were used to calculate the values that required moving the femur in order to achieve the controlled input values for extension, flexion, abduction and adduction. The Vertical line represents the position of the femur in the static frame (neutral position) and Y represents the extended position of the femur in the dynamic trial.

4.5.2.4 Data analysis

Calibration of ASIS

As previously stated, artefacts caused by skin movement relative to the underlying bone are frequently reported when using marker based techniques to measure human motion. Placement of the markers on a thick layer of skin and soft tissue over a bony prominence is postulated to be the source of these errors which can be large (Leardini et al., 2005). Cappozzo et al. (1996) have shown that a marker on the lateral femoral epicondyle will introduce an error of up to 40 mm for 120° of knee flexion. The soft tissue and skin movement around the pelvis would probably introduce a small amount of error and can have a profound effect on the measured pelvic kinematics. Cappozzo et al. (1996) proposed a method to calibrate the positions of certain anatomical landmarks which are not ideal for use in dynamic trial or can introduce high errors. The method which is known as CAST, measures the positions of anatomical landmarks relative to the tip of a pointer of known dimensions; then the anatomical landmark positions are defined relative to the technical coordinate frame on the same segment in a static trial and are then used for the remainder of the experiment. The technical coordinate frame was defined using three markers placed on the segment in positions that have least amount of skin-to-bone movement and have minimum interference with the anatomical calibration procedure. To minimize the effect of skin and soft tissue artefact around the pelvis, the same method has been used to calibrate the position of the ASIS with respect to the technical coordinates of the 'sacral cluster'. A full description of the method is given below.

To digitise the ASIS position, a static trial was conducted (Section 4.5.2.3) with the tip of the pointer positioned on the ASIS as shown in Figure 4-4. To calculate the ASIS positions, first a coordinate frame was defined using three markers on the pointer as follow and shown in Figure 4-6;

O_P: the origin coincides with marker 'b' on the pointer

X_P: the line connecting marker 'a' and marker 'b', pointing towards 'a'

$$X_P = \frac{(\bar{a}-\bar{b})}{\|\bar{a}-\bar{b}\|} \tag{4.1}$$

Y_P: the line connecting marker 'c' and marker 'b', pointing towards 'c'

$$Y_P = \frac{(\bar{c}-\bar{b})}{\|\bar{c}-\bar{b}\|} \tag{4.2}$$

Z_P: the line perpendicular to the X_p and Y_P axes, pointing upwards

$$Z_P = X_P \times Y_P \tag{4.3}$$

After defining the coordinate frame for the pointer, the position of each ASIS was calculated based on the known distances between the marker 'b' on the pointer and the landmark position. The position of ASIS with respect to the global coordinate frame was calculated using the following equations:

$$\overline{\mathrm{LASIS}} = O_P + (l\,(-X_P) + h\,(-Z_P)) \tag{4.4}$$

$$\overline{\mathrm{RASIS}} = O_P + (l\,(-X_P) + h\,(-Z_P)) \tag{4.5}$$

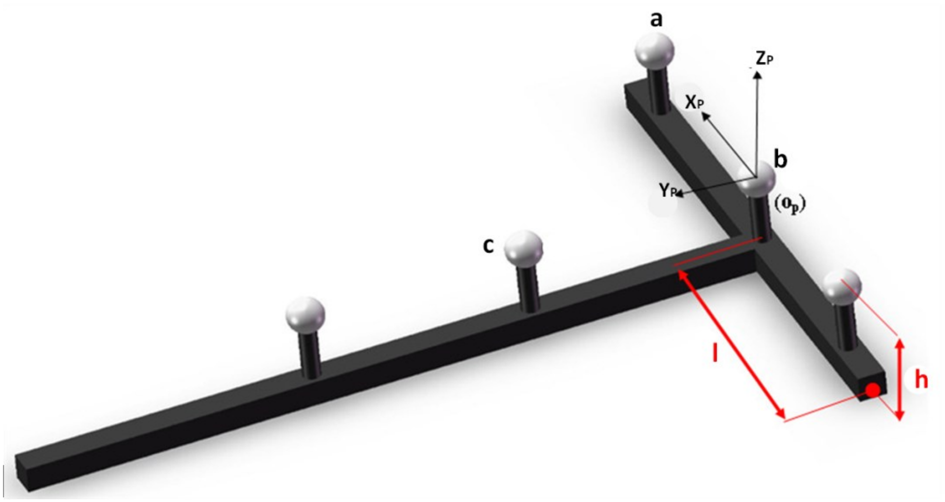

Figure 4-6 Coordinate frame of the pointer. Markers a,b, and c where used to define the coordinate frame. Also the l and h distances were used to find the postion of the landmarks.

By using Equations 4.4 and 4.5, the positions of both ASIS were defined with respect to the global coordinate frame during the static trial. During dynamic trials, the positions of the ASIS were defined relative to the technical markers on the pelvis. Therefore a technical coordinate frame for the sacral cluster was defined as follows:

O_C: the origin coincides with marker 'C_1' on the sacral cluster

X_C: the line connecting the 'C_3' and 'C_2', pointing towards 'C_2'

$$X_C = \frac{(\overline{C2}-\overline{C3})}{\|\overline{C2}-\overline{C3}\|} \tag{4.6}$$

Y_C: the line perpendicular to the plane formed by 'C_1', 'C_2' and 'C_3', pointing forward

$$Y_C = \frac{\left((\overline{C2}-\overline{C1})\times(\overline{C3}-\overline{C2})\right)}{\left\|\left((\overline{C2}-\overline{C1})\times(\overline{C3}-\overline{C2})\right)\right\|} \tag{4.7}$$

Z_C: The line perpendicular to the X_C and Y_C axes, pointing upward

$$Z_C = X_C \times Y_C \tag{4.8}$$

The position of each ASIS was then transformed from the global coordinate system to the technical coordinate system using the following equations:

$$\overline{\mathrm{LASIS}}_{\mathbf{C}} = (\overline{\mathrm{LASIS}} - O_C)\, T_{GT} \tag{4.9}$$

$$\overline{\mathrm{RASIS}}_{\mathbf{C}} = (\overline{\mathrm{RASIS}} - O_C)\, T_{GT} \tag{4.10}$$

Where T_{GT} is the transformation matrix from the global frame to the pelvis technical coordinate frame (sacral cluster coordinate frame) and was formed as follows:

$$T_{GT}=\begin{bmatrix} X_{GT} \\ Y_{GT} \\ Z_{GT} \end{bmatrix} = \begin{bmatrix} x_X & y_X & z_X \\ x_Y & y_Y & z_Y \\ x_Z & y_Z & z_Z \end{bmatrix} \tag{4.11}$$

In dynamic trials, the position of the LASIS$_c$ and RASIS$_c$ will be defined relative to the coordinate of the technical frame on the pelvis (Figure 4-7) and will be used in the definition of the anatomical coordinate frame.

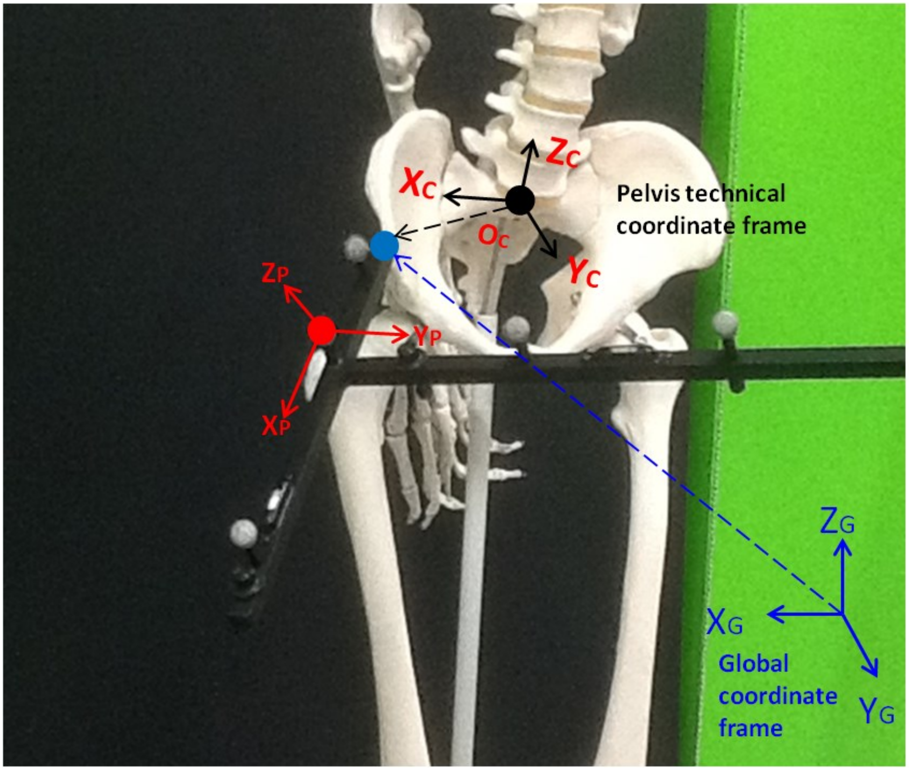

Figure 4-7 Transforming the position of the RASIS from the global coordinate frame to the technical coordinate frame on the pelvis (sacral cluster coordinate frame). The black dotted line represents the position of the RASIS with respect to the pelvis technical coordinate frame, while the dotted blue line represents its position with respect to the global coordinate frame.

The Hip joint centre

The HJC along with the lateral and medial epicondyles have been used to define the anatomical coordinate frame of the femur (Cappozzo et al. 1995; Wu et al. 2002). Anatomical landmarks that are not palpable are called internal anatomical landmarks, and the HJC is one example of an internal landmark. In human motion analysis, the articular surface between the head of femur and acetabulum are assumed to have spherical shapes and a common centre, therefore the hip joint is assumed to be a ball-and-socket joint. The accuracy and precision in which the HJC is estimated is critical (Kadaba et al., 1990). The HJC location can be estimated using either the functional method or a prediction approach. The former was originally proposed by Cappozzo (1984) in which he described the HJC as a pivot point of a 3-D relative movement of the pelvis and the femur. Recent studies have established that the collection of an adequate hip range of motion to estimate the reliable position of HJC is far more important than the type of the motion. In the absence of STA, it was shown that the error in determining the pivot point location can reach 5 mm and 10 mm when performing 30° and 15° rotation, respectively. Some studies have focused on mathematical models to estimate the HJC location, and two algorithms have been proposed (Gamage et al., 2002; Halvorsen et al., 1999). There are several authors who suggested that the performance of the functional method can be strongly affected by variation in its execution (Piazza et al., 2004; Camomilla et al., 2006; Ehrig et al., 2006). The functional method requires an additional dynamic trial in the gait analysis, and it can be applied effectively only to those who are able to perform significant hip motion. Nonetheless, the functional method at present remains the only clinically feasible method to estimate subject-specific location of the HJC.

The prediction approach uses regression equations with pelvic anthropometric measurements as independent variables. These variables have been obtained by either using imaging techniques based on a relatively small samples of living adult males (Murphy et al., 2011; Davis et al., 1991; Bell et al., 1990) or by direct measurements on a large sample of cadaver specimens (Seidel et al., 1995). The prediction methods suggested by Davis et al. (1991) and Bell et al. (1990) are currently the most widely used even though they are based on a very limited and specific population of subjects.

Several studies have compared the performance of the prediction and functional methods and these have indicated that the functional method is preferable when considerable amount of range of hip motion can be performed (McGibbon et al., 1997; Leardini et al., 1999; Besier et al., 2003). There are a few studies which claim that the prediction method provides more accurate estimations than the functional method (Bell et al., 1990). In the study conducted by Leardini and colleagues (1999), it was shown that the functional error limited the mean estimation error to 12 mm, performing better than the other two prediction methods in which they produced mean errors of 23 mm and 21 mm, respectively. In another study, the reliability of the prediction method was compared with the actual measurement of the HJC location using an imaging technique (Jenkins et al., 2000). They have reported that the maximum discrepancy between predicted and measured HJC locations was 40 mm and 85 mm for a normal child and a child with cerebral palsy (CP), respectively. Also, it was suggested that the mean errors of HJC location was significantly higher in children with CP (55 mm) than in normal children (22 mm) and adults (17 mm). Consequently, this study has pointed out the importance of the effect of age, gender and pathological conditions in locating the HJC; therefore specific regression parameters are needed to address these conditions.

All the current methods are expected to generate some error in determining the HJC location, but the use of the functional method has been recommended as it prevents the volunteers from being exposed to ionizing radiation (Camomilla et al., 2006; Leardini et al., 1999). It also provides the motion analysis community with a robust and detailed series of regression equations for HJC location and kinematic-based estimation.

In this study, a functional method proposed by Gamage and Lasenby (2002) was used to estimate the HJC position using kinematic data of the motion of the markers on the femur (GT, ME, LE, THI) in relation to the sacral cluster; this least-squares functional algorithm is reported to perform better than other sphere fitting functional methods under the same testing conditions (Ehrig et al., 2006; Camomilla et al., 2006; Gamage et al., 2002; Halvorsen, 2003).

Step 1: Kinematic data

Kinematic information about two segments while one segment moves relative to the other were used and the functional method applied to estimate the position of the centre of rotation.

To estimate the position of the HJC, the subject was asked to move the femur (in this case the investigator moved the skeleton’s femur) while exploring the full range of motion in all planes; this includes: flexion/extension, abduction/addiction and circumduction. As described in experimental protocol (Step 4, Section 4.5.2.3), the femur was moved while the pelvis had minimal movements.

Step 2: Transformation to the anatomical coordinate frame of the pelvis

Before being able to use kinematic data to estimate the HJC, the trajectories of the femoral markers were transformed from the global coordinate frame to the anatomical coordinate frame of the pelvis. This step is very important, because using the positional data of the femur with respect to the global coordinate frame means the pelvis is completely stationary. This would be an acceptable assumption if the pelvis was completely immobilised but since this is not the case in a clinical situation; the smallest movement of the pelvis will violate this assumption.

The first step to estimate the HJC is to define the anatomical coordinate frame of the pelvis which is as follows:

O_{Pelvis}: The origin is at the midpoint between $\overline{\mathrm{LASISc}}$ and $\overline{\mathrm{RASISc}}$

X_{Pelvis}: the line connecting the $\overline{\mathrm{LASISc}}$ and $\overline{\mathrm{RASISc}}$, pointing towards $\overline{\mathrm{RASISc}}$

$$X_{pelvis}=\frac{(\overline{RASIS_c}-\overline{LASIS_c})}{\|(\overline{RASIS_c}-\overline{LASIS_c})\|} \tag{4.12}$$

Z_{Pelvis}: the line perpendicular to the plane defined by PSIS and $ASIS_c$, pointing upward.

$$Z_{pelvis}=\frac{(\overline{RASIS_c}-\overline{Sacr})\times(\overline{RASIS_c}-\overline{LASIS_c})}{\|(\overline{RASIS_c}-\overline{Sacr})\times(\overline{RASIS_c}-\overline{LASIS_c})\|} \tag{4.13}$$

Where, $\overline{Sacr}=\frac{(LPSIS+RPSIS)}{2}$ (4.14)

Y_{Pelvis}: the line perpendicular to the plane defined by X_{Pelvis} and Z_{Pelvis}, pointing forward.

$$Y_{Pelvis}= Z_{Pelvis} \times X_{Pelvis} \tag{4.15}$$

A transformation matrix from global coordinate frame to the anatomical coordinate frame of the pelvis was defined:

$$T_{GA}=\begin{bmatrix} X_{GA} \\ Y_{GA} \\ Z_{GA} \end{bmatrix} = \begin{bmatrix} x_x & y_x & z_x \\ x_y & y_y & z_y \\ x_z & y_z & z_z \end{bmatrix} \tag{4.16}$$

To define the femoral markers relative to the anatomical coordinate of the pelvis, the markers were translated relative to the origin of the pelvis anatomical coordinate frame and then multiplied by global-to-anatomical transformation matrix of the pelvis.

$$V^p= (V_g^p-O_{Pelvis})\, T_{GA} \tag{4.17}$$

Where V^p is the pth vector of a femoral marker in the pelvic coordinate frame, V_g^p is the pth vector of a femoral marker in the global coordinate frame, O_{Pelvis} is the origin of the pelvic coordinate frame and T_{GA} is the transformation matrix from global to anatomical coordinate frame of the pelvis (Figure 4-8).

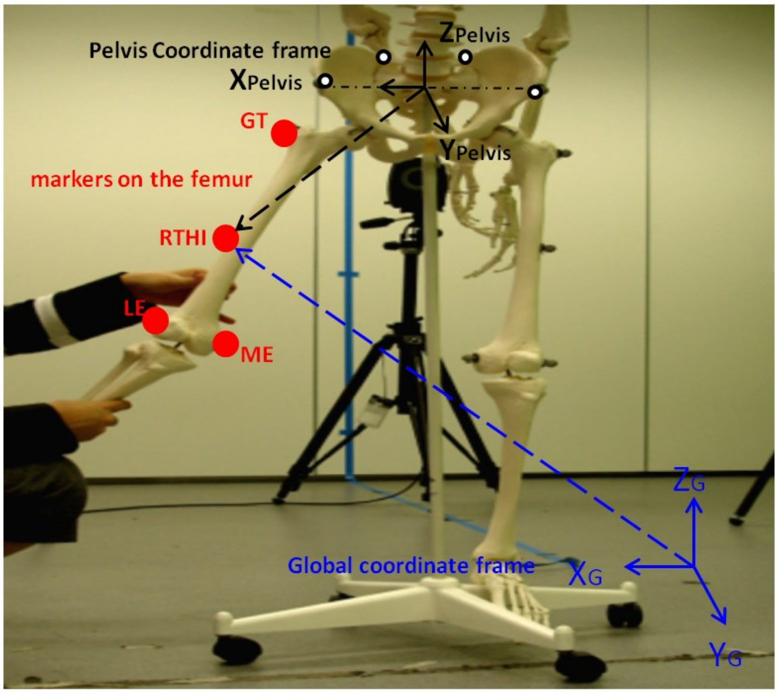

Figure 4-8 **The global coordinate frame and anatomical coordinate frame of the pelvis including representation of the RTHI femoral marker in both coordinate frames. The red circles on the femur represent the location of femoral markers. The black and white circles represent the location of anatomical landmarks on the pelvis used to define the anatomical coordinate frame for the pelvis.**

Step 3: Least square method

After defining the femoral markers with respect to the anatomical coordinate frame of the pelvis, the Gamage and Lasenby (2002) cost function can be used to estimate the hip joint centre. The sphere-fitting algorithm is used. This method assumes that the makers trace out a sphere centred at the centre of rotation (CoR) of the segment as shown in Figure 4-9.

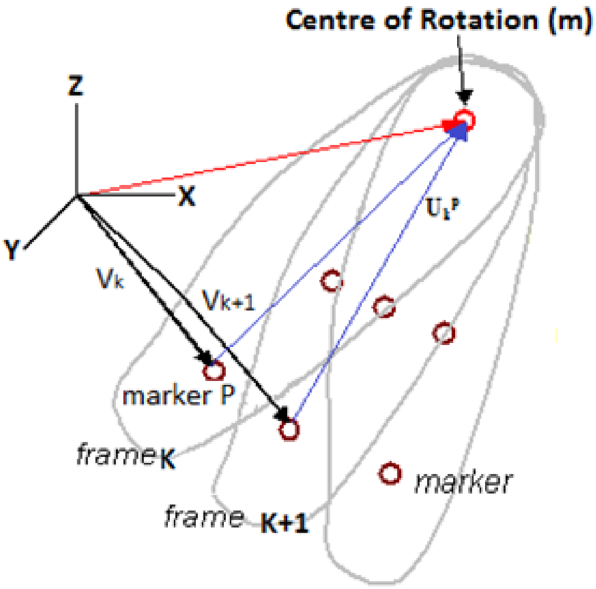

Figure 4-9 Schematic of the Gamage and Lasenby (2002) least square solution. The method assumes that the markers on the femur trace out a sphere centered at the centre of rotation (CoR). V_k is the p^th^ vector at the K^th^ time instance. m is the vector of the centre of rotation, U_k^p is the vector between the CoR and the p^th^ marker at the K^th^ time instance.

Using these assumptions the following cost function *C* is formed:

$$C = \sum_{p=1}^{P}\sum_{k=1}^{K}\left[\left(V_k^p - \mathbf{m}\right) - (r^p)^2\right]^2 \tag{4.18}$$

Where, V_k^p is the position of marker p at the k^{th} time instance and **m** represent the CoR, r^p is the radius of the sphere formed by the p^th^ vector, P is the number of markers on the femur (GT, LE, ME and LTHI) and N is the total number of frames. The above equation was simplified using geometric algebra and the following equations were used to estimate the CoR **m** (the full derivation is available in Gamage and Lasenby, 2002 paper).

$$A = \mathbf{m}\,\mathbf{b} \tag{4.19}$$

$$A = 2\sum_{p=1}^{P}\left[\left(\frac{1}{N}\sum_{k=1}^{N} V_k^p\left(V_k^p\right)^T\right) - \overline{V^p}\left(\overline{V^p}\right)^T\right] \tag{4.20}$$

$$\mathbf{b} = \sum_{p=1}^{P}\left[\left(\overline{V^p}\right)^3 - \overline{V^p}\left(\overline{V^p}\right)^2\right] \tag{4.21}$$

where,

$$\left(\overline{V^p}\right)^3 = \frac{1}{N}\sum_{k=1}^{N}\left(V_k^p\right)^3 \tag{4.22}$$

$$\left(\overline{V^p}\right)^2 = \frac{1}{N}\sum_{k=1}^{N}\left(V_k^p\right)^2 \tag{4.23}$$

$$\left(\overline{V^p}\right) = \frac{1}{N}\sum_{k=1}^{N} V_k^p \tag{4.24}$$

The result from Equation 4.19 was used to define the origin of the anatomical coordinate frame of the femur. All the above algorithms were scripted in MATLAB (R2011a, The MathWorks, Natick, USA).

Segmental coordinate frames

The knowledge of the anatomical landmark positions relative to the technical coordinate frame allows for the definition of anatomical coordinate frames and their orientation. A precise determination of the anatomical coordinate frame is crucial for joint reliability (Cappozzo et al., 1996; Wu et al., 2002). Therefore, defining the anatomical coordinate frame for both, femur and pelvis, is the first step to determine the segment/joint kinematics.

Femur: the coordinate frames for the femur was defined according to the ISB recommendation (Wu et al., 2002), using HJC, LE and ME.

O_{Femur}: the origin coincides with the HJC

Z_{Femur}: the line connecting the HJC to the midpoint of the LE and ME, pointing upward.

$$Z_{Femur}=\frac{(\overline{HJC}-\overline{MID})}{\|\overline{HJC}-MID\|} \tag{4.25}$$

Where, $\overline{MID}=\frac{(LE+ME)}{2}$ (4.26)

Y_{Femur}: the line perpendicular to the plane defined by HJC, ME and LE, pointing forward.

$$Y_{Femur}=\frac{\left((HJC-LE)\times(LE-ME)\right)}{\left\|\left((HJC-LE)\times(LE-ME)\right)\right\|} \tag{4.27}$$

X_{Femur}: the line perpendicular to the plane formed by Z_{Femur} and Y_{Femur}, pointing toward LE.

$$X_{Femur}= Y_{Femur} \times Z_{Femur} \tag{4.28}$$

Pelvis: the anatomical coordinate frame of the pelvis was used to calculate the HJC as described before. Here, a summary of the definition of the pelvic coordinate frame according to the Cappozzo et al. (1995) recommendation is presented:

O_{Pelvis}: The origin is at the midpoint between the digitised $\overline{\mathrm{LASISc}}$ and $\overline{\mathrm{RASISc}}$

X_{Pelvis}: the line connecting the $\overline{\mathrm{LASISc}}$ and $\overline{\mathrm{RASISc}}$, pointing towards $\overline{\mathrm{RASISc}}$

Z_{Pelvis}: the line perpendicular to the plane defined by PSIS and $ASIS_c$**,** pointing upward.

Y_{Pelvis}: the line perpendicular to the plane defined by X_{Pelvis} and Z_{Pelvis}, pointing forward.

Segment and joint rotation

There are different ways of representing the rotation of a segment in 3-D kinematic study; one is the rotation of the segment with respect to the fixed global coordinate system which is known as a segment kinematics; or the rotation of one segment relative to another which is known as joint kinematics (Figure 4-10). In this study the latter method was used to develop the kinematic model.

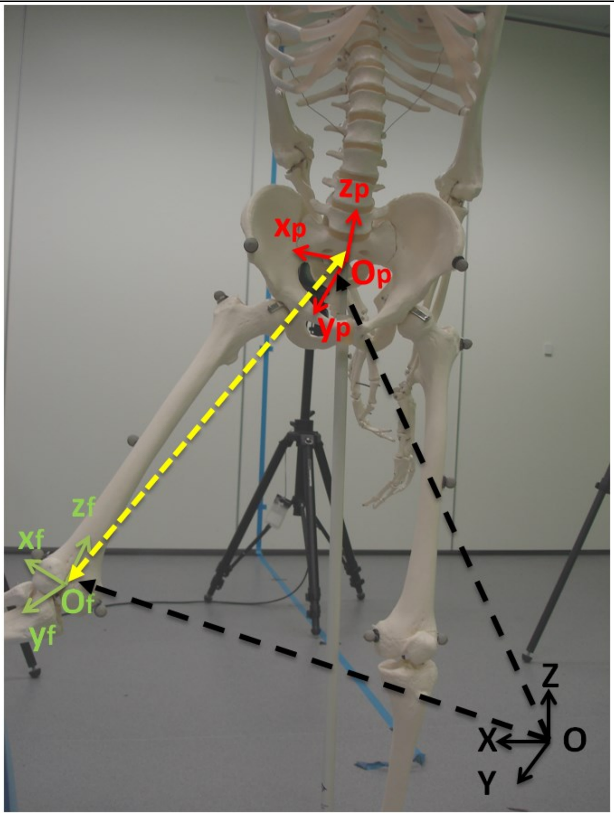

Figure 4-10 Representation of the anatomical coordinate frames of the femur and pelvis. The rotation of the segment in 3-D study can be defined either with respect to the fixed global coordinate frame (OXYZ) or relative to another segment (O_f x_f y_f z_f). One should note that in this study the origin of anatomical coordinate frame of the femur is coincide with HJC not midpoint between LE and ME.

Therefore, the rotation of femur relative to the fixed pelvis was obtained using Euler angle with $X\text{-}Y'\text{-}Z''$ Cardan sequences where rotation about X, Y and Z were the flexion/extension, abduction/adduction, and rotation. This sequence means that the first rotation occurs around X-axis, the second rotation occurs around the new Y-axis (Y') and the last rotation occurs around the new Z-axis (Z'') (Figure 4- 11).

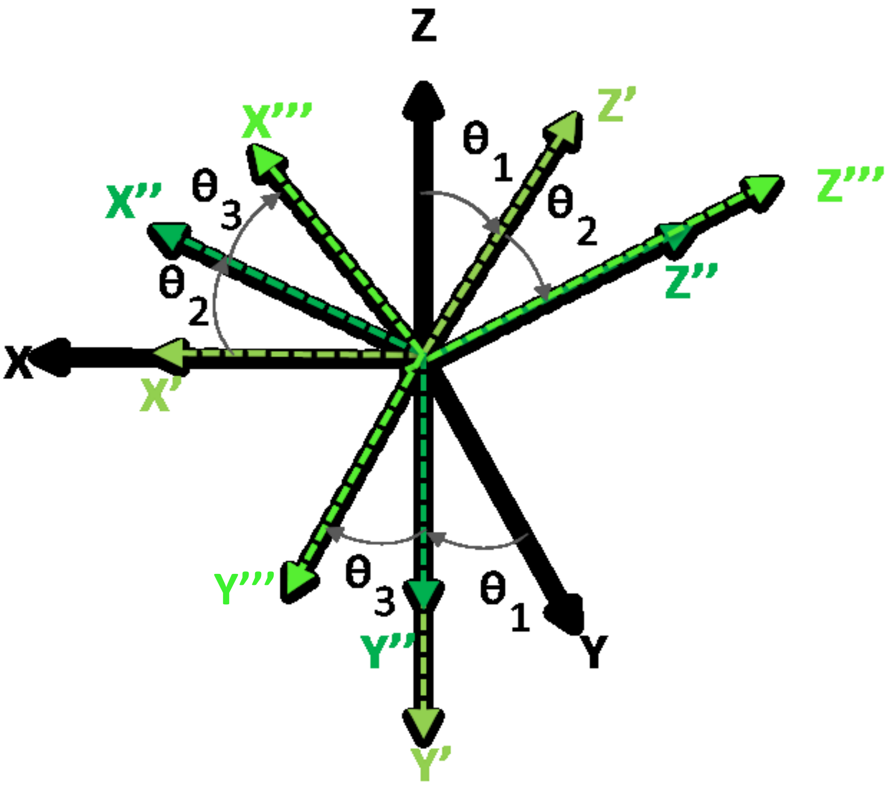

Figure 4- 11 An example of Cardan sequence of three rotations about X, Y, Z axes. Θ_1 is the first rotation about the X axis to get X', Y', Z'; Θ_2 is the second rotation about the new Y' axis to get X'', Y'', Z''; and the final rotation is Θ_3, about the new Z'' axis to get the desired X''',Y''',Z'''.

This sequence is the most common method used in gait analysis and would give means for comparison between studies (Winter, 2005; Kadaba et al., 1990; Davis et al., 1991). However there are six possible Cardan sequences in which Crawford et al. (1996) made a strong case that appropriate sequence will depend on joint geometry and existing clinical convention. The sequence of flexion/ abduction /internal rotation is known as a conventional sequence and has been used in many commercial gait analysis software packages such as Vicon (Oxford, UK).

A description of calculation of the Euler rotations is given in Appendix A. Coordinate frame definitions and Euler rotations were scripted in Vicon BodyBuilder (Version 3.6.1, Oxford, UK) and MATLAb (R2011a, The MathWorks, Natick, USA), respectively.

4.5.3 Results and Discussion

Figure 4-12 illustrates the output values for the described kinematic model. The values of femoral flexion and extension with respect to the neutral position of the femur (static frame) in the pelvic coordinate frame were 24.4° and 35.1°, respectively.

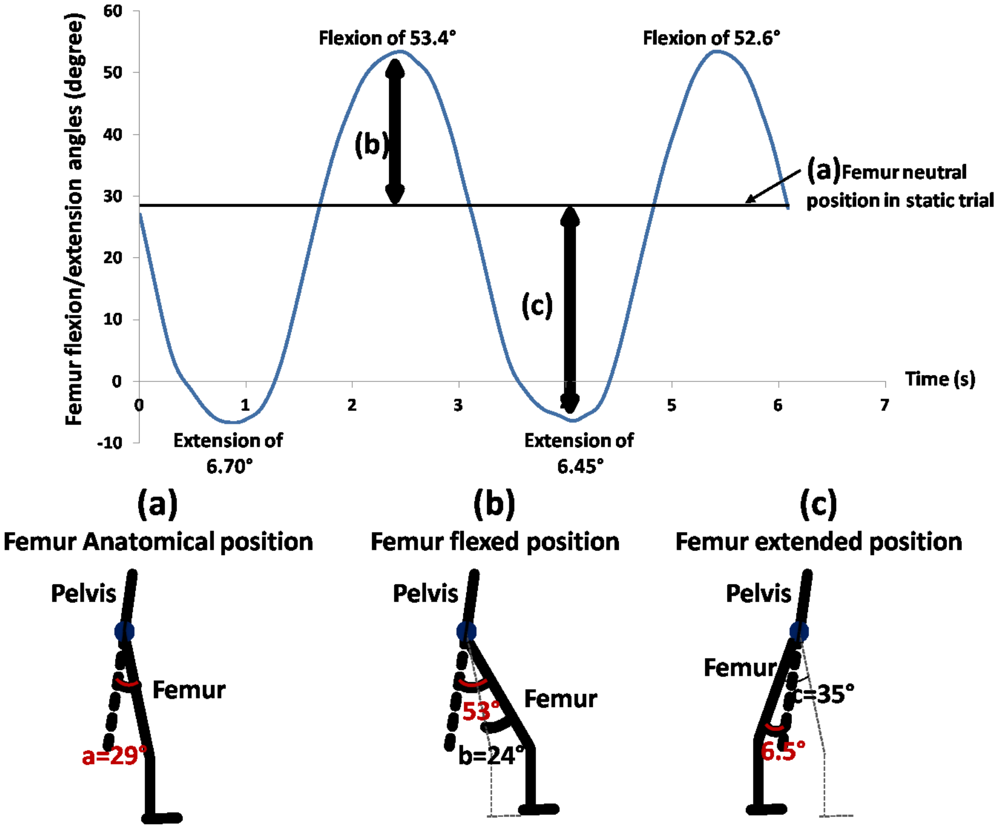

Figure 4-12 Graph showing the experimental values obtained while flexing and extending the femur with respect to the pelvis in the sagittal plane (a) neutral position (anatomical posture) of the femur in the static trial with respect to the pelvis, (b) in the dynamic trial, the position of flexed femur was measured relative to its neutral position in the static trial, (c) in the dynamic trial, the femur was extended with respect to its neutral position about 35°.

Figure 4-13 shows the values of femoral abduction and adduction of 23.6° and 9.8°, respectively with respect to the femur neutral position in the frontal plane of the pelvis.

The RMSE was used to measure the difference between values predicted by the model and the values actually observed from the dynamic trial using equation 4.29.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs} - X_{model})^2}{n}} \tag{4.29}$$

These RMSE values are as follows 0.6°, 0.1°, 1.4° and 0.2° for femur flexion, extension, abduction and adduction, respectively. The obtained results showed a small difference between the obtained values from the kinematics model and measured valued during the experiment, thus demonstrating the validity of the underlying mathematical transformations.

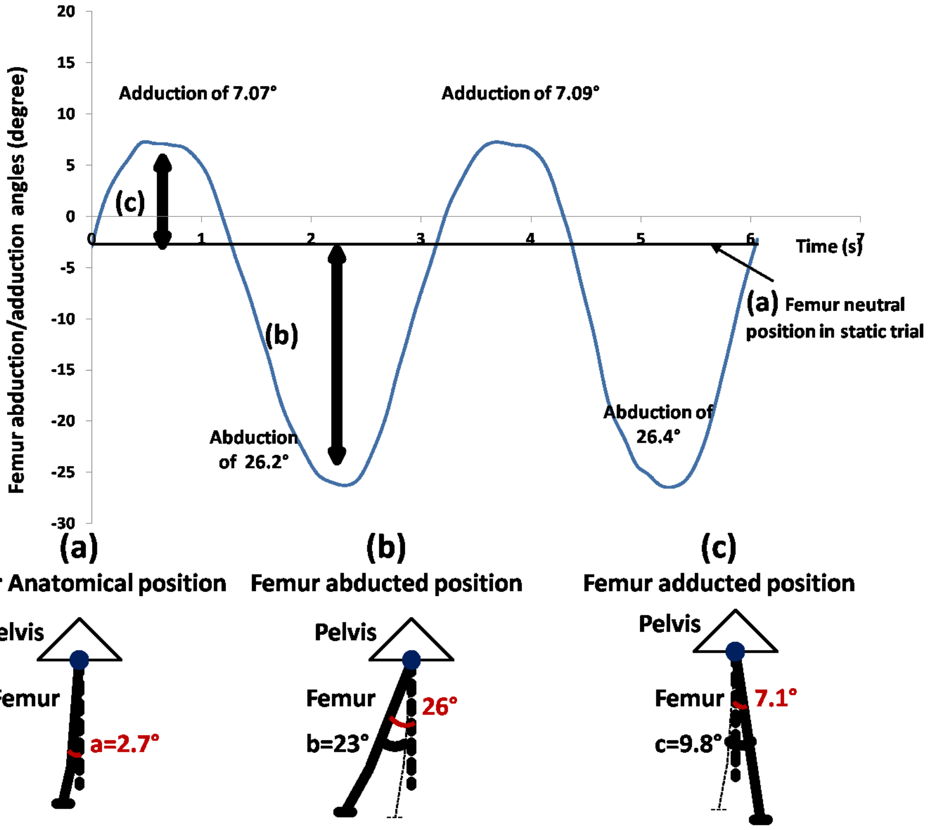

Figure 4-13 Graph showing the femur adduction and adduction plotted against time in seconds. The black line represents the femur neutral position in the static trial while the blue curve represents the femur adduction and abduction in the dynamic trial. Vertical black lines represent the amount of femur rotation from its neutral position in the frontal plane. (a) represents the neutral position of the femur in the frontal plane in the static trial, (b) represents the femur abduction in the dynamic trial from its neutral position in the static trial, (c) represents the femur adduction in the dynamic trial from its neutral position.

As the skeleton was used in this study, an obtained error does not reflect soft tissue artefact or skin movement. These errors are purely based on the instrumental and experimental error. However the result of this study showed that the performance of the developed kinematic model was satisfactory as the RMSE of the system was on average 0.57°. Therefore this model is used for the rest of this chapter.

In this study, the performance of the developed kinematic model was evaluated to estimate the instrumental error; however, more research is required to measure the sensitivity of the model to skin motion and landmark identification as this is one of the main steps in defining the new technical coordinate system. In the next section the model will be used on different individual and the effect of the calibration of the ASIS and PSIS on pelvic kinematics will be investigated.

4.6 Study II: The effect of digitising the PSIS positions and size of digitising pointer on pelvic kinematics

4.6.1 Aim and objectives

The aims of this study are (a) to investigate the effect of PSIS position on pelvic kinematics using two different methods, and (b) to determine if the precision of manual palpation of the ASIS could be improved by using a smaller pointer (L-frame).

To achieve the first aim, the PSIS positions were digitised with respect to the sacral cluster using (1) the skin markers in the static trial, and (2) the digitisation pointer (L-frame). It has been mentioned in previous studies that digitising some of the bony landmarks may reduce the errors due to skin movement (Cappozzo et al., 1996). In a study conducted by Cappozzo and colleagues (1996), a marker on the lateral epicondyle of the femur was found to introduce errors of up to 40 mm for 120° of knee flexion. Although the errors introduced by the PSIS markers in pelvic kinematics has not been studies in depth, one would expect the errors to be smaller as there is less skin movement in comparison to ASIS positions. For this reason, one has to explore the effect of PSIS positions on pelvic kinematics. To calculate pelvic kinematics, the position and orientation of the anatomical coordinate system relative to the technical coordinated system is obtained using the positional data of the anatomical landmarks on the pelvis. As discussed, the positions of PSIS were digitised by placing the L-frame on the palpated PSIS. Researchers reported the important role of locating the palpable anatomical landmarks precisely in the anatomical landmark calibration procedure and how these uncertainties will propagate to joint/segment kinematics (Della Croce et al., 2005; Della Croce et al., 1999). It has been shown that the anatomical landmarks for the pelvis and lower limbs may exhibit a root mean square value in rage of 10-25 mm when identified by different operators and consequently the anatomical coordinate frame orientation of the same segments had a root mean square value in range of 3°-10° (Della Croce et al., 1999). This error will clearly propagate to the calculation of segment and joint kinematics. Therefore it is important to determine if the repeatability or precision of manual palpation procedures of the ASIS could be improved by using a smaller pointer (L-frame). The benefit of the smaller pointer is the ability to push the tip of pointer relatively deep in soft tissue toward the palpated anatomical landmarks; the pointer with smaller dimension is also easier to control.

4.6.2 Materials and methods

4.6.2.1 Study population

10 subjects (4 males, and 6 females) from Imperial College London participated in this study. Their mean age was 25.3 years (range: 18-44 years) and mean BMI was 21.7 kg/m^2 (range: 19.0-23.6 kg/m^2).

4.6.2.2 Equipment and lab set up

The experiment took place at Motion Analysis Laboratory at Imperial College London as discussed in Section 4.5.2.1. An optical motion tracking system was used at an acquisition rate of 150 Hz and reflective markers were attached to bony landmarks on the femur and pelvis as described in Table 4-1 and Figure 4-14. The 3-D sketch of the sacral cluster is available in Appendix B.

Figure 4-14 Marker locations for pelvis and femur

4.6.2.3 Experimental protocol

The experimental protocol was as defined in Section 4.5.2.3 with some additions as follows:

- Five static trials to digitise RPSIS and LPSIS positions using pointer,
- Five static trials to digitise RPSIS and LPSIS positions using skin marker,
- Five static trials to digitise ASIS positions using the VICON pointer (V-Pointer), and

- Five static trials to digitise ASIS positions using the small pointer (S-Pointer).

First, 5 trials were recorded using the pointer to digitise the PSIS positions, and then another five trials were recorded while the subject was standing in the upright position where the PSIS positions were recorded directly using the reflective markers. After digitising the PSIS, the positions of the ASIS were digitised two times for each trial using V-Pointer and S-Pointer (Figure 4-15). After finishing the digitisation, all participants were asked to complete a task which was picking up the light box by bending their knees.

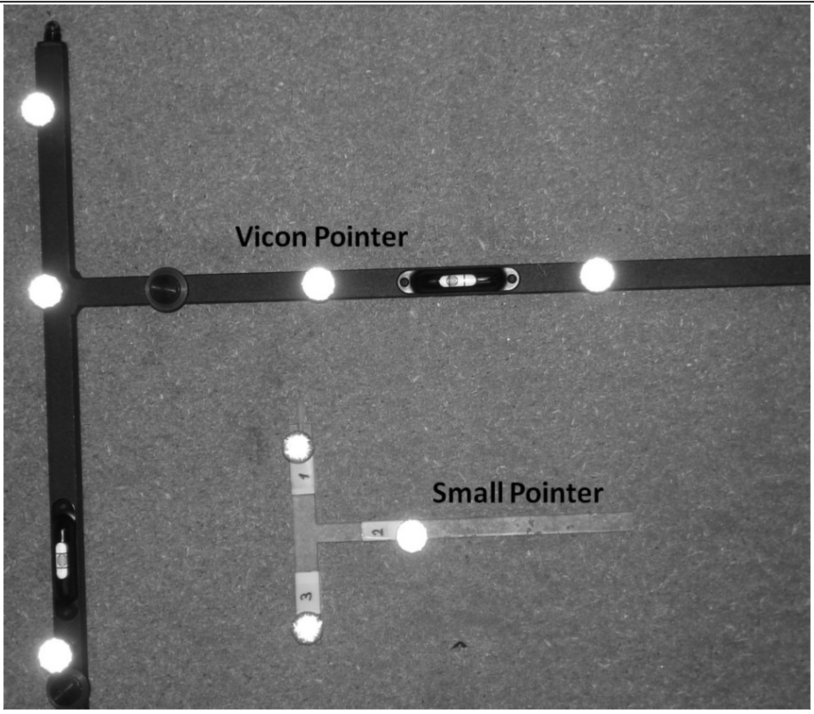

Figure 4-15 The positions of ASIS were digitised using two different digitiser wands: the Vicon Pointer (L-frame) and Small Pointer

4.6.2.4 Data analysis Statistical analysis

The data analysis in this study was executed in the same way as described in Section 4.5.2.4 which includes the estimation of HJC and definition of the coordinate frames. In this study the positions of the PSIS were digitised in two different ways (Figure 4-16): using the calibration pointer (PP) and using the skin markers to digitise them (MP). The digitisation of the ASIS positions was similar to Section 4.5.2.4 with some addition in which the ASIS positions were digitised in neutral position using two different pointers (S-Pointer and V-Pointer). The data analysis in this study was processed as described in Section 4.5.2.4.


[redacted]
[redacted]

RPSIS **LPSIS**


[redacted]

Figure 4-16 The positions of PSIS were digitised with respect to the pelvic cluster using the digitisation wand (top pictures), the positions of PSIS were digitised with respect to the pelvic cluster using the markers directly in static trial.

The ROM of pelvic tilt, obliquity and rotation from 5 dynamic trials for each subject were averaged and subsequently presented as a mean ROM of pelvic tilt, obliquity, and rotation and SD. The SD was used to measure the variability between the different trials. Low standard deviations are an indicator that the measurements are reliable whilst high standard deviations indicate that the measurements are spread out over a large range of values. The SD was calculated according to the following equation:

$$SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad (4.30)$$

Where N is the size of the sample and $\bar{x}$ is the mean value given by the following equation:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (4.31)$$

The coefficient of multiple correlation (CMC) was also used as a statistical measure to evaluate the similarity between the kinematic waveforms. The CMC has been used in different studies to evaluate the similarity and repeatability of the waveform in gait analysis (Kadaba et al., 1989; Ferrari et al., 2010; Collins et al., 2009). The CMC values ranged from 0 (dissimilar waveforms) to 1 (similar waveforms) and were first proposed by Kadaba et al. (1989) in order to test the intra-subject repeatability for within- and between-day kinematic data by defining two formulas, named as within-day and between-day.

In this study, the within-day CMC (Equation 4.32) was used to assess the repeatability of ROM of pelvic tilt generated in 5 trials for each subject for each method.

$$\text{Within-day } \mathbf{CMC} = \sqrt{1 - \frac{\sum_{s=1}^{S}\sum_{w=1}^{W}\sum_{f=1}^{F}\left(Y_{swf}-\bar{Y}_{sf}\right)^{2}/SF(W-1)}{\sum_{s=1}^{S}\sum_{w=1}^{W}\sum_{f=1}^{F}\left(Y_{swf}-\bar{Y}_{s}\right)^{2}/S(WF-1)}} \qquad (4.32)$$

Where *s* is the number of experimental days/sessions, *f* is the number of frames and *w* is the number of waveforms/trials. Y_{swf} is subject's joint/segment angles of frame *f*, of the trial *w* and of the session *s*; $\bar{Y}_{sf}$ is the average pelvic angle at frame *f*, of the average waveform among *w* waveforms of session *s*; and finally $\bar{Y}_{s}$ is the grand average of the pelvic angles of session *s*.

While the above formula was used to measure the within-trials repeatability of the 5 trials of picking up the light box for each digitisation positions, the new CMC formulation which was proposed by Ferrari et al. (2010) was used to measure the similarity among the waveforms acquired by different methods of digitisation. The new CMC formula, known as Inter-Protocol CMC (IP-CMC), measures the similarity of the waveforms obtained with different protocols within each gait cycle and is cleared from, (1) biological variability of the subject's kinematics such as speed, (2) variability in the propagation of the soft-tissue artifact and (3) variability in the measurement performance. Equation 4.33 shows the formulation for IP-CMC which also takes values that range from 0 (dissimilar waveform) to 1 (similar waveforms).

$$\text{IP-}\mathbf{CMC} = \sqrt{1 - \frac{\sum_{g=1}^{G}\left[\sum_{p=1}^{P}\sum_{f=1}^{F}\left(Y_{gpf}-\bar{Y}_{gf}\right)^{2}/GF_{g}(P-1)\right]}{\sum_{g=1}^{G}\left[\sum_{p=1}^{P}\sum_{f=1}^{F}\left(Y_{gpf}-\bar{Y}_{g}\right)^{2}/G\left(PF_{g}-1\right)\right]}} \qquad (4.33)$$

G is the total number of kinematic cycles (trials), P is the number of protocols/methods. Y_{gpf} is the joint/segment angle at frame f of each waveform provided by protocol P at kinematic cycle g. $\bar{Y}_{gf}$ ordinate at frame f of the average waveform among the P waveforms for the kinematic cycle of g, $\bar{Y}_{gf} = \frac{1}{P}\sum_{p=1}^{P} Y_{gpf}$, and finally $\bar{Y}_g$ is the grand average for the kinematic cycle g among its P waveforms, $\bar{Y}_g = \frac{1}{PF}\sum_{p=1}^{P}\sum_{f=1}^{F} Y_{gpf}$. In some cases the CMC values over the joint-angles with limited range of motion (ROM) are complex number which should be interpreted as a complete dissimilarity of the waveforms, to avoid this coefficient of multiple determination (CMD) was evaluated and reported instead (Equation 4.34).

CMD= $(\text{IP-CMC})^2$ (4.34)

Statistical differences between each method were assessed using a repeated measures analysis of variance test (ANOVA) with one within subject factor (method of calibration) and nonparametric Friedman' test was used to measure the statistical differences between CMD values. The SPSS (Version 19.0, Chicago, USA) was used to do the statistical test.

4.6.3 Results and Discussion

The mean pelvis ROM for all three rotations, mean maximum pelvic tilt, obliquity and rotation, the mean standard deviation, within-day CMC and CMD values for digitisation of PSIS and ASIS positions using different methods are given in Table 4-2. In the sagittal, frontal and transverse planes, the ROM and the maximum anterior tilt obtained from kinematics data over 5 trials was similar between the methods to digitise the PSIS (MP,PP) and ASIS (V-Pointer, S-Pointer) and the statistical test showed no significant differences between them ($0.281<p<0.891$). The intra-variability of the kinematic data for all methods in all three rotations were small and there were no significant differences between the two methods for digitising the PSIS and ASIS positions ($p>0.05$). The within-day CMC values in the sagittal plane indicate an excellent repeatability of the kinematic waveforms among the MP, PP and V-Pointer, S-Pointer for pelvic tilt. The calculated CMD value for the pelvic tilt indicates the high intra-repeatability and consistency between the MP and PP (Figure 4-17). And high values of CMD for different pointers were also another indication of consistency and repeatability of the kinematic waveforms between the two methods and the CMD value calculated for the pelvic tilt was significantly higher than that of the other two rotations ($x^2(1)=10.600$, $p<0.05$).

Method	ROM (SD)	Max.Angle (SD)	Std.Deviation (SD)	Within-day CMC (SD)	CMD (SD)
Pelvic tilt (in degrees)					
MP	25.0(8.10)	-36.0(8.60)	2.73(0.85)	0.91(0.13)	0.82(0.01)
PP	25.0(8.02)	-36.4(10.3)	2.75(0.84)	0.91(0.02)	
V-Pointer	24.5(4.81)	-36.5(4.9)	1.30(1.76)	0.93(0.03)	**0.84(0.08)***
S-Pointer	24.0(4.94)	-36.4(4.9)	1.33(1.22)	0.95(0.01)	
Pelvic obliquity (in degrees)					
MP	5.33(1.53)	-1.77(5.59)	0.72(0.43)	0.67(0.02)	0.66(0.03)
PP	5.46(1.59)	-1.70(4.43)	0.74(0.44)	0.68(0.02)	
V-Pointer	4.86(3.11)	-1.05(4.54)	0.79(1.00)	0.81(0.14)	0.68(0.12)*
S-Pointer	4.21(3.07)	-0.98(4.23)	0.75(1.06)	0.83(0.09)	
Pelvic rotation (in degrees)					
MP	7.12(2.86)	-1.17(3.44)	1.41(0.83)	0.64(0.03)	0.69(0.06)
PP	7.02(2.68)	-2.45(2.15)	1.40(0.82)	0.63(0.03)	
V-Pointer	11.43(5.2)	-2.94(3.99)	0.96(1.78)	0.87(0.01)	0.79(0.06)*
S-Pointer	10.65(4.6)	-2.01(4.01)	0.90(1.14)	0.87(0.02)	

Table 4-2 Mean range of motion, maximum angle of pelvic movement, between the trials standard deviation of maximum pelvic tilt, within-day CMC and CMD values for pelvic movement during the dynamic trials are given (* represents the significant difference between the CMD values of the three planes of rotation).

In the frontal and transverse planes, the acquired within-day CMC values for digitised PSIS and ASIS positions showed a moderate to good repeatability of kinematic waveforms among the methods. The low CMC values in the frontal and transverse planes may, in part, relate to small range of motion of the pelvis in these two planes as the CMC is based on the ratio of error variance to true variance.

The results obtained from the MP and PP methods lead to the conclusion that the two methods are similar and there were no differences in pelvic kinematics obtained by digitising the PSIS positions using the pointer or skin markers. Although the V-Pointer and S-Pointer methods for digitising the ASIS positions lead to similar results, it must be noted that the latter method seems advantageous. It allows a more natural palpation since the finger-tip must not leave the palpated anatomical landmark surface prior to digitisation; in addition the S-Pointer is lighter than the V-Pointer which minimized the unwanted movement of the pointer due to its weight and dimension during digitisation of anatomical landmarks in static trials. Furthermore its tip is finely defined which allows it to be positioned directly on the anatomical landmarks with no concern that the pointer may slide. Therefore the S-Pointer will be used in the rest of the studies.

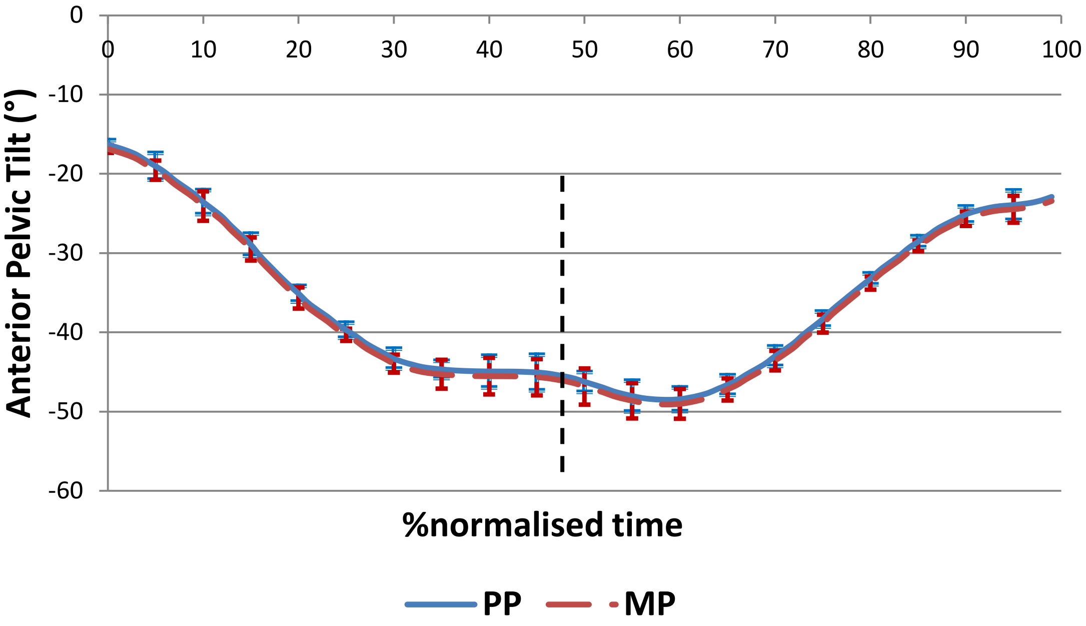

Figure 4-17 The anterior pelvic tilt waveforms for two methods MP, and PP and their standard deviation are shown as error bars for one subject. The dashed line shows the time that the subject reaches the box.

To conclude this study, there were no significant differences between MP and PP methods to digitise the PSIS position and no significant difference was found between the two pointers to calibrate the position of ASIS. Therefore in future the positions of PSIS will be digitised with respect to the sacral cluster using the skin markers in static trial and ASIS position will be digitised using the S-Pointer, as there is more fat deposition over ASIS than PSIS.

In the next chapter (Chapter 5), the sacral cluster will be validated and its repeatability and reliability will be tested by comparing it to HH marker set. The results of this chapter will be used to develop a kinematic model. Therefore, the positions of the ASIS will be digitised with respect to the sacral cluster in neutral position (single calibration) using S-Pointer. The PSIS positions will be digitised directly using skin markers.

4.7 Study III: The effect of pelvic orientation in digitising the ASIS positions

4.7.1 Aim and objectives

As described in Chapter 3, one of the critical sources of error recognised in gait analysis is STA and landmark misplacement and the fact that markers are not stationary with respect to the underlying bone, mostly due to the soft tissue. The use of technical markers and the concept of the CAST (Cappozzo et al., 1995) were the first steps toward the solution of this problem. In CAST, the location of the specific anatomical landmarks that are either not practical for use in dynamic experiments or can introduce high errors, is estimated relative to the technical coordinate frame in static trial and then during dynamic trials their position is expressed with respect to the technical markers; this technique which known as single calibration, is very practical and allows for the assessment of the anatomical landmarks in awkward positions.

In this section, positions of specific anatomical landmarks (ASIS) of the pelvis are calibrated using the single calibration technique. The aim of this study is to 1) investigate the amount of movement of the cluster with respect to the underlying bone (STA), 2) investigate the anatomical landmark mislocation as a result of investigator error during calibration process, and 3) assess the joint kinematic sensitivity to STA and landmark mislocation. To achieve this, five different pelvic orientations were completed by the participants for digitising the ASIS and to examine their effect on pelvic kinematics quantification.

4.7.2 Materials and methods

4.7.2.1 Study population

Five male subjects from Imperial College London participated in this study. Their mean age was 24.8 years (range: 19-27) and mean body mass index (BMI) was 21.1 kg/m^2 (range: 19.2-24.0 kg/m^2).

4.7.2.2 Equipment and lab set up

The experiment took place at Motion Analysis Laboratory at Imperial College London as described in Section 4.5.2.1. An optical motion tracking system was used at an acquisition rate of 150 Hz. Reflective markers were attached to bony landmarks on the femur and pelvis as shown in Figure 4-14 using double sided tape and adhesive spray. Prior to the experiment the investigator was trained to palpate the bony landmarks of the pelvis and femur.

4.7.2.3 Experimental protocol

The experimental protocol was as defined in Section 4.5.2.3 with some additions as follows:

- Five static trials to digitise LASIS position
- Five static trials to digitise RASIS position
- A static trial of the marker setup
- A dynamic trial to estimate the HJC position

After digitising the ASIS positions, every subject was asked to complete a task which was picking up a light box by bending their knees (Figure 4-18).

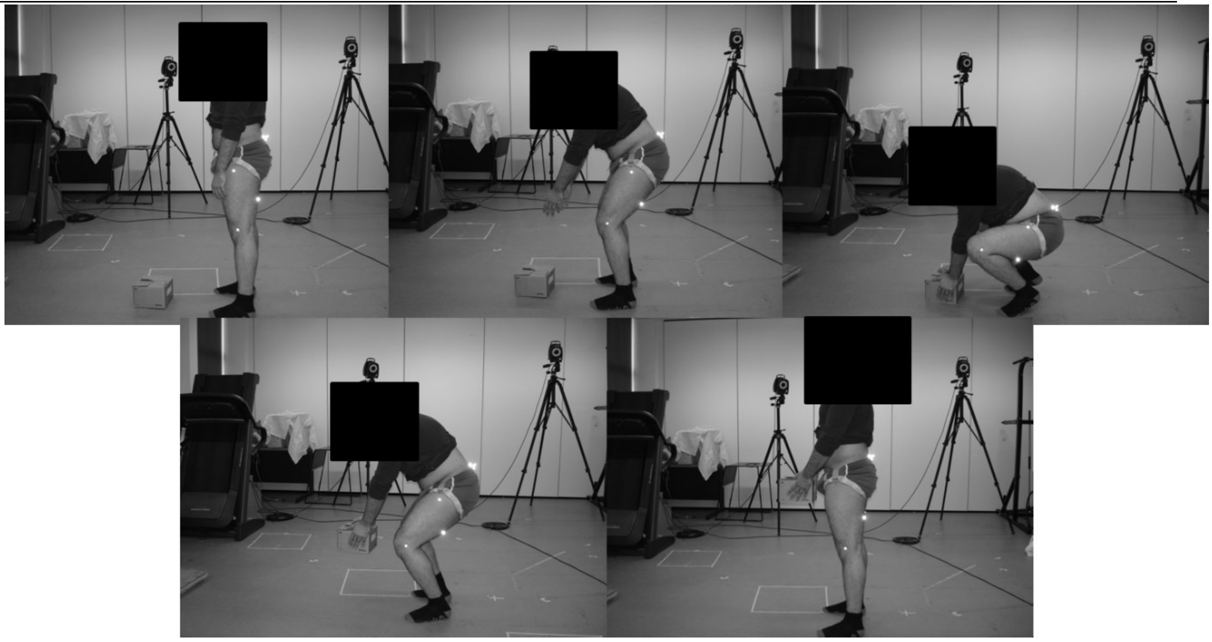

Figure 4-18 Subjects were asked to pick up a light box while bending their knees

4.7.2.4 Data analysis

Most of the data analysis in this study was executed in the same way as described in Section 4.5.2.4 which includes calibrating the ASIS positions, estimating the HJC position, defining the coordinate frames and calculating the pelvic rotations. However, in this study five different positions of the pelvis where used to digitise ASIS. These were: pelvis in neutral position (PI), pelvis fully tilted anteriorly by bending trunk forward (PII), pelvis fully tilted posteriorly by flexing the femur (PIII), pelvis fully rotated to the left (PIV) and pelvis fully rotated to the right (PV) (Figure 4-20). For every dynamic trial and all pelvic orientations, the positions of ASIS were reconstructed with respect to the position of the sacral cluster using the same techniques as in Section 4.5.2.4.

To accomplish the aims in Section 4.7.1, here are the steps taken:

1) **STA:** to assess the STA associated with the movement of the cluster with respect to the underlying bone in each calibration position of the pelvis, the standing erect position was defined as the origin. Therefore, the displacement vectors between the positions of the cluster and ASIS were defined and used for later comparison. The positions of the ASIS were defined with respect to the cluster therefore if its position changes, the position of the ASIS will be affected by the same amount. When the pelvis moves from PI to PII, the defined displacement vector between the ASIS positions and the cluster in PI should be equal to PII with only changes in its orientation (if there is no skin artefact). However, because of STA, the displacement vector in PI is not the same as that in PII. To evaluate the amount of STA affected the displacement vector, the steps below were taken.

    1. The position of ASIS was defined with respect to the global coordinate frame) and the position of the cluster was defined with respect to the ASIS in PI, PII, PIII, PIV and PV (Figure 4-19).

    2. When the orientation of the pelvis changed, the transformation matrix between the vector Ō1 and Ō2 was calculated for PII, PIII, PIV and PV (Figure 4-19).

    3. The transformation matrix obtained in step 2 was multiplied by Ā1 in order to calculated the Ā2’ which in theory should be equal to Ā2 in PII (if there is no STA). However in the experimental data, Ā2’ is not equal to the Ā2 due to the effect of skin motion (Figure 4-19).

    4. The position of the cluster can be calculated from Ā1, Ā2’ and Ā2 vectors. In theory, the cluster position obtained from Ā2’ and Ā2 vectors should be equal. However in experimental data, the position of the cluster obtained from Ā2’ and

Ā2 vectors were not equal. These differences in the cluster position represent the effect of skin motion on the position of the cluster in different pelvic orientations.

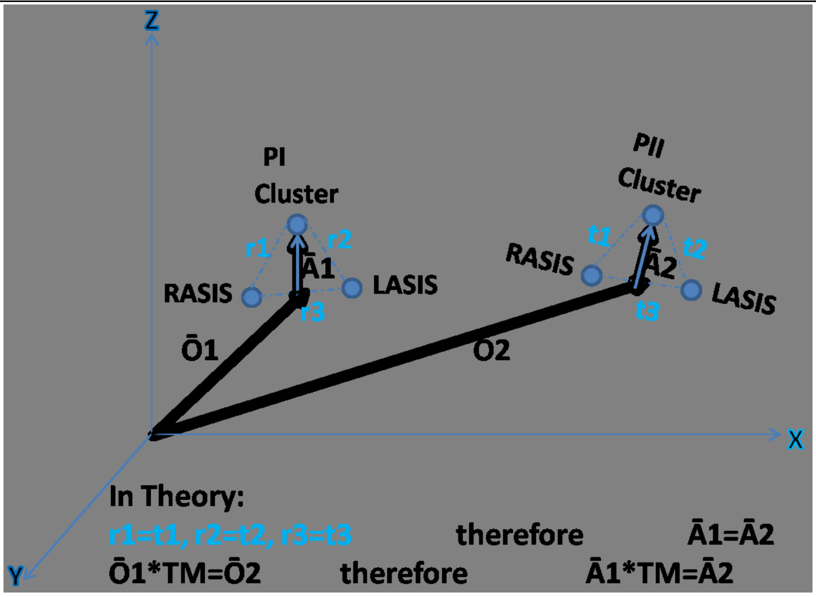

Figure 4-19 A graphical representation of the comparison between the displacement vectors from one orientation of the pelvis to another. r1, r2, r3, t1, t2, and t3 represent the displacement vector between RASIS, LASIS and cluster. If there is no STA, the displacement vector in PI should be equal to displacement vector in PII. Therefore Ā1 and Ā2 are equal. TM is the transformation matrix between vectors Ō1 and Ō2. By multiplying the Ā1* TM, the position of the cluster can be estimated in PII. Any differences between Ā1* TM and PII cluster represent the STA.

2) **Anatomical landmark mislocation:** To investigate the error associated with the incorrect location of ASIS through palpation, the positions of the calibrated ASIS for each trial (5 trials of calibration) were calculated and their standard deviation over 5 trials for each subject were calculated. These values also represent the investigator error in palpating the ASIS positions.

3) **Joint kinematics sensitivity to STA and anatomical landmark mislocation:** The pelvic rotations (tilt, obliquity and rotation) were measured relative to the global coordinate frame using the same Cardan sequence described in Study I. The data were also filtered using a 4th order low-pass Butterworth filter with cut off frequency of 6 Hz, in accordance with the previous studies and literature recommendations (Winter, 2005; Collins et al., 2009). To achieve the goals discussed in the introduction section, range of motion (ROM) of pelvic tilt, obliquity and rotation were calculated for every pelvis position and dynamic trials and their differences were investigated. Differences

between the kinematic data obtained in various pelvic orientations represent the effect of both STA and landmark mislocation in calculating the joint.

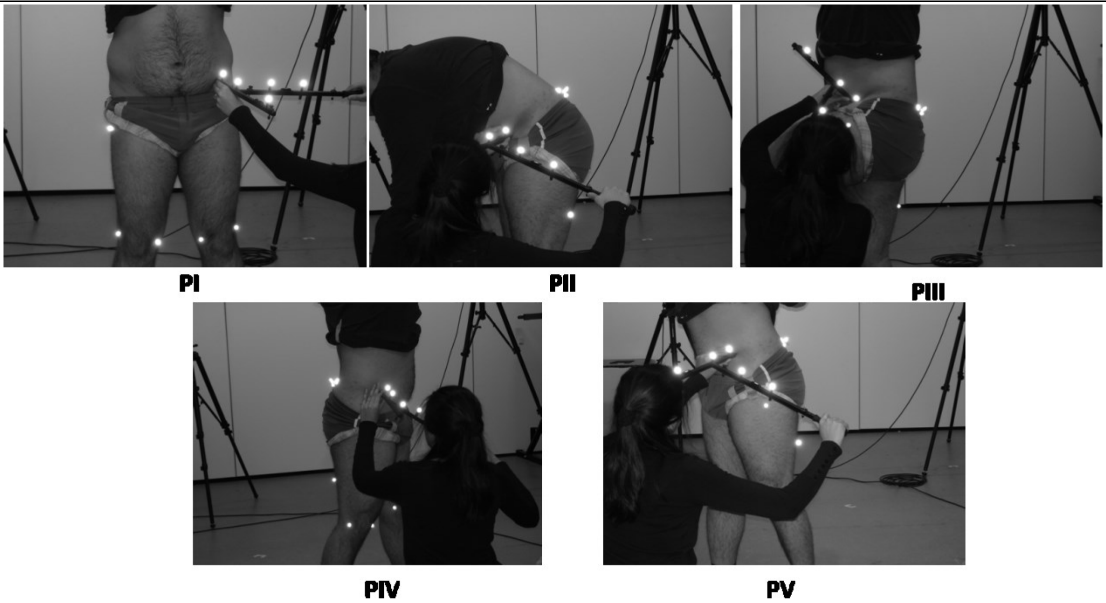

Figure 4-20 ASIS positions were digitised with respect to the sacral cluster in different pelvic orientations (PI) neutral position (PII) anteriorly tilted position (PIII) posteriorly tilted position (PIV) rotated to the left position (PV) rotated to the right position

The data for each subject were normalised to 100% of the activity (that was defined from 20ms before starting the task to 20ms after finishing the task) to eliminate the effect caused by variations in speed across different trials within the same subject as well as between different subjects.

4.7.2.5 Statistical analysis

The STA associated with the changes in the position of the cluster in different pelvic orientations, for each subject, was calculated and averaged over 5 static trials and presented as the STA in X, Y and Z directions. The investigator palpation error in each pelvic orientation was calculated using SD as a measurement of variability between the trials for each pelvic orientation. The ROM of pelvic tilt, obliquity and rotation from 5 dynamic trials for each subject were averaged and subsequently presented as a mean ROM of pelvic tilt, obliquity, and rotation. The SD, within-day CMC and CMD were used to evaluate the variability within-trials and similarity of the kinematic waveforms among five trials generated for each subject (Section 4.6.2.4).

Statistical differences between each position were assessed using a repeated measures analysis of variance test (ANOVA) with one within subject factor (pelvic orientation from

PI to PV) and non-parametric Friedman's ANOVA was used to investigate any differences between CMC and CMD values with alpha level set at 0.05. The entire statistical test was completed using SPSS (Version 19.0, Chicago, USA).

4.7.3 Results and Discussion

Table 4-3 summarises the STA obtained as a result of the cluster movement due to changes in pelvic orientations. It was assumed that there was no skin motion between the positions of the ASIS and cluster in PI, however, when the subject flexed the trunk forward position of the cluster will be affected by pelvic motion as well as skin motion. Therefore the aim was to calculate the true position of the cluster if there was no skin movement based on the subject's erect position.

The results show that there were significant differences between the position of the cluster in the neutral position (PI) and PII, PIII, PIV and PV. In the X-coordinate, the cluster position in PIII was more similar to PI while there were significant differences between the cluster position in PIII and PII, PIV, PV. Greater values of PII, PIV and PV indicate that the cluster position is more affected by skin motion in these orientations than the PIII. In Y- and Z-coordinates, the smaller values of the PII and PIII indicate that the position of cluster was less affected by skin motion than in other orientation of the pelvis.

Pelvic Orientation	**Cluster-X (mm) Mean(SD)**	**Cluster-Y (mm) Mean(SD)**	**Cluster-Z (mm) Mean(SD)**
PII -PI	21.5 (4.1)$^{(1,2,3)}$	5.23 (3.9)$^{(1,2)}$	4.4 (3.0)$^{(1,2)}$
PIII-PI	4.20 (3.9)$^{(1,4,5)}$	3.6 (2.8)$^{(3,4)}$	3.3 (3.2)$^{(3,4)}$
PIV-PI	10.1 (4.0)$^{(2,4)}$	15.7 (4.9)$^{(1,3)}$	24.7 (5.2)$^{(1,3)}$
PV-PI	12.4 (4.8)$^{(3,5)}$	16.8 (4.0)$^{(2,4)}$	20.8 (6.8)$^{(2,4)}$

Table 4-3 Average of estimated STA associated with the changes in the position of the cluster due to the changes in pelvic orientation. X, Y, and Z represent the skin motion in the sagittal, frontal and transverse planes. ($^{1-5}$ represent the significant differences, $p<0.05$). SD represents the inter-subject variability.

Table 4-4 summarises the results for anatomical landmark mislocation due to the investigator errors.

Pelvic Orientation		X-mislocation (mm) Mean(SD)	Y-mislocation (mm) Mean(SD)	Z-mislocation (mm) Mean(SD)
PI	**LASIS**	0.7 (5.3)	2.0 (4.1)	2.6 (5.0)
	RASIS	0.9 (4.9)	2.2 (2.9)	2.0 (6.3)
PII	**LASIS**	6.7 (8.1)	5.7 (4.9)	4.0 (3.2)
	RASIS	7.4 (3.9)	5.9 (6.1)	4.4 (4.8)
PIII	**LASIS**	1.2 (4.2)	1.8 (5.7)	3.8 (3.9)
	RASIS	1.6 (6.1)	2.1 (4.9)	2.2 (4.7)
PIV	**LASIS**	2.2 (3.2)	3.7 (7.7)	4.1 (6.4)
	RASIS	3.2 (4.1)	4.1 (6.5)	3.8 (3.3)
PV	**LASIS**	2.9 (4.2)	3.9 (4.9)	4.9 (4.2)
	RASIS	2.4 (5.1)	3.4 (5.3)	4.1 (7.1)

Table 4-4 Investigator precision of the palpable anatomical landmark position components in different pelvic orientations. The values represent the average of 5 trials for 5 subjects for each pelvic orientation. SD represents the inter-subject variability.

The maximum error of palpation was 7.4 mm in the PII orientation. There were no significant differences between the palpation error between different landmarks and pelvic orientations. However, it is important to investigate the propagation of the palpation error on the pelvic kinematics. So far, in Tables 4-3 and 4-4, the errors associated with the new marker set were presented which included the STA (skin motion) and anatomical landmark mislocation. In this study, the effect of these two errors on pelvic kinematics was also investigated and is presented in Table 4-5 and Figure 4-21.

Table 4-5 summarises the results of pelvic ROM when the subject picked up a light box. The repeated measures ANOVA revealed that the mean range of the motion of pelvic tilt and rotation were significantly different between the five pelvic digitisation positions (PI to PV). The findings indicate that PII, PIV and PV measured a greater range of pelvic tilt than position PI and PIII. The mean range of the motion for the pelvic rotation at PII, PIV and PV was significantly different ($p<0.05$) from that of the PI and PIII. Position PII measured more pelvic rotation in transverse plane than any other positions of calibration. In the frontal plane, there were no significant differences between the five positions of calibration ($p=0.567$).

The standard deviation for ROM of pelvis for each subject were calculated over 5 trials for each digitised position, and presented in Table 4-5 as mean SD. The calculated values of pelvic tilt for positions PI and PIII were 0.88° (±1.92°) and 0.98° (±1.98), respectively; these were significantly less than those values calculated for the PII, PIV and PV ($p<0.05$). For pelvic obliquity, the standard deviation for PI and PIII were significantly less than that of the PII, PIV and PV ($p<0.05$). The mean standard deviation of the ROM of the pelvis in the transverse plane for position I was significantly less than those calculated for PII, PIII, PIV and PV ($p<0.05$).

	Pelvic tilt (X) (in degrees)		**Pelvic Obliquity (Y') (in degrees)**		**Pelvic rotation (Z") (in degrees)**	
Position	**Mean (SD)**	**Std. Deviation**	**Mean (SD)**	**Std. Deviation**	**Mean (SD)**	**Std. Deviation**
PI	35.8(3.30)	0.88(1.92)	3.48(1.00)	0.45(1.20)	4.06(1.49)	1.34(1.81)
PII	41.5(5.21)	2.05(2.40)*	3.77(1.04)	1.41(2.01)*	11.3(2.30)*	4.70(2.10)*
PIII	35.1(3.78)	0.98(1.98)	3.70(2.99)	0.61(1.83)	5.47(1.90)*	4.73(2.08)*
PIV	43.7(4.29)	2.70(2.65)*	3.10(1.78)	1.17(0.88)*	4.57(1.40)	4.76(2.10)*
PV	43.4(4.54)	2.73(2.76)*	3.95(1.08)	1.26(1.10)*	4.72(1.10)	4.86(2.22)*

Table 4-5 Mean ranges of motion of the pelvis with its SD in all three planes for 5 subjects are given. The average of standard deviations of ranges of motion for all 5 subjects for each digitised position is also given (*represents the significant differences, p<0.05).

The within-day CMC for pelvic rotation in all three planes were calculated and they were all greater than 0.80 which indicates a good consistency and repeatability of the waveforms patterns obtained in the five trials for each subject (Table 4-6). The CMC values were interpreted as follows (Garofalo et al., 2009).

- 0.95<CMC<1 Excellent
- 0.85<CMC<0.95 Very good
- 0.75<CMC<0.85 Good
- 0.65<CMC<0.75 Moderate

	Pelvic tilt (X)		**Pelvic obliquity (Y')**		**Pelvic rotation (Z")**	
Position	**Within-day CMC**	**CMD**	**Within-day CMC**	**CMD**	**Within-day CMC**	**CMD**
PI	0.99(0.02)	0.56 (0.16)	0.86(0.01)	0.52 (0.26)	0.89(0.02)	0.50 (0.21)
PII	0.93(0.08)		0.83(0.27)		0.88(0.71)	
PIII	0.96(0.13)		0.88(0.05)		0.78(0.06)	
PIV	0.88(0.12)		0.86(0.03)		0.83(0.13)	
PV	0.86(0.05)		0.86(0.02)		0.82(0.09)	

Table 4-6 Within-day CMC and CMD values for pelvic movement during the picking up the box task for all five positions of digitisation are given.

There were no significant differences between the within-day CMC for the positions of digitisation for all rotations ($x^2(4)=2.600$ $p=0.085$). No significant differences were found for CMD values for each pelvic movement ($x^2(4)=1.650$ $p=0.230$).

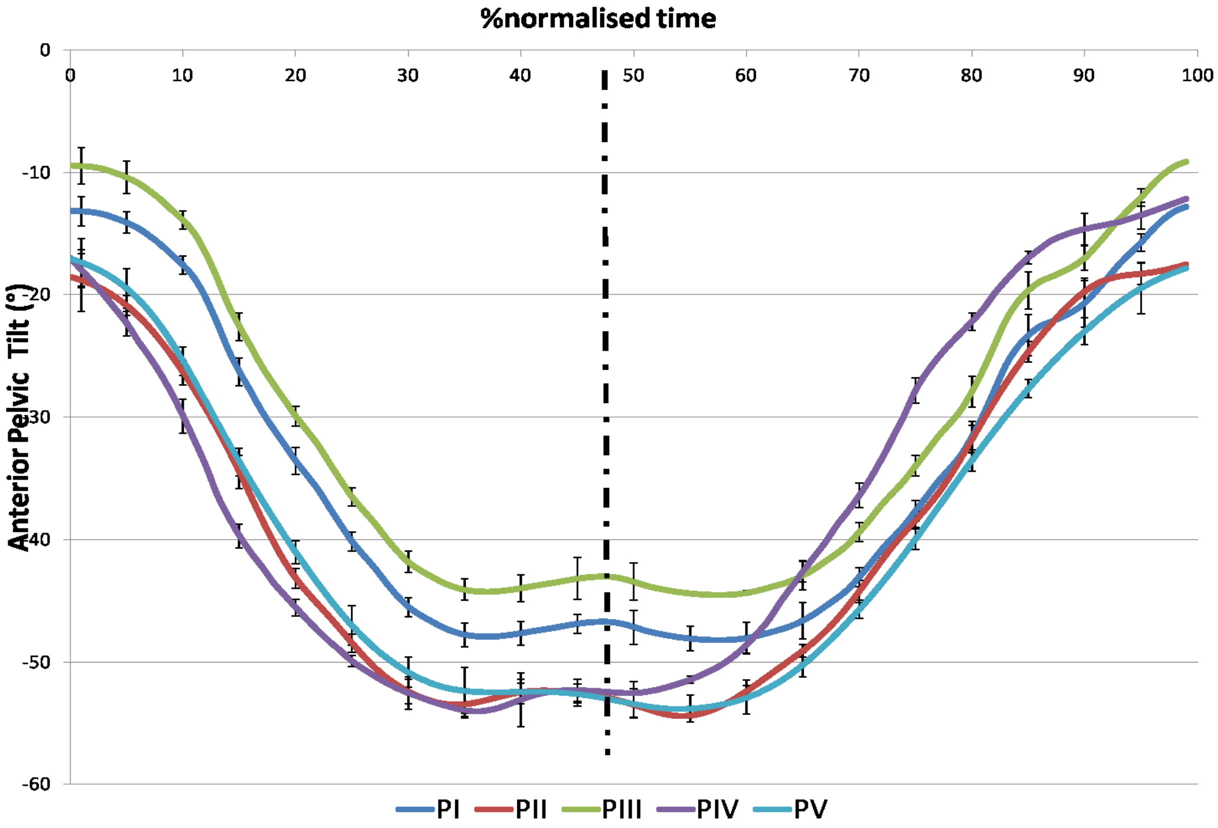

Figure 4-21 Anterior pelvic tilt for one subject plotted against normalized% of picking up the box activity for every digitised position of ASIS (PI to PV), dotted line represent the time that the subject reached to the box as defined by the markers placed on the hand and box.

One of the primary aims of this study was to establish the effect of single calibration on pelvic kinematics. The original CAST protocol was usually carried out in a neutral position (while the subject stands in an upright posture) independently of physical exercise to be performed. In this study different orientation of the pelvis were used to digitise the ASIS positions and their effects on pelvic kinematics were investigated. During the task (picking up a light box by bending knees), PII, PIV and PV were found to measure a greater ROM of the pelvis in the sagittal plane (pelvic tilt) which suggest that the relative movement between the cluster and underlying bone affects the digitised landmarks at these pelvic orientation. In PI, the maximum anterior pelvic tilt achieved was -46.8° (±1.88) while it was -54.5° (±2.73) for PII. In PIII, in which the pelvis is fully extended (posteriorly tilted), the maximum pelvic tilt achieved during the task was -43.1° (±1.86); there is no significant difference between the maximum pelvic tilt for PI and PIII ($p=0.320$). This can be justified as the pelvic extension was achieved by flexing the femur rather than moving the trunk. The effect of skin motion in different pelvic orientations was investigated and it was shown that the cluster position in PII, PIV and PV was more affected by skin motion than in PI and PIII. The skin movement over the sacrum can be used to explain the over- and under-estimation of maximum pelvic tilt in PII, PIV and PV. Errors in calibrating the ASIS positions can also propagate to the kinematic data, Figure 4-21 shows the kinematic waveform for different pelvic orientation when the subject picks up a light box. The vertical off-sets between the waveforms represent the errors in anatomical landmarks palpation as well as skin movement over the sacrum.

When a subject completes the task there should be a limited movement in frontal and transverse plane as the task involves a motion of pure pelvic tilt. All five positions showed a limited pelvic obliquity and there were no significant differences between the result obtained (p=0.710); while there was significant pelvic rotation in PII in comparison to the rest of the positions (p<0.05). As well as kinematic data, the mean SD was used to compare the within-trial variability of each position. The most significant variability between the digitised positions was observed in pelvic tilt; the within-trial variability of the ASIS positions which digitised with the pelvis in neutral position (PI) or with the pelvis extended (PIII) was significantly lower in the sagittal and frontal planes. The within-day CMC values for pelvic tilt with range of 0.90 - 0.99 were also an indication that the curves obtained in all 5 trials for each subject were reproducible for all digitisation positions. The CMD values for each rotation measure the similarity among the waveforms acquired by five positions of digitisation. There were no significant differences found for all rotations. This concludes that digitising the ASIS positions using a single calibration in neutral position of the pelvis has more promising results especially when measuring changes in the frontal and transverse planes as the propagation of STA and landmark mislocation mainly affects the joints characterised by a small range of motion (Cappozzo et al., 1995). Table 4-7 summarises the final results for this section.

Pelvic movement	**PI (Neutral)**	**PII (Tilted by trunk)**	**PIII (Tilted by femur)**	**PIV (Rotated to left)**	**PV (Rotated to right)**
Tilt (X)	Good	Bad	Good	Bad	Bad
Obliquity(Y')	Good	Good	Good	Good	Good
Rotation (Z")	Good	Bad	Bad	Bad	Bad

Table 4-7 Summary of the results in Section 4.6. Good represents low standard deviation.

4.8 Study IV: Single and double anatomical landmark calibration

4.8.1 Aim and objectives

It has been shown that optimal calibration parameter and technical markers configuration are time-varying due to the displacement of the markers with respect to the underlying bone (Cappello et al., 1997). Therefore it is necessary to improve the reconstruction of anatomical landmark trajectories by performing multiple calibrations of anatomical landmarks for different ranges of movement of the body segment as originally proposed by Cappello et al. (1997) to compensate for STA in lower limb kinematics during cycling. This idea was derived as a result of the concept that the soft tissues around calibrated anatomical landmarks tend to move with respect to the underlying bone following a quasi-linear loop (Cappello et al., 1997). During the calibration process the landmarks are calibrated at the two extremes of the expected range of motion (once with the closest joint flexed and once when extended), then the positions of anatomical landmarks between these configuration are calculated by linear interpolation in time. One study has also proposed a novel compensation technique to reduce STA on knee kinematics based on the double anatomical landmark calibration in which the shape and the position of the anatomical landmarks relevant to the technical frame is assumed to change significantly during motion. Therefore the calibration of the anatomical landmarks are performed in two body postures within the expected range of motion in the specific task which reported the RMSE in order of 1°-2° for knee rotations (Cappello et al., 2005). In another study conducted by Stagni et al. (2006) the position of the anatomical landmarks of the thigh and shank were calibrated in two different positions, while shank and thigh were fully flexed and fully extended (Stagni et al., 2006). It has been shown in the previous studies that the double calibration of anatomical landmarks significantly compensates for the effects of STA on knee rotations and translation by 20° and 15 mm, respectively (Cappello et al., 2005, Stagni et al., 2006). While there are number of studies that investigated the effect of double calibration on the lower limbs, no study has reported its effect on pelvic kinematics.

The aim of this study was to compare the effect of single anatomical landmark calibration and double anatomical landmark calibration on pelvic kinematics.

4.8.2 Materials and methods

4.8.2.1 Study population

Five male subjects from Imperial College London participated in this study. Their mean age was 24.8 years (range: 19-27) and mean BMI was 21.1 kg/m^2 (range: 19.2-24.0 kg/m^2). The experiment took place at the Motion Analysis Laboratory at Imperial College London as described in the previous sections. An optical motion tracking system (Vicon, Oxford, UK) was used at an acquisition rate of 150 Hz. Reflective markers were attached to bony landmarks on the femur and pelvis (Section 4.7.2.2) using double sided tape and adhesive spray.

4.8.2.2 Experimental protocol and data analysis

The experimental protocol and data analysis defined in Sections 4.6.2.4 and 4.7.2.5 was also used in this study. Each subject was asked to complete a task which was picking up the light box by bending their knees. Single calibration of ASIS positions were performed as explained in Section 4.7.2.4 which includes: PII- pelvis tilted anteriorly by bending trunk forward, PIII-pelvis tilted posteriorly by flexing the femur, PIV- pelvic rotation to the left, PV-pelvic rotation to the right. In the double anatomical landmark calibration method, two body postures are identified within the expected full range of motion which is typically the two extremes of motion. The linear interpolation can be performed between the two calibrations as it is assumed that the local coordinates of the anatomical landmarks in the relevant technical frame and the shape of the cluster change in a linear manner during the motor task between the two selected extreme postures (Cappello et al., 2005). The segmental coordinate frames were defined as described in Section 4.5.2.4, and pelvic angles were calculated using Euler angles with the Cardan sequence of X-Y'-Z''. The data for each trial were then normalised to 100% of the time of activity which is 20ms prior to start the task to 20ms after finishing the task. The range of the motion and maximum pelvic movement were averaged over the 5 trials and presented as mean pelvic angles. The repeatability and variability of the data were tested by calculating the SD among the five trials for each subject and presented as mean SD.

4.8.2.3 Statistical analysis

The within-day CMC and CMD were used to evaluate the similarity of the kinematic waveforms among five trials generated for each subject (Section 4.7.2.4). Non parametric Friedman's ANOVA was used to investigate any differences between the values obtained with alpha level set at 0.05.

4.8.3 Results and Discussion

The single calibration were calculated using position I, while for the double calibration two positions were used, including PII and PIV. The within-day CMC values for anterior pelvic tilt were 0.99 (±0.02), 0.97 (±0.01) and 0.98 (±0.01) for single calibration, double calibration of PI-II and double calibration of PI-IV, respectively. Also high similarities of the kinematic waveforms were obtained for the pelvic obliquity and pelvic rotation with average value of 0.80 (±0.12). There were no significant differences between the mean ranges of motion of the pelvis for all three methods (p=0.412). The similarity of the kinematic waveforms was compared between each method using CMD values. There were no significant difference between the CMD value obtained for single/double (PI, PII) and that of the single/ double (PI, PIV); these values are 0.56 (±0.26) and 0.51 (±0.39), respectively ($x^2(2)$=1.570 ,p=0.640)..

The summary of the results for the mean ROM of the pelvis and SD are given in Table 4-8.

	Pelvic tilt (X) (in degrees)		**Pelvic obliquity (Y') (in degrees)**		**Pelvic rotation (Z") (in degrees)**	
Method	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**
Single calibration	35.8 (3.30)	0.88 (1.92)	3.48 (1.00)	0.45 (1.20)	4.06 (1.49)	1.34 (1.81)
Double calibration (PI, II)	36.1 (2.15)	1.81 (0.98)	5.6 (1.01)	3.72 (1.23)	5.01 (1.81)	2.5 (1.07)
Double calibration (PI,IV)	33.6 (2.03)	1.98 (1.50)	4.80 (2.09)	1.55 (0.94)	4.89 (2.1)	1.23 (0.99)

Table 4-8 Mean ranges of motion of the pelvis in all three planes are presented for single and double calibrations.

In this study the effect of double calibration of anatomical landmarks on pelvic kinematics were investigated and the results indicated that the intra-repeatability of the methods were similar and no significant differences were reported between the models (Figure 4-22).

For the single calibration, the result of previous study (Section 4.7) showed that digitisation of the ASIS position in neutral position is more repeatable and has less variability between the trials. Therefore in this study the double calibration was performed between this position (PI) and PII (pelvis fully tilted anteriorly). And the second double calibration was performed between the PI and PIV (pelvis fully rotated to the left).

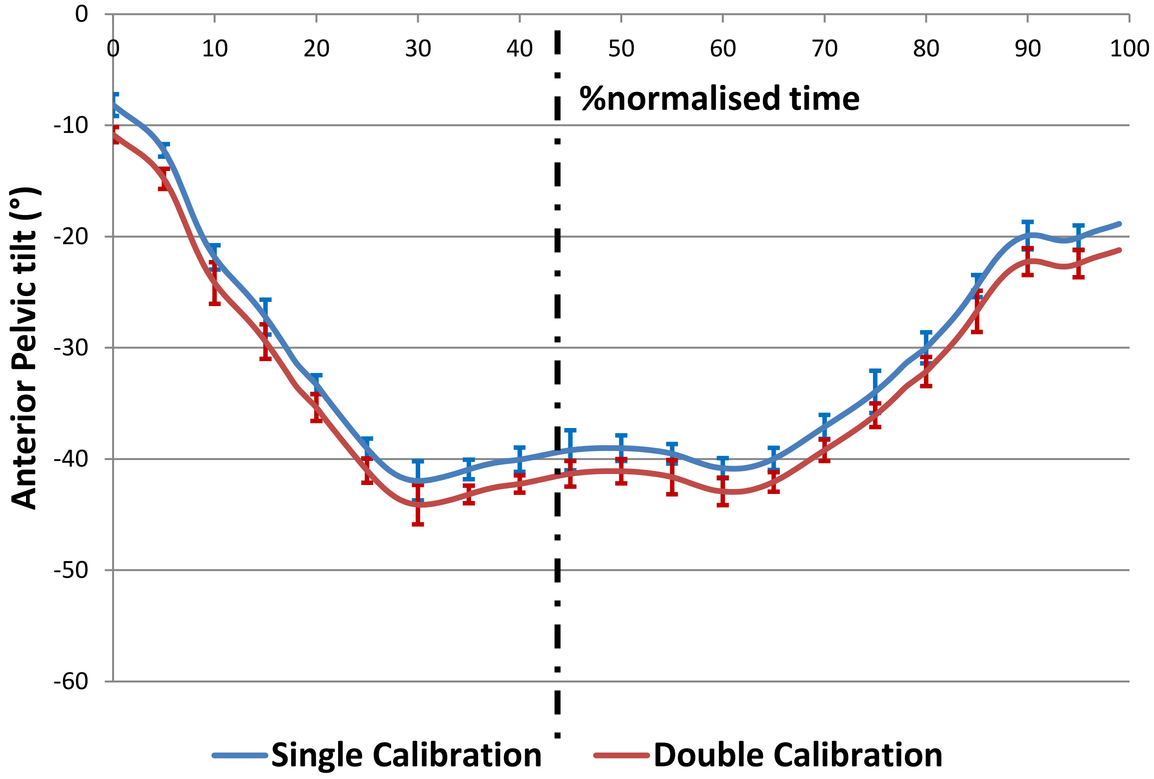

Figure 4-22 Kinematic waveform of anterior pelvic tilt single and double calibration (PI, PIV) for one subject averaged over 5 trials and standard deviations are shown as error bars for both graph. The black dashed line is representing the time that the subject reaches the box.

Since the STA and its effect on pelvic kinematics are strongly dependent on the motor task under analysis, it can be useful to investigate the effect of other tasks such as cycling, stair climbing and running on pelvic kinematics. Also the effect of calibrating the anatomical landmarks of the pelvis in other pelvis orientation should be investigated (medial and lateral pelvic obliquity). The previous studies that examined the effect of double calibration on knee kinematics have shown that this method improves the accuracy in knee kinematic by limiting the propagation of STA to knee kinematic due to anatomical landmark misplacement (Stagni et al., 2006) therefore this method could be used to improve the reliability of pelvic kinematics for an inexperienced examiner.

4.9 Summary

Different simplified marker sets and related model have been used in kinematic gait analysis. The majority of these models were developed with low resolution imaging systems therefore various assumption are required to minimize their limitations include STA and anatomical landmark misidentification. In kinematic studies of the pelvis the position of the RASIS and LASIS increase the difficulty of measuring pelvic movement due to occlusion of the anatomical landmarks during the dynamic trials. An alternative marker set and its kinematic model was proposed and developed in this chapter and its sensitivity to pelvis orientation (by digitising the specific anatomical landmarks, single and double anatomical landmark calibration and different size of calibrating wand) was quantitatively assessed through indirect measurement approaches by calculating the range of the pelvic motion and its maximum motion in all three directions.

The developed method was found to be sensitive to the position of the pelvis during the digitisation of its anatomical landmarks. It was shown that digitising the ASIS position with the pelvis in neutral position has less variability to any other orientation. The STA associated with the movement of the cluster on the sacrum was less when the ASIS were digitised in the neutral position of the pelvis (PI) and when the femur was flexed (PIII). The result for single and double anatomical landmark calibration showed that there were no significant differences between the intra-repeatability of the two methods. In this study the effect of digitising the positions of PSIS on pelvic kinematic was investigated in which the results showed that there were no significant differences between the kinematics data obtained using the PSIS position directly (from PSIS markers in static trial) and digitising the PSIS position.

As discussed before, anatomical landmark misplacement introduces uncertainties that will propagate to joint kinematic as STA. Therefore the precision of manual palpation procedures of the pelvis could be improved by using smaller pointer (L-frame). This study investigated the effect of calibrating the anatomical landmarks using two pointers with different dimensions. Even though both methods showed no significant differences in the calculated kinematic data but the smaller pointer appeared advantageous.

To conclude, the sensitivity of the proposed technique and its kinematic model was investigated and its effect on kinematic data was shown. To validate the technique its repeatability, reliability and reproducibility should be tested and compared to previous methods. Therefore in subsequent chapter, the new technique will be validated whilst the positions of the ASIS will be digitised using S-Pointer in the neutral position of the pelvis and PSIS positions will be digitised using skin markers directly.

Chapter 5*

Pelvic tracker validation

Aim In the previous chapter a kinematic model to measure pelvic motion using a pelvic tracker was developed and the sensitivity of a novel model to calibrate the anatomical landmarks was investigated. The aim of this chapter is to validate the pelvic tracker by investigating its repeatability and reliability within different body weight groups as well as among different activities of daily living.

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5.1 Introduction

Over the past decade the understanding of how the pelvis moves during gait has improved despite a lack of clearly defined measurement standards. The most commonly used model in gait analysis is the kinematic model described by Kadaba et al. (1990) and Davis et al. (1991). In the latter model, calculation of lower limb kinematics is based on the anterior superior iliac spines (ASIS) to estimate the position of the hip joint centre which is then used in the calculation of femur and knee joint rotations. Therefore, occlusion of these markers for all or part of the trial will result in loss of some data. Occlusion of the ASIS could be as a result of soft tissue around the anterior abdomen (a common issue in overweight and obese subjects), arm movement, or activities that require high degrees of hip and trunk flexion, such as running or stair climbing (Saari et al., 2005). One known modification to overcome ASIS occlusion is to introduce two technical markers to the pelvis positioned an equal distance laterally and posteriorly to the ASIS marker (often placed on the iliac crest as discussed in Chapter 3) (McClelland et al., 2010). In order to use these technical markers, the ASIS marker positions can be expressed in relation to a technical coordinate system created using the technical markers in a static trial where the subject is stationary for couple of seconds with both anatomical and technical markers on the pelvis. However, having these technical markers on the lateral side of the waist does not guarantee reliable results, as again this is a site for fat deposition and consequently a substantial amount of fat and skin tissue can be present.

There are no reports to date on how reliable this method is for overweight and obese subjects. Generally, in previous studies, minimizing soft tissue artefacts for overweight and obese subjects when performing motion analysis during different functional activities has not been reported. Another measurement method that has been used previously is a triad of markers directly placed on the posterior aspect of the pelvis. This was used to define directly the pelvic anatomical coordinate frame (Frigo et al., 1998; Pohl et al., 2010) but it was noted that this may not be the most reliable method to define the pelvic movement as the location of the triad of markers on the segment surface has no anatomical relevance and must satisfy some key requirements to be anatomically relevant (Cappozzo et al., 1995). A potential solution to this problem is the use of a cluster of three orthogonal markers attached to a rigid based as technical markers (sacral cluster) as proposed in Chapter 4. The ‘Cluster’ is attached to the sacrum as this provides more accurate results than the ASIS and has less skin artefact (Bull et al., 2000). Use of the ‘calibrated anatomical system technique’ (CAST) (Cappello et al., 2005; Benedetti et al., 1998) allows the position of ASIS to be defined relative to the Cluster in a static trial and then during dynamic trials the position of the ASIS is linked to the Cluster and thus affected by the same skin movement artefact that affects the Cluster (Cutti et al., 2006). The aim of this study is to compare the ‘Cluster’ method with the ‘Traditional’ method, which is the use of four surface markers on the right and left anterior superior iliac spine and left and right posterior superior iliac spine, in a population of healthy volunteers with varying BMI. Different BMI groups (normal, overweight and obese) are included in this study to investigate the effect of the soft tissue and skin movement around the abdomen on repeatability and reliability of the kinematic data as discussed previously in Chapters 3 and 4.

5.2 Material and methods

5.2.1 Study population

Thirty healthy subjects participated in this study (mean± SD age and BMI of 32.5±12.3 years, and 26.39±4.20 kg/m², respectively). They were divided in three equal groups of normal, overweight, and obese according to their BMI (normal 19-24 kg/m², overweight 25-27 kg/m², and obese 28-35 kg/m²). These levels correspond to National Health Service guidelines. Table 5-1 presents a summary of study participants’ demographics. None of the subjects had any history of lower back pain, surgery to the hip or lower limbs. They had no musculoskeletal injuries or disorders that affect walking ability. Written informed consent was obtained prior to participation. This study was approved by the Imperial College Research Ethics Committee (ICREC).

N=30	**Age**		**BMI** (kg/m²)		**Gender**	
	Mean (SD)	**Range**	**Mean (SD)**	**Range**	**Female**	**Male**
Normal	25.3 (7.89)	18-44	21.7 (1.77)	19.0-23.6	6	4
Overweight	37.3 (13.2)	18-55	26.3 (0.97)	25.0-27.9	5	5
Obese	34.9 (12.8)	18-60	30.9 (2.94)	28.1-35.9	2	8

Table 5-1 **Subjects details**

In this study each subject completed three sessions, each one week apart.

5.2.2 Equipment, lab set up and subject preparation

The optical motion tracking system as described in Chapter 4 (Study I-V) was used to track reflective markers attached to the bony landmarks on the pelvis and femur (Figure 5-1). Data were acquired at 150 Hz. The same assessor carried out all data collection and analysis.

Figure 5-1 An optical motion tracking system consisting of 9 high speed cameras at an acquisition rate of 150Hz was used together with spherical reflective markers of 14 mm in diameter.

Before each session, the subjects were weighed and their height was measured. Spherical reflective markers of 14 mm in diameter (Figure 5-1) were applied concurrently in the following configuration: (a) RASIS, LASIS, LPSIS, and RPSIS (Traditional); (b) a rigid cluster of three markers on sacrum (Cluster). In addition, four markers were attached to the femur as summarised in Table 4-1 and three markers were attached to bony landmarks on the right and left foot to determine toe-off events. These were the 2nd Metatarsal, 5th Metatarsal and Calcaneus. Marker locations are shown in Figure 5-2.

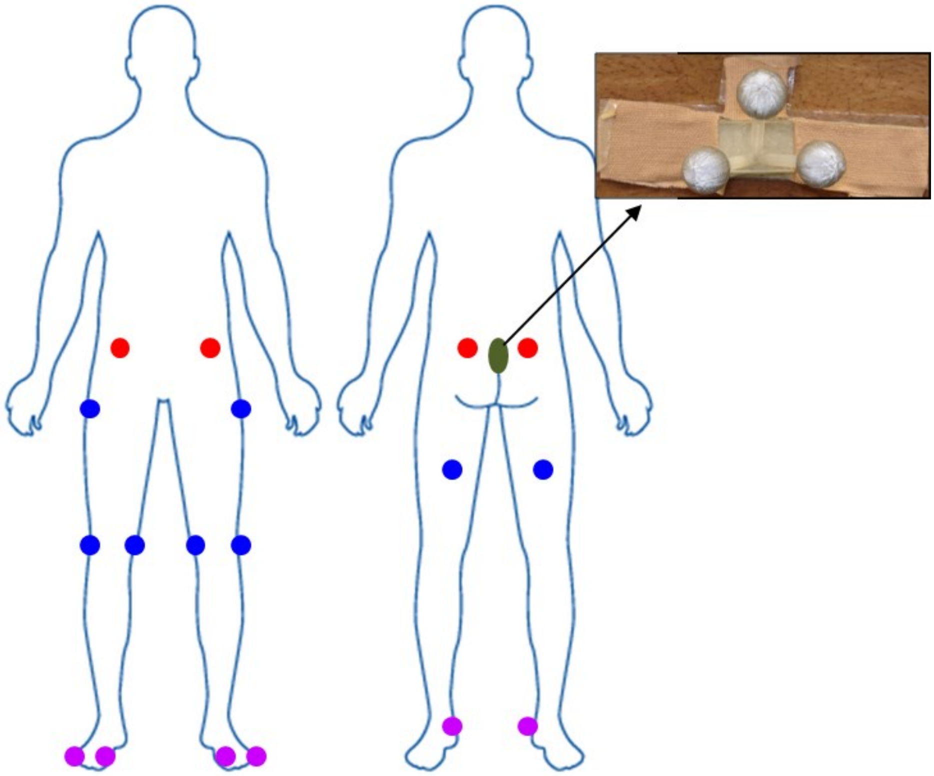

Figure 5-2 Schematic of marker set up. The markers in red ● are anatomical landmarks that were used in the Traditional method. The green colour ⬮ represents the position of the marker cluster used in the Cluster method. The blue ● represents the marker positions on the femur. The pink ● markers were used to determine the toe off events. (Modified from SOLARAZE GEL)

5.2.3 Experimental protocol

The experimental protocol for this study is the same as the one described in Chapter 4 (Study I) with some modifications. After setting up the laboratory and preparing the subjects, two static trials were obtained to calibrate the positions of ASIS with respect to the sacral cluster with the subject standing in the upright position as described in Chapter 4 (Study II). Following this, another static trial was taken with the subject standing still with the arms hanging next to the body with two sets of markers applied concurrently. This trial was used to 1) label the marker for post processing, and 2) define the positions of PSIS with respect to the sacral cluster for the Cluster method. The post processing of these trials are described in Section 4.5.2.4.

A dynamic trial was captured in order to estimate the HJC. In this trial the subject was asked to move rotate the femur about the pelvis (i.e. move the hip joint) in all planes The movements were: flexion/extension, abduction/adduction and circumduction whilst trying to maintain the pelvis as static as possible. The HJC was calculated the same way as describd in Section 4.5.2.4 (Figure 5-3).

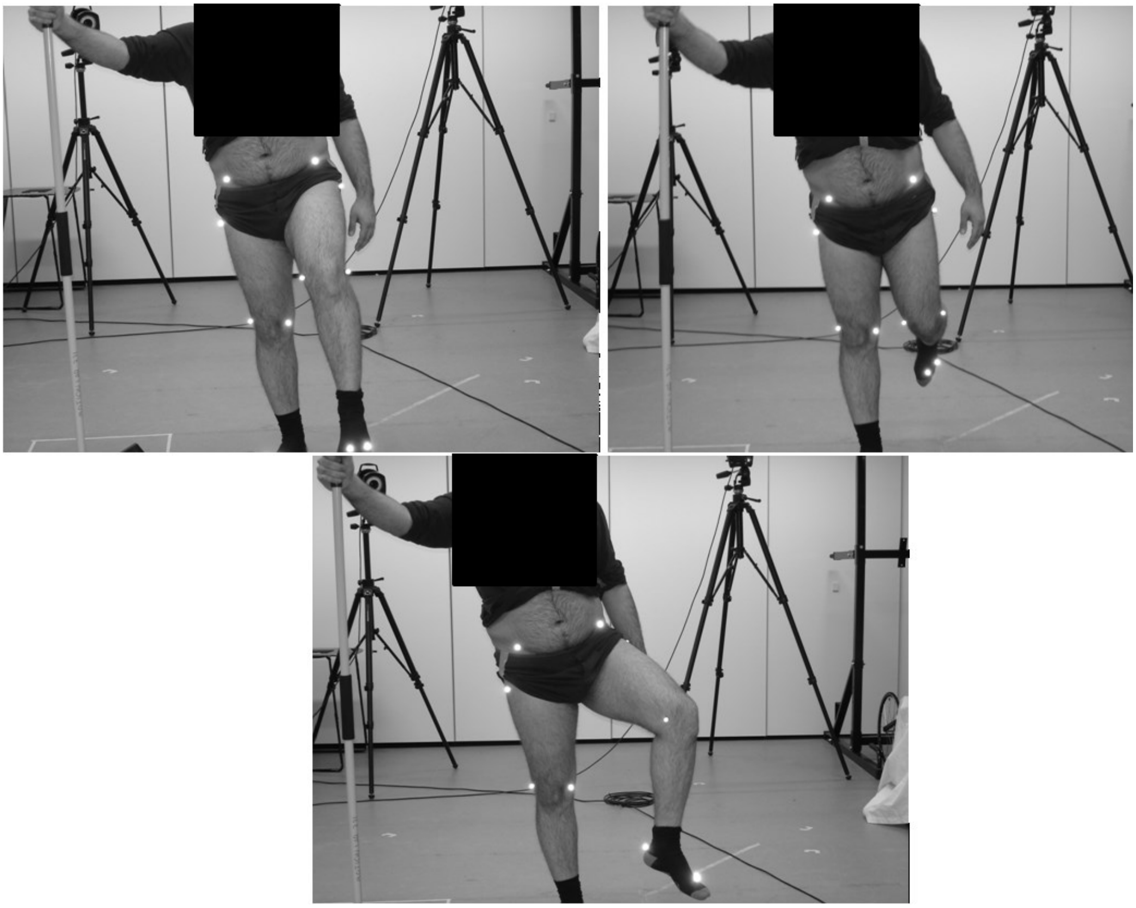
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Figure 5-3 Estimation of the HJC. The subject moves the femur in such a way to explore the full range of hip joint motion in different planes. The knee was held flexed at between 60-90°

After completing the static and dynamic trials to digitise the landmarks and estimate the HJC, subjects were asked to complete eight different activities of daily living (ADL); each ADL was repeated five times in each session. These activities are described below.

5.2.3.1 Walking

The subjects were asked to walk at their self-selected speed for 3 metres (Figure 5-4) along the walkway in the Motion Analysis Laboratory at Imperial College London. Only one gait cycle between two successive left toe-offs was processed and the time was normalised from 0% to 100% of the gait cycle.

Figure 5-4 **Illustration of the walking of the participant**

5.2.3.2 Reaching toes (Toe)

One of the chosen activities of daily leaving was reaching toes without bending the knees. In this activity the pelvis reaches the full range of movement in the sagittal plane. The data were time normalised to 100% of the pelvis movement defined from 20 ms prior to bending to 20 ms after finishing the task. Figure 5-5 shows the subject completing the task.

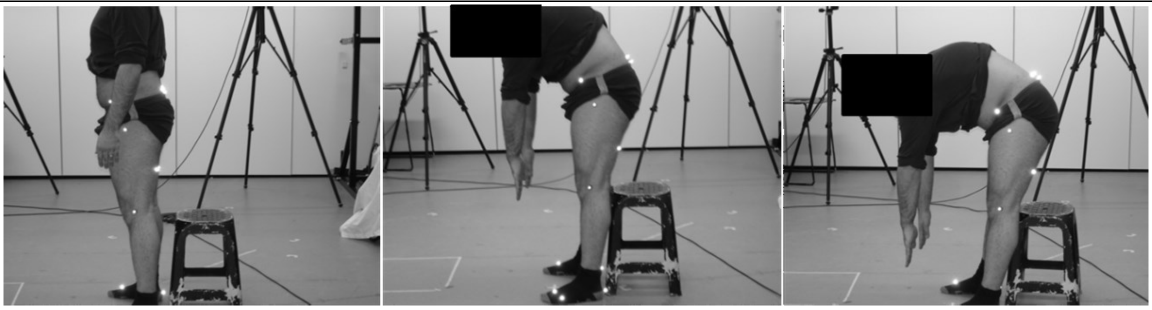


Figure 5-5 **Toe reaching without a knee bend**

5.2.3.3 Sit-to-stand and stand-to-sit (STS)

Another activity that subjects were asked to complete was rising from a seated position and returning to the seated position. Figure 5-6 shows a subject completing the task. On the instruction of the investigator the subject stood from the backless stool (height of 46 cm) and returned to sitting.

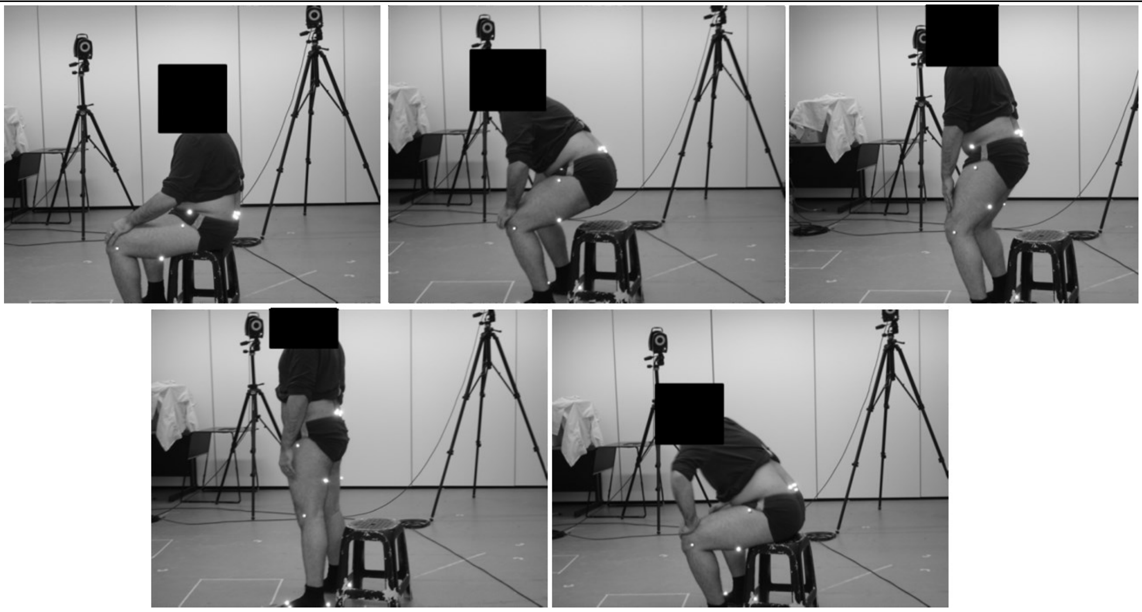


Figure 5-6 **Subject is rising from the seated position, then started to sit down**

The data for this activity was normalised from 0% to 100% of the pelvis movement defined from 20 ms before standing to 20 ms after finishing the task.

5.2.3.4 Squat

Subjects were asked to squat from a standing position until their legs touched the stool, as soon as the legs touched the stool the subject was instructed to return to the standing position (Figure 5-7).

Figure 5-7 **The subject is squatting until the legs touch the stool**

The data from this activity was normalised in the same way as the Toe and STS.

5.2.3.5 Picking up a box (Box)

For this activity the participant was instructed to bend their knees while lifting a light box (Figure 5-8). The aim of this activity was to investigate the range of the movement of the pelvis while comparing the kinematic waveforms obtained using the two protocols (the Traditional and Cluster methods).

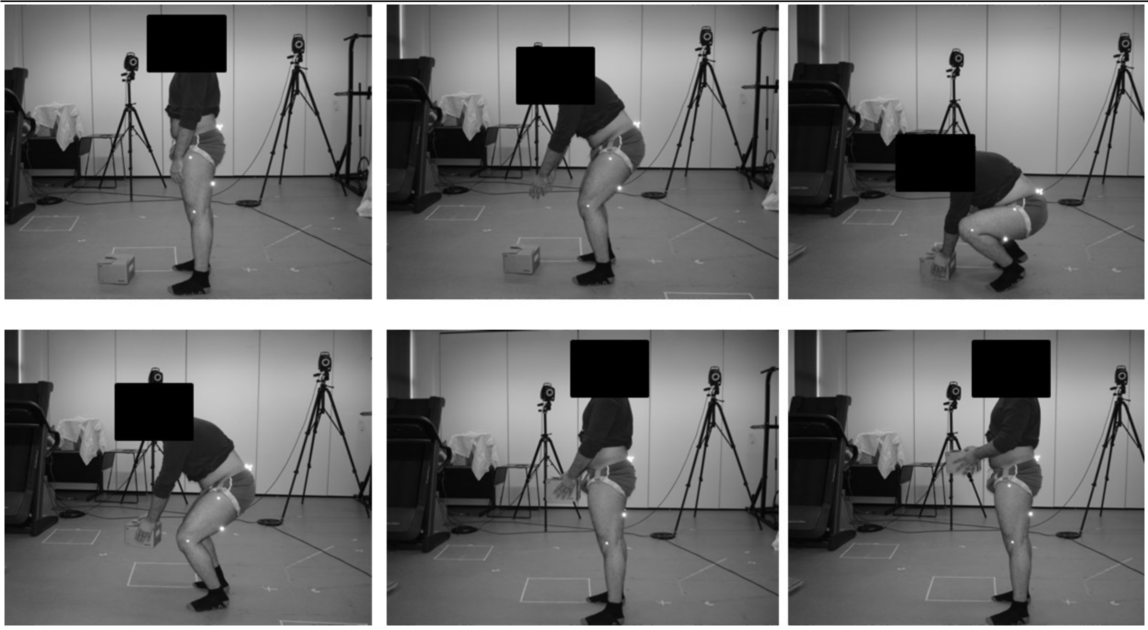


Figure 5-8 A participant picking up a light box while bending the knees

5.2.3.6 Stairs ascending (Stairs-up)

In this study bespoke steps were designed and manufactured. The subject was asked to go up the stairs (steps), each time starting with the right foot (Figure 5-9). The data was then normalised from 0% to 100% of the gait cycle between two successive left toe-offs.

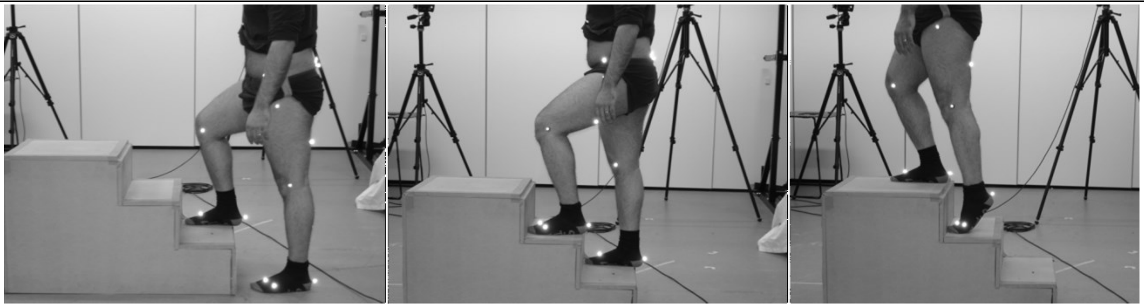


Figure 5-9 Ascending the stairs staring with the right foot

5.2.3.7 Stairs descending (Stairs-down)

The participants were asked to descend the stairs (steps) starting with their right leg (Figure 5-10). The data were normalised from 0% to 100% of gait cycle as described in Section 5.2.3.6.

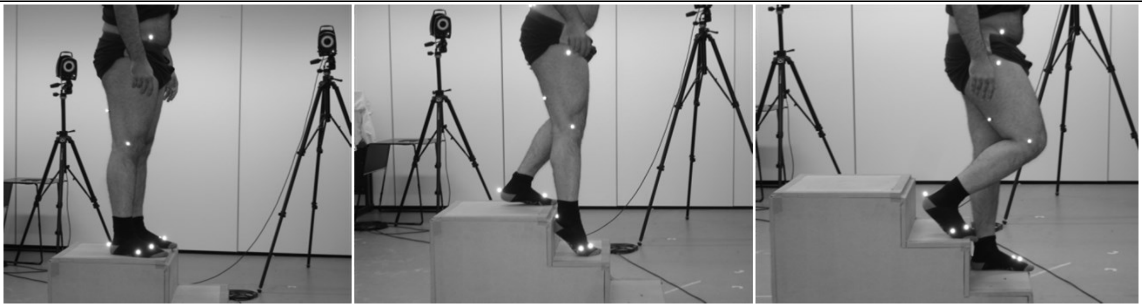


Figure 5-10 Descending the stairs starting with the right foot

5.2.3.8 Time up and go (Time up)

The participant was asked to rise from a backless stool, walk for 2 metres, turn and return to the stool and sit down (Figure 5-11). They were asked to complete this task as fast as possible. To investigate the effect of the speed on the two marker sets, two consecutive gait cycles were chosen.

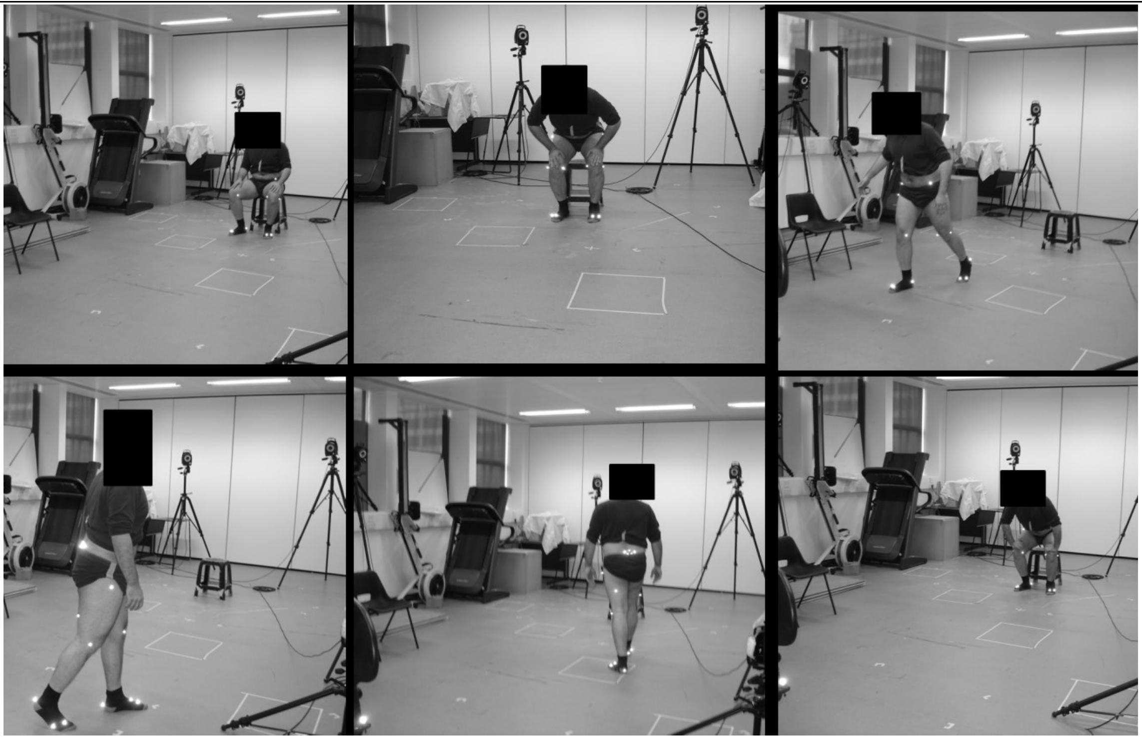


Figure 5-11 The participant stands from a backless stool, walks for two metres and returns back to the stool and sits down. The participant was asked to perform this activity as fast as possible.

The gait cycle in this activity was normalised in the same way as the walking, Stairs-up and Stairs-down.

5.2.4 Data Analysis

Most of the data analysis in this chapter was completed in the same way as described in Chapter 4. The calibrations of the ASIS positions as well as estimation of the HJC were described in Section 4.5.2.4. There are however, a number of differences in data analysis in this study which are described below.

5.2.4.1 Digitisation of PSIS Positions

To digitise the positions of the PSIS with respect to the cluster, as described in Section 4.5.2.4, a technical coordinate frame was defined for the sacral cluster. Equations 4.6, 4.7 and 4.8 represent the X_C, Y_C and Z_C axes where the origin coincides with marker C1 on the sacral cluster (Figure 5-12).

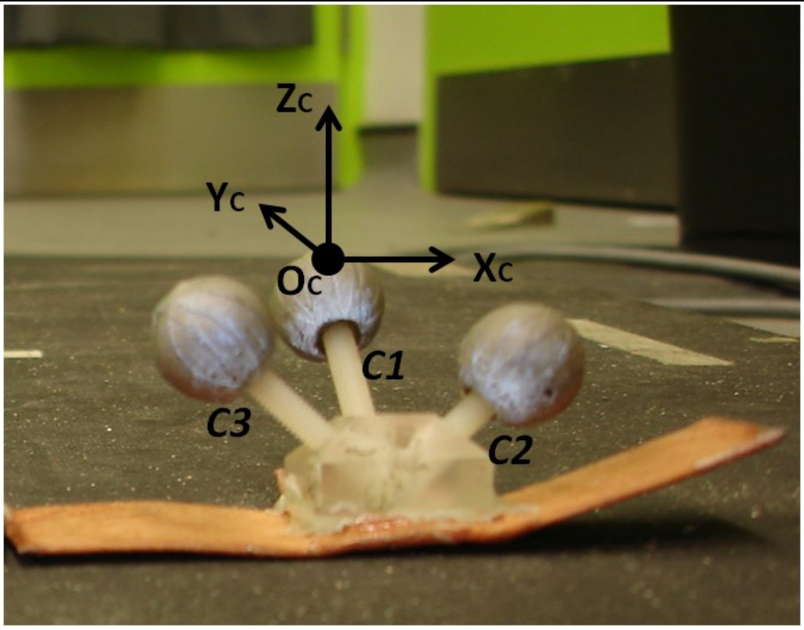


Figure 5-12 **Technical coordinate frame for the sacral cluster**

The position of each was then transformed from the global coordinate system to the technical coordinate frame suing the following equations:

$$\overline{\mathrm{LPSIS}}_{\mathbf{C}}=(\overline{\mathrm{LPSIS}}-O_C)\,T_{GT} \tag{5.1}$$

$$\overline{\mathrm{RPSIS}}_{\mathbf{C}}=(\overline{\mathrm{RPSIS}}-O_C)\,T_{GT} \tag{5.2}$$

Where the T_{GT} is the transformation matrix from the global coordinate system to the pelvis technical coordinate frame and was given in Equation 4.11. The calibrated positions of the LPSIS and RPSIS were then used to define the anatomical coordinate frame of the pelvis which is described in the next section.

5.2.4.2 Pelvic coordinate frame

As the aim of this study is to compare the Traditional marker set to the Cluster, two anatomical coordinate systems were defined which are as follows.

Traditional method

For the Traditional method the anatomical coordinate frames of the pelvis were defined according to the Cappozzo et al. (1995). The origin was defined at the midpoint between the LASIS and RASIS. The X-axis was defined as the line that connects the two ASISs pointing towards RASIS. The Z-axis is the line perpendicular to the plane defined by PSIS and ASIS pointing upwards. Finally, the Y-axis is the line perpendicular to the plane defined by X-axis and Z-axis, pointing forward. In this marker set the positional data obtained from each marker attached directly to the pelvis is used to calculate the pelvic kinematics.

Cluster method

The aim of the Cluster method is to digitise the anatomical landmarks of the pelvis with respect to the sacral cluster in order to minimise the effect of soft tissue artefacts. Therefore, as the subject moves during the dynamic trials, the positions of ASIS and PSIS markers were defined relative to the technical coordinate frame of the sacral cluster and later these relative positions were used to define the anatomical coordinate frame for the Cluster method. The origin of the anatomical coordinate frame for the Cluster method was defined as a midpoint between the $LASIS_C$ and $RASIS_C$ (**c** represents the digitised landmarks). The X-axis is defined as a line connecting $LASIS_C$ and $RASIS_C$ pointing towards $RASIS_C$ (Equation 4.12). The Z-axis is the perpendicular line to the plane defined by $PSIS_C$ and $ASIS_C$, pointing upwards (Equation 4.13). Finally, the Y-axis is the cross product of the Z-axis and X-axis, pointing forward (Equation 4.15).

Figure 5-13 summarises the description of the anatomical coordinate frame of the pelvis for the two methods.

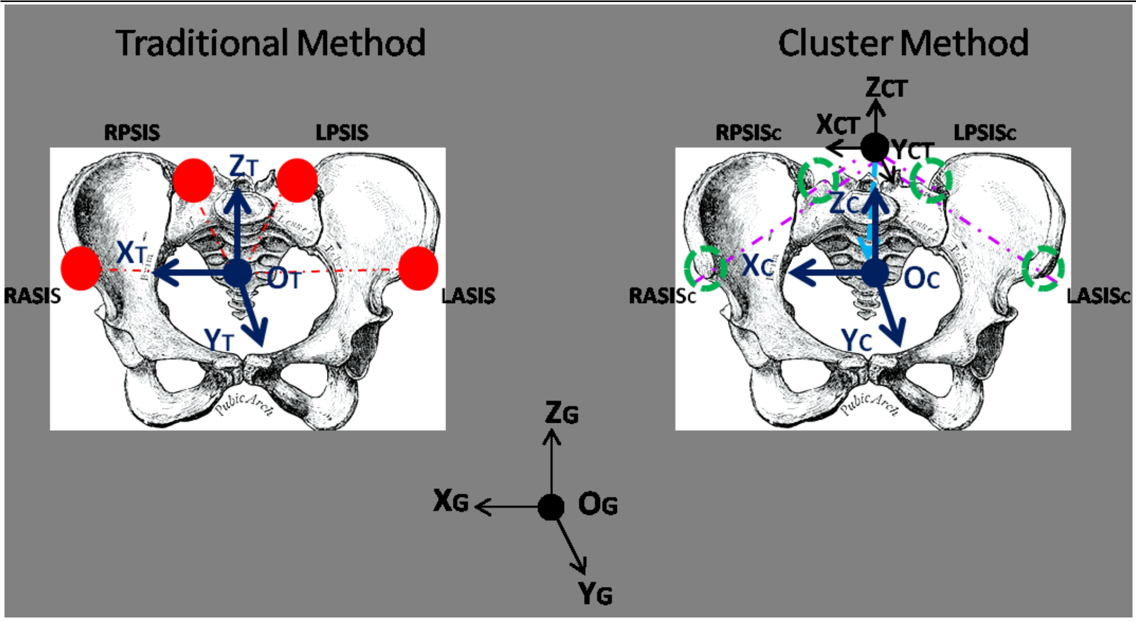


Figure 5-13 The two pelvis coordinate frames. The red circles represent bony landmarks that were used to define the anatomical coordinate frame of the pelvis for the Traditional method. The green dotted circles represent the digitised anatomical landmarks that were used to define the anatomical coordinate frame of the pelvis for the Cluster method. O_G, O_T and O_C represent the origin of the global coordinate frame, the origin of the anatomical coordinate frame of the pelvis for the Traditional method and the origin of the anatomical coordinated frame of the pelvis for the Cluster method, respectively. The light blue dotted line connects the origin of the technical coordinate frame of the sacral cluster to the anatomical coordinate frame of the Cluster method. Therefore, in the dynamic trials the orientation and position of the anatomical coordinate frame will be describe with respect to that of the technical coordinate frame of the sacral cluster (picture of the pelvis is adopted from Wikipedia,2012)

5.2.4.3 Pelvic rotation

Unfortunately the HJC data obtained for 7 subjects were corrupted (combination of occlusion of femur markers and data lost), thus to maintain the consistency between the data and make it more suitable for comparison purposes the pelvic rotation was calculated with respect to the global coordinate frame (laboratory coordinate frame).

Therefore the pelvic angles were calculated using the XY’Z’’ Cardan rotation sequence (tilt, obliquity, and rotation) which is the conventional sequence in many commercial gait analysis software packages (Vicon Clinical Manager, Oxford Metrics, UK) and previous studies (Lamontagne et al.,2011; McClelland et al., 2010).

5.2.4.4 Data normalisation

The three-dimensional trajectories of reflective markers attached to the bony landmarks produce a three-dimensional coordinate (X, Y and Z) of the markers in the global coordinate frame of the system at all time frames. Therefore the segment rotations were calculated for each time frame using the defined three-dimensional coordinate frames of the marker trajectories and then a graph can be plotted for the segment rotation against time (Figure 5-14).

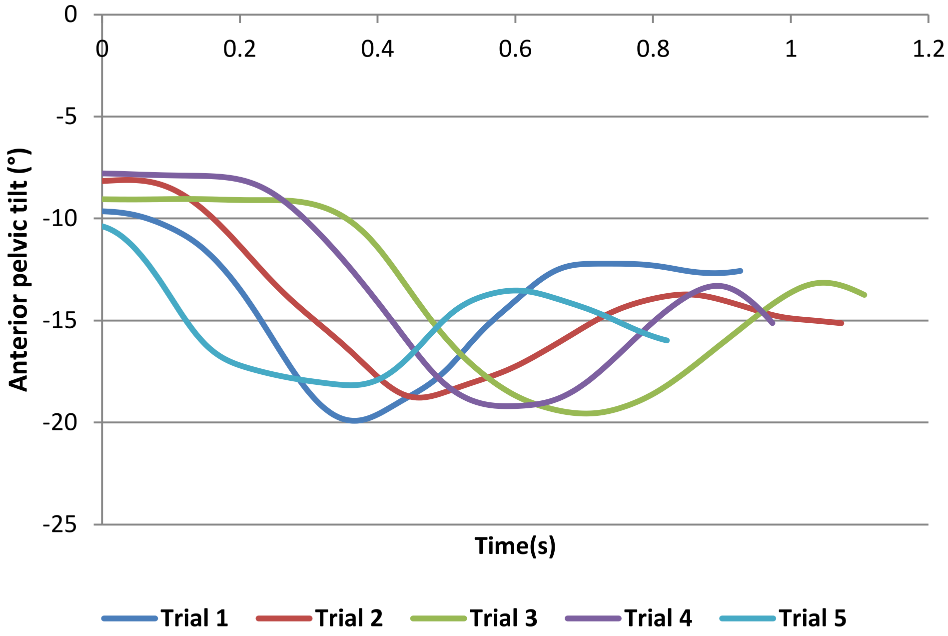


Figure 5-14 Anterior pelvis tilt plotted against time for 5 trials using the Traditional method during squatting for a single subject.

Figure 5-14 is the pelvic anterior tilt plotted against time during squatting. Five trials were carried out by the same subject. However, variation between trials caused by differences in speed, starting and finishing points can be falsely perceived as differences in rotations. To resolve the issues the data was normalised against time to 100% of the pelvic movement which was defined from 20 ms prior to start the task to 20 ms after finishing the task for the following activities: Toe, squat, Box and STS (Figure 5-15). For the remainder of the tasks the data for one stride of each trial were normalised from 0% to 100% of the gait cycle between two successive toe-offs (walking, Time up, Stairs-up and Stairs-down).

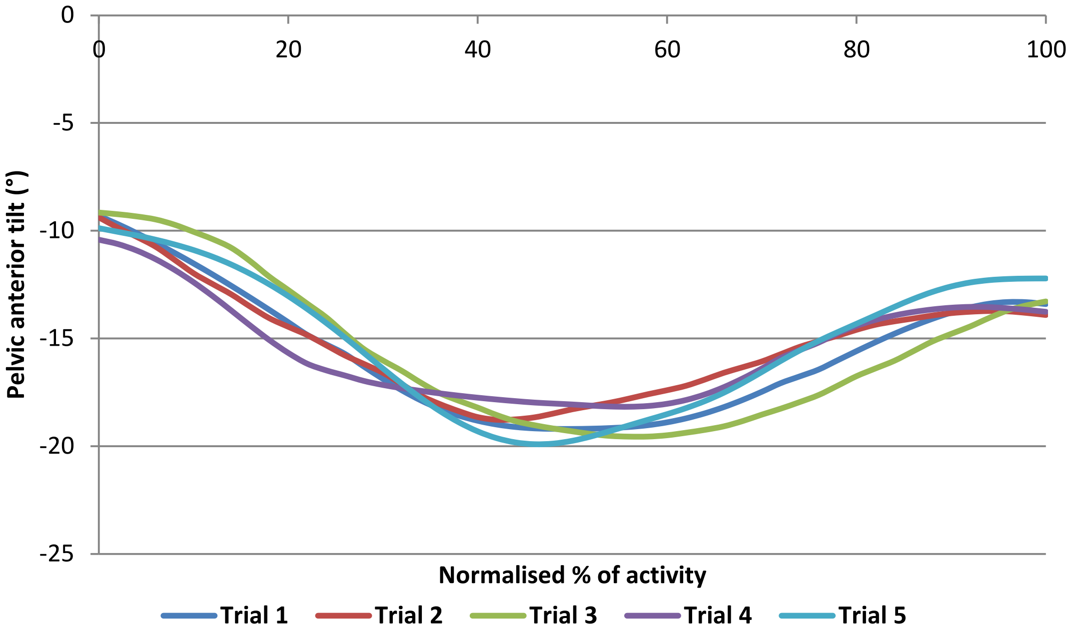


Figure 5-15 Anterior pelvic tilt during squatting as presented in Figure 5-14, but the data normalised against time of the completion of the pelvis movement

MATLAB (R2010a, The Mathworks, Natick, USA) was used in this section to normalise the kinematic data and the relevant codes are available in Appendix C.

5.2.4.5 Variables measured (mean and standard deviations)

The main objective of this study was to validate the Cluster method by examining the effect of the Cluster method on the reliability of the kinematic data and to compare it to the most common market set used to measure pelvic kinematic (Traditional Method). In this study, the reliability was assessed by investigating the within-sessions (intra-session) and between-sessions (inter-session) variations for each subject. To accomplish this, standard deviation was used as a measure of variability. For each subject, standard deviations of the range of discrete parameters were calculated using key features that were consistently identifiable in the sets (Traditional and Cluster) which were maximum and minimum of pelvic tilt, obliquity, and rotation. It was also decided to discard any trials that were partially or completely missing. If the number of missing frames were equal or greater than the half of the total frames in that trial, no interpolation would be done and data will be replaced by '×'. For example, if a walking trial has 800 frames and 450 of the frames are missing as a result of marker occlusion or STA, then the trial will be discarded and no longer will be used for further analysis.

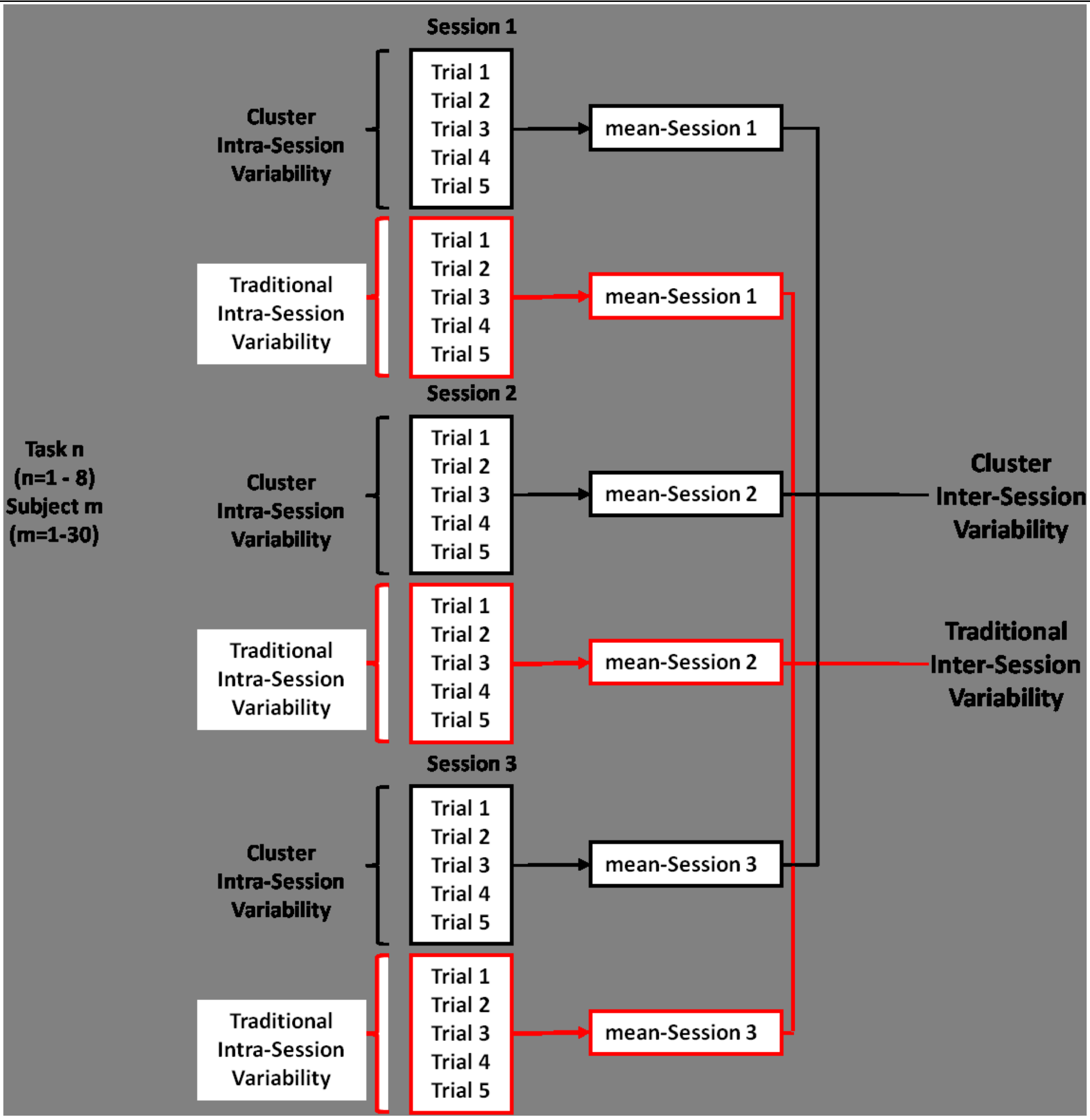


Figure 5-16 Illustration of the trials and sessions used to calculate the intra- and inter-sessions variability of the two methods (Cluster and Traditional).

The mean ROM value and standard deviation of the three rotations (tilt, obliquity and rotation) over the five trials were calculated separately for each of the three sessions, each activity of daily living and the two methods. The standard deviation obtained represents the intra-session variability. For inter-session variability, as shown in Figure 5-16, the mean values of the three rotations were calculated for each session. Then the standard deviation between the three sessions was calculated for each subject, activities of daily living and the two methods. As well as the ROM, the maximum pelvic rotations of the pelvis in the three planes (sagittal, frontal and Transverse) were calculated among all activities of daily living, between two methods and across all BMI groups.

5.2.4.6 Statistical Analysis

Another objective of this study was to measure the repeatability or reproducibility of the kinematic data obtained using the Cluster method and to compare it to the Traditional method. As previously explained (Section 4.6.2.5), within-day CMC was used as a statistical measure to evaluate the similarity within the sessions. The same equation (Equation 4.32) was used to measure the between-day CMC values.

Statistical differences between the two methods were assessed using repeated measures analysis of variance test (ANOVA) with three within-subject factors (number of trials, number of sessions and two protocols) and one between-subjects factor (BMI). A Nonparametric analysis, Friedman test, was also used to measure the statistical differences between the CMC values. The entire set of statistical tests was completed using SPSS (version 20.0, Chicago, USA).

5.3 Results

5.3.1 Static posture of the pelvis

The neutral pelvic position was defined as the orientation of the pelvis when the subject assumed a relaxed standing posture. The data obtained from the static trial in Section 5.2.3 was assessed and the mean values of pelvic static orientation in the sagittal, frontal and transverse planes for two methods were calculated. The result of the ANOVA test revealed that there were no significant differences between the mean values obtained across three sessions for the pelvic static orientation in the sagittal (F(2, 54) = 1.667, p=0.198), frontal (F(2, 54) = 2.631, p=0.81), and transverse planes (F(2, 54) =1.753, p=0.183) using the two methods whilst the subjects stand still. This shows that most of the subjects maintained the same posture between the three sessions for the static trials. Furthermore, the results showed that the two marker sets had no significant effects on static positional data obtained in the sagittal (tilt F(1, 27) =4.105, p=0.053), frontal (obliquity F(1, 27) =0.548, p=0.465) and transverse planes (rotation F(1, 27) = 1.519, p=0.228). The two methods measured the same pelvic orientation in all three planes and also no differences were noted between the static posture of the normal, overweight and obese subjects. Table 5-2 summarises the mean differences between the two methods across different BMI group and in all three planes of pelvic rotations. On average, the mean differences between the two methods in the sagittal, frontal and transverse planes are 1.0°, 0.45° and 0.37°, respectively. Therefore, values in the Table 5-2 represent a good level of agreement between the two methods in the static trial. These values can be used as a base of differences between the two methods and one should expect the same differences in kinematics measurements obtained from the two methods in the dynamic trials.

Pelvic movement	BMI	Mean°	Std. Deviation	Std.Error Mean	95% Confidence Interval	
					Lower Bound	Upper Bound
Pelvic tilt	**Normal**	-1.19	2.96	0.94	-3.31	0.92
	Overweight	-0.15	2.15	0.68	-1.68	1.38
	Obese	-1.66	2.93	0.92	-3.75	0.43
Pelvic obliquity	**Normal**	0.37	1.49	0.47	-0.69	1.43
	Overweight	-0.75	1.56	0.49	-1.87	0.36
	Obese	-0.23	1.43	0.45	-1.25	0.80
Pelvic rotation	**Normal**	0.05	1.63	0.52	-1.12	1.22
	Overweight	0.73	1.33	0.42	-0.22	1.67
	Obese	0.34	1.92	0.61	-1.04	1.71

Table 5-2 Mean differences between the two methods in measuring the pelvic static posture. The standard deviation, Standard error, 95% Confidence Interval of differences between the two methods across all BMI groups are given.

The variability of the two methods was also compared within-subject groups using the standard deviation of maximum static positional data of the pelvis in the sagittal, frontal and transverse planes. The inter-session variability of the two methods is presented in Table 5-3. The ANOVA test showed that there were no significant differences between the inter-session variability of the two methods in the sagittal (F(1, 27)=0.861, p=0.362) and transverse planes (F(1,27)= 0.552, p=0.464). The inter-session variability of the two method was significantly different in the frontal plane (F(1,27)= 10.37, p<0.05). The inter-session variability of the Cluster method was significantly less than the Traditional method. The performance of the two methods was also compared across different BMI groups. The tests of between-subject effect showed that the inter-session variability was significantly different in the sagittal plane (F(1,27)=5.68, p<0.05). The *post hoc* analysis revealed that the inter-session variability of the static posture of normal subjects were significantly higher than that of the obese subjects in the sagittal plane (p<0.05); while there were no significant differences between the overweight and normal subjects (p=0.871).

Pelvic movement	BMI	Method	Mean Inter-var	Std.Error	95% Confidence Interval	
					Lower Bound	Upper Bound
Pelvic tilt	**Normal**^{1}	**Cluster**	2.63	0.47	1.66	3.60
		Traditional	3.23	0.48	2.25	4.21
	Overweight	**Cluster**	2.44	0.47	1.47	3.41
		Traditional	2.75	0.48	1.77	3.73
	Obese^1	**Cluster**	1.18	0.48	0.21	2.15
		Traditional	1.12	0.47	0.14	2.10
Pelvic obliquity	**Normal**	**Cluster**	1.60*	0.31	0.96	2.24
		Traditional	1.74	0.16	0.42	1.06
	Overweight	**Cluster**	0.88*	0.31	0.69	1.97
		Traditional	0.89	0.16	0.56	1.20
	Obese	**Cluster**	0.58*	0.31	0.54	1.82
		Traditional	0.68	0.16	0.36	1.00
Pelvic rotation	**Normal**	**Cluster**	2.32	0.38	1.54	3.10
		Traditional	1.90	0.28	1.32	2.48
	Overweight	**Cluster**	1.29	0.38	0.50	2.07
		Traditional	1.07	0.28	0.49	1.65
	Obese	**Cluster**	1.42	0.38	0.64	2.20
		Traditional	1.68	0.28	1.10	2.26

Table 5-3 Mean value for inter-session variability for the two marker sets and three BMI group for static orientation of the pelvis in the sagittal, frontal and transverse planes in static trial. The standard error and 95% confidence level are also given (*represents the significant differences between the two methods and ^{1} represents the significant differences between the normal and obese subjects, $p<0.05$).

The differences between the variability of the normal and obese group would be expected as the excessive tissues around the abdominal area restricts the movement of the upper body as well as lower body, therefore the obese group can maintain the similar posture from one session to the other.

The three way interaction between the method, session and BMI for static pelvic position showed a significant interaction in the mean values obtained in the sagittal plane, suggesting that the mean static pelvic position obtained is not consistent through all the three sessions and two methods (F(4, 54) = 4.293, p<0.05). The nature of this interaction could be discussed by referring to Figure 5-17. The graph for normal subjects shows that the value of pelvic posture in the sagittal plane during the static trial for each session obtained by the Traditional method is similar to the Cluster method across the sessions.

In overweight subjects, even though the mean pelvic orientation in the sagittal plane obtained by the two methods is similar, the measured values are more consistent over 3 sessions for the Cluster method than for the Traditional method. In obese subjects there is a small difference between the mean pelvic orientation obtained in the sagittal using the Traditional method and Cluster method, but the Cluster method measured a greater value of anterior tilt than the Traditional method, and the measured values over 3 sessions are more consistent for the Cluster than the Traditional method. Another aspect of static pelvic posture is the variability of the pelvic posture between different BMI groups.

As shown in Table 5-4, the inter-subject variability increases as the BMI values increased. A *post hoc* analysis, with Sidak adjustment, reveals that there is a significant difference between the inter-subject variability of the normal and obese subjects ($p<0.05$). As the inter-subject variability is higher in obese subjects, this could be as a result of different compensation technique that the obese subjects use to maintain their equilibrium; this also could be as a result of discrepancy within the range of BMI values which are much greater than the BMI range for the normal subjects (Table 5-1).

BMI	**Standard deviation of anterior pelvic tilt**	
	Cluster (in degrees)	**Traditional (in degrees)**
Normal	4.48^1	4.61^2
Overweight	6.06	5.41
Obese	7.51^1	9.65^2

Table 5-4 Summary of inter-subject variability of the static posture of pelvic within normal, overweight and obese subjects (^{1} and ^{2} represent the significant differences between the normal and obese subject, $p<0.05$).

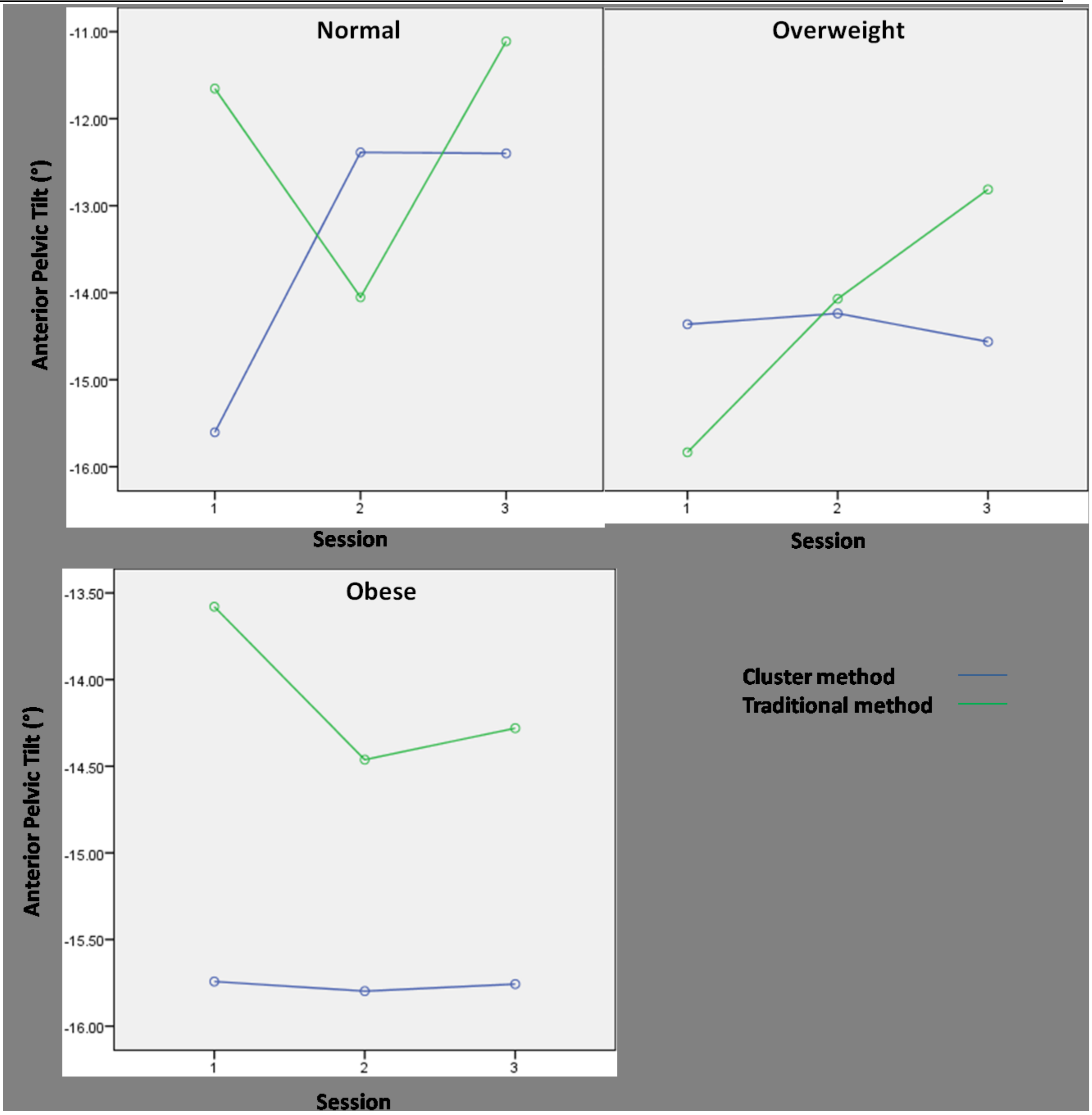


Figure 5-17 Graphs showing the interaction between the sessions, methods and BMI groups in the sagittal plane, green lines represents the Traditional method and blue lines represents the Cluster method

5.3.2 Pelvic motion during dynamic activities (Walking/Stairs-up/Stairs-down/Time-Up)

One of measures to assess the reliability of the Cluster method was to measure ROM of the pelvis during cyclic activities such as walking, ascending and descending stairs and Time-up. The findings for these four activities are averaged and summarised in Table 5-5. As a result of marker occlusion during walking, the positions of ASIS markers on the pelvis were not tracked properly therefore most of the trials were unusable. The interpolation was also not valid as more than half of the trials were missing. However, data obtained using the Cluster method was tracked clearly with no marker occlusion. Therefore, only the result of Cluster method is presented in this section. The thorough results for each activity are presented in Appendix E.

BMI	ROM Mean (±SD)	Intra-Session Variability	Inter-Session Variability	Within-day CMC (SD)	Between-day CMC(SD)
Pelvic tilt(X) (in degrees)					
Normal	16.1(15.1)	2.20(1.00)	3.70(0.80)	0.883(0.03)	0.844(0.11)
Overweight	16.5(16.0)	1.40(0.70)	2.60(0.40)	0.909(0.02)	0.861(0.05)
Obese	15.6(12.1)	1.40(0.50)	2.00(1.00)	0.895(0.05)	0.891(0.09)
Pelvic obliquity(Y’) (in degrees)					
Normal	23.9(22.3)	2.20(1.40)	2.40(1.80)	0.909(0.01)	0.935(0.02)
Overweight	23.8(22.7)	1.80(1.00)	1.80(0.90)	0.944(0.02)	0.938(0.02)
Obese	22.6(20.1)	1.60(0.70)	1.70(1.10)	0.907(0.03)	0.944(0.01)
Pelvic rotation(Z”) (in degrees)					
Normal	20.1(6.40)	4.5(2.83)	3.4(1.60)	0.780(0.17)	0.800(0.12)
Overweight	19.1(3.91)	2.5(0.95)	4.0(1.90)	0.860(0.08)	0.859(0.11)
Obese	15.0(3.66)	2.4(1.09)	3.2(1.52)	0.825(0.14)	0.872(0.09)

Table 5-5 Mean values of the ROM, intra-session and inter-session variability, within-day and between-day CMC values of the kinematics waveforms for normal, overweight and obese subjects for all three ranges of motion during dynamic activities (walking/Stairs-up/Stairs-Down/Time-up) obtained using the Cluster method

Intra-session and Inter-session variability of cluster method were calculated and presented in Table 5-5. No statistical test can be performed between the two methods as almost all of the data obtained using Traditional method was invalid as a result of marker occlusion. The Cluster method showed acceptable values for intra- and inter-session variability, especially for overweight and obese subjects.

The within-day CMC values obtained for the Cluster method showed excellent to very good repeatability in all three planes for all BMI groups (Table 5-5). The repeatability of the Cluster method between the test days for dynamic activities was also investigated and showed excellent to very good repeatability for all BMI groups.

On average, 77% of the trials obtained from the Traditional method were occluded, either partially or completely, therefore the decision was taken to not interpolate the data as it will maximize the error associated with untrue values. Therefore the Traditional method failed to provide useful results.

5.3.3 Pelvic motion during static activities (Box/Toe/STS/squat)

The ROM measured by the Cluster method for static activities are summarised in Table 5-6, while data obtained using the Traditional method could not be calculated as the ASIS markers were occluded, on average, for 74% of the trials. Therefore the decision was taken to not present the data, as interpolation in this case is almost meaningless. As most of the data obtained using the Traditional method was occluded, therefore no further statistical analysis was done. The intra- and inter-session variability and within- and between-day CMC values of the Cluster method for all static activities (Box/Toe/STS/squat) are averaged and presented in Table 5-6. The inter-session variability was greater than the intra-session variability across all BMI groups for all three ranges of motion.

BMI	ROM Mean (±SD)	Intra-Session Variability	Inter-Session Variability	Within-day CMC (SD)	Between-day CMC(SD)
Pelvic tilt(X) (in degrees)					
Normal	35.6(14.1)	2.03(0.63)	4.36(1.04)	0.924(0.01)	0.890(0.04)
Overweight	34.8(12.4)	1.70(0.41)	3.67(0.50)	0.934(0.03)	0.932(0.02)
Obese	31.7(6.89)	1.75(0.30)	2.97(0.31)	0.926(0.03)	0.923(0.05)
Pelvic obliquity(Y’) (in degrees)					
Normal	5.41(0.88)	0.82(0.08)	2.25(0.77)	0.894(0.03)	0.753(0.03)
Overweight	4.69(0.58)	0.91(0.06)	1.58(0.84)	0.864(0.02)	0.827(0.05)
Obese	4.18(0.98)	0.66(0.04)	1.29(0.62)	0.866(0.01)	0.848(0.02)
Pelvic rotation(Z”) (in degrees)					
Normal	4.41(1.29)	1.36(0.29)	1.92(0.38)	0.818(0.04)	0.682(0.04)
Overweight	4.83(0.97)	1.27(0.20)	1.69(0.33)	0.787(0.05)	0.820(0.03)
Obese	4.78(0.90)	1.02(0.31)	1.16(0.23)	0.886(0.02)	0.882(0.04)

Table 5-6 Mean values of the ROM, intra-session and inter-session variability, within-day and between-day CMC values of the kinematics waveforms for normal, overweight and obese subjects for all three ranges of motion during static activities (Box/Toe/STS/squat) obtained using the Cluster method

The repeatability of the Cluster method in the sagittal plane was categorised as excellent and was slightly higher than the other two planes. In the frontal and transverse planes, the repeatability of the Cluster method was categorised as very good to excellent. The repeatability of the kinematic waveform obtained from the Cluster method was excellent in the sagittal plane. The repeatability in the frontal and transverse planes was lower than the sagittal plane, but the values represent the high repeatability (Garofalo et al., 2009).

All the data for each activity, including the maximum pelvic movement for each BMI group in all three planes are provided in Appendix E.

To summarise the performances of the Cluster and Traditional methods in measuring the pelvic kinematics, Table 5-7 summarises the robustness of the Cluster method in comparison to the Traditional method.

Dynamic activities	**% of occluded data**				**Static activities**	**% of occluded data**		
	Normal	**Over-weight**	**Obese**			**Normal**	**Over-weight**	**Obese**
Walking	50%	80%	100%		**Box**	40%	60%	100%
Stairs-up	60%	70%	100%		**Toe**	60%	90%	100%
Stairs-down	60%	80%	100%		**STS**	40%	90%	100%
Time up	50%	80%	100%		**Squat**	50%	60%	100%

Table 5-7 Robustness of the Traditional method as assessed by occlusion percentage. Performance of the traditional method across different BMI group and activities of daily living was analyzed by calculating the percentage of the occluded data. None of the data obtained using the Cluster method was interpolated. For obese subjects the Cluster method is 100% more robust than the Traditional method as in the Traditional method all of the trials were missing, either partially or completely, as a result of ASIS occlusion.

The robustness of the two methods was compared and presented as a percentage of interpolated data in the Traditional method versus uninterpolated data using the Cluster method. None of the data was interpolated using the Cluster method; however on average most of the data obtained using the Traditional method was interpolated in order to calculate the pelvic kinematics (Section 5.4, Figure 5-20). Interpolating the data will result in unreliable data; therefore the kinematic data obtained using the Traditional method is not as reliable as the Cluster method and was not presented in this chapter.

5.4 Discussion

Establishing the reliability and repeatability of measuring 3-D kinematics of the pelvis during different activities of daily living is critical if one wishes to distinguish the pathological changes from technical or experimental artefacts (Schache et al. 2002). The variability and repeatability of the 3-D kinematic data can be affected by a number of sources such as instrumental errors, skin movement artefacts and human performance. The combined effect of these factors needs to be investigated so that the repeatability of the 3-D kinematic data during different activities of daily living is known.

The results obtained from this study showed that on average the range of motion of the pelvis decreases as the BMI of subjects increased, this could reflect the fact that the obese subject had more soft tissue around their abdomen therefore the ROM of these obese subjects may be restricted, or it could suggest that the soft tissue masked the underlying skeletal movement.

The ROM obtained using the Traditional method was discarded as a result of marker occlusion. It was decided to not include any trials in data analysis if the number of interpolated frames was equal or greater than the half of the total number of frames for that trial. On average 50%, 80% and 100% of the trials were completely interpolated for normal, overweight and obese subjects, respectively. Therefore, all data obtained using the Traditional method was invalid based on the criterion used in this thesis. This occlusion arises from STA and marker occlusion during the data collection due to excess of soft tissue (for overweight and obese subjects); while introducing the technical frame and the concept of anatomical landmark calibration in the Cluster method minimised the effect of STA and marker occlusion. Calibrating the anatomical landmarks for obese and overweight subjects allows the investigator to access the bony landmark by pressing the pointer (calibrating wand) toward the particular anatomical landmark as shown in Figure 5-18.

STA and excess fat tissue around abdomen for overweight and obese subjects did affect the performance of the Traditional method across activities of daily living by marker occlusion or marker displacement relative to the underlying bony landmarks as shown in Figure 5-19. For normal subjects, arm movement was the main factor that caused the marker occlusion.

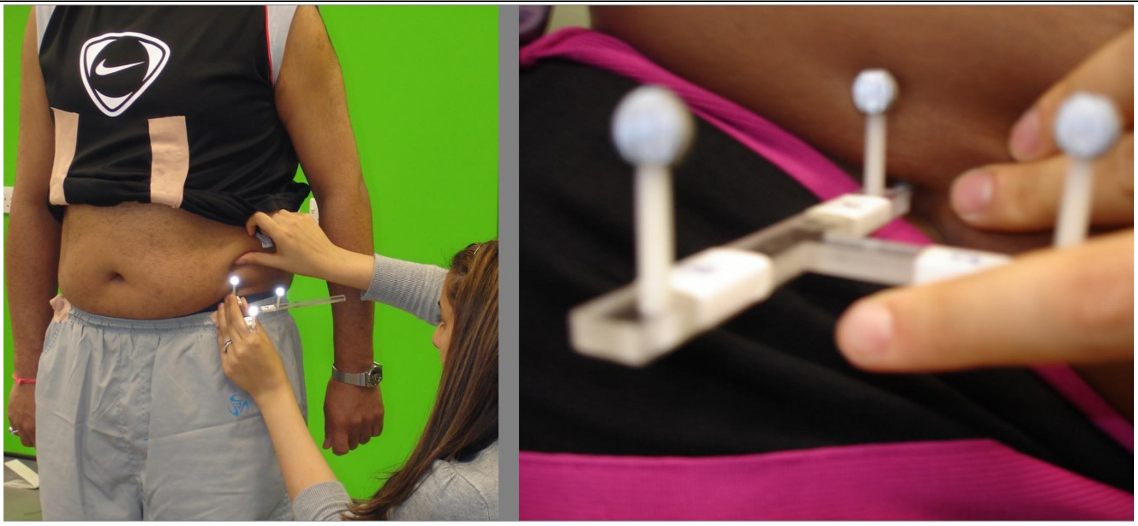


Figure 5-18 Calibrating the anatomical landmarks using the pointer enables the investigator to access the bony landmarks by pressing the tip of the pointer against the landmarks while holding the soft tissue around the abdomen

The result of this study revealed that the performance of the Cluster method was superior to the Traditional method, and can replace the Traditional method especially for activities that requires the full ROM of the pelvis. Table 5-7 revealed that the Cluster method is 80% and 100% more robust than the Traditional method to measure pelvic kinematics for overweight and obese subjects.

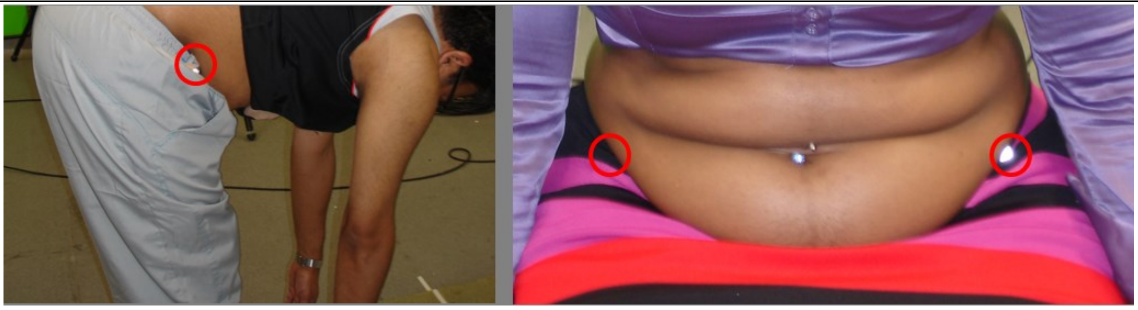


Figure 5-19 Illustration of marker occlusion during the Toe and STS activities. The red circles represent the position of ASIS markers. While the subject is seated the markers around the ASIS move relative to the underlying bone because of the soft tissue around the abdomen

The variability of the kinematic data was investigated by calculating the intra-session and inter-session variability of the pelvic movement in each plane. The results indicated that the inter-session variability of the data was on average greater than the intra-session variability across all three BMI groups particularly in the plane where the pelvis had the greatest ROM. The greater inter-session variability may have arisen from the non-invasive determination of the bony landmarks, skin movement, instrumental errors and finally a level of inherent physiological variability within the same performer over repeated trials and sessions. All of these potential sources of errors can cause variability in both within and between test days. The intra-session variability is not impacted by marker placement differences.

This study also investigated the repeatability of the kinematic data using both the Cluster and Traditional methods. For static activities such as Toe, STS, squat, and Box the within-day CMC values were on average greater than 0.90 for the Cluster method in the sagittal plane which indicates a high repeatability within the method. The within-day CMC values obtained using the kinematic waveforms in the frontal and transverse planes showed a moderate repeatability using the Cluster method. As all of the above mentioned activities involve full range of motion of the pelvis in the sagittal plane with little or no movement in the frontal and transverse planes therefore the CMC values obtained from the latter planes were smaller than the CMC values obtained from the sagittal plane. This could be explained more by referring to the concept of the CMC which is based on the ratio of error variance to true variance therefore lower mean values will result in lower CMC values.

The between-day repeatability of the kinematic data was measured by calculating the between-day CMC values. On average the between-day CMC values were smaller than the within-day CMC values which could be associated with marker reapplication between sessions. Even though the same investigator performed all marker reapplications and took extreme care to follow an experimental protocol such errors, however small, will influence the anatomical coordinate frames. For activities such as walking, Stairs-up, Stairs-down and Time up, on average the CMC values were greater than 0.80 (good repeatability) in the frontal and transverse planes. The between day-CMC values obtained for the sagittal plane were on average smaller than that of the frontal and transverse as less movement occurs in the sagittal plane during gait cycle.

One of the objectives of this study was to show how the Cluster method might improve the repeatability and consistency of the kinematic data in comparison to the Traditional method. To this end, the CMC values obtained during the walking activity in this study was compared to the CMC values previously obtained in other studies, which shows improvement in the repeatability of the kinematic waveforms using the Cluster method as shown in Table 5-8.

Pelvic tilt (in degrees)	Sample size	Within-day CMC	Between-day CMC
Cluster method	N=30	0.933(0.019)	0.867(0.065)
Collins et al. a	N=10	0.672(0.133)	0.634(0.198)
Collins et al. b	N=10	0.638(0.141)	0.747(0.194)
Growney et al.	N=5	-	0.639(0.025)
Kadaba et al.	N=40	0.669(0.134)	0.244(0.180)

Table 5-8 Summary of comparison between CMC values of the Cluster method from this study to the previous studies

This study also compared the influence of BMI on repeatability of pelvic kinematics. The within-day CMC and between-day CMC values for overweight and obese subjects on average showed high repeatability for the Cluster, for all planes.

In conclusion, it is important to determine whether the cluster mounted on the sacrum does minimise the effect of the STA; these results of this study can be compared with Bull and McGregor (2000) in which they demonstrated that it is possible to accurately measure the motion of the lumbo-sacral spine (subjects' height:1.80- 1.96 m, and weight: 78- 100 kg), using a sensor attached to the sacrum and provide useful and important information on the motion of the body segments during rowing with average error of ±1.0°. The Cluster method overcomes a number of theoretical and experimental limitations such as minimising the effect of movement of markers relative to each other as well as to the underlying bone, fewer cameras are required to track the sacral cluster with implications for cost and laboratory set up procedures. Also, less time is needed for post processing the data as there is no marker occlusion in the dynamic trials therefore no further programming is needed to fill the gaps in dynamic trials. This study provides evidence that a new technical marker set is superior for 3-D data collection of overweight and obese subjects, and when the ASIS markers are occluded for all or part of the trial. Figure 5-20 illustrate kinematic waveforms of the pelvic tilt during the Box. As shown, the maximum pelvic tilt for the Traditional method is a straight line after filling the gaps (green waveform) while the maximum value of the pelvic tilt for the Cluster method is clearly visible without the need of extra programming to fill the gaps. This demonstrates that by interpolation of the data set, the values are not reliable and do not represent the true values of pelvic tilt.

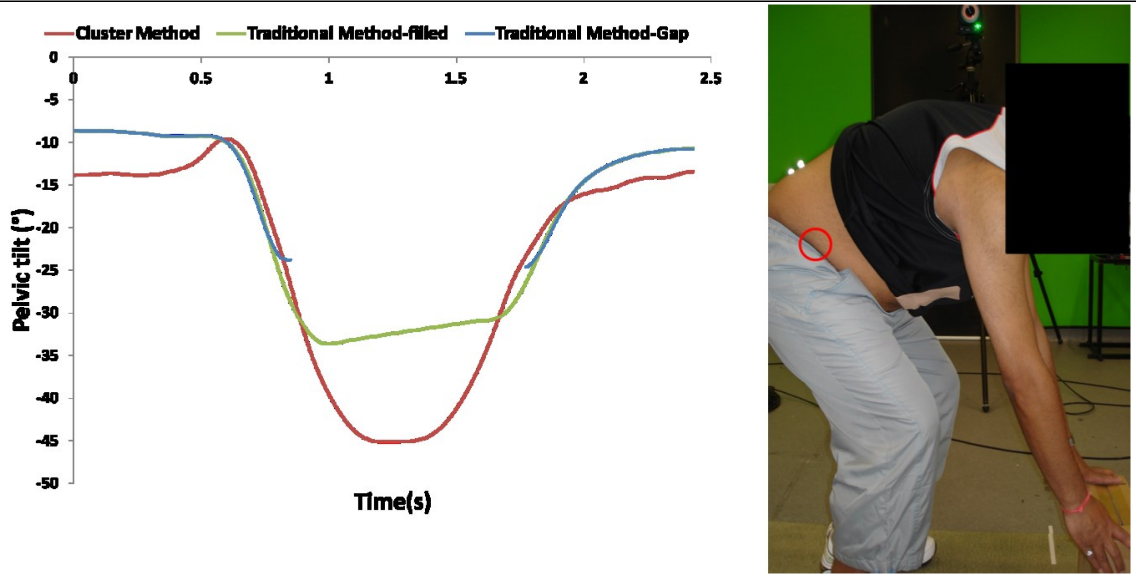


Figure 5-20 An example of why data obtained using the Traditional method should not be interpolated. The graph shows the differences between the two methods with regards to the post processing procedure. The red line represents the kinematic waveform for pelvic tilt during the Box activity, while the blue line represents the kinematic waveform obtained using the Traditional method for the same task. As the figure on the right hand side shows, the ASIS markers are not visible therefore there is a big gap in the data. The green line represents the new kinematic waveform for the pelvis after filling the gap which is not similar to the kinematic waveform obtained using the Cluster method and is clearly missing a key section of data. Therefore filing the gap for the Traditional method is not reliable when the ASIS markers are missing

As a final point, for any new marker set or method to be clinically useful, it must be valid. In this study the validation of the Cluster method was achieved by measuring its reliability and repeatability, however the validity criterion is harder to assess due to the lack of an invasive 'gold-standard'. In the absence of a gold-standard, the Helen Hayes method is the most widely accepted in literature for measuring joint angles. Clearly this is not a study that has provided a measure of accuracy of tracking the movement of the underlying bone, and as such has limitations. Notwithstanding these limitations, a repeatable measure of pelvic motion has been tested in this study.

5.5 Summary

Multiple marker sets and models are currently available for assessing pelvic kinematics in gait. Despite the presence of a variety models, there are still debates on their reliability and consistency, and consequently there is no clearly defined standard. Two marker sets were evaluated in this study: the 'Traditional' where markers are placed at the anterior and posterior superior iliac spines (ASISs, PSISs); and the 'Cluster', where a cluster of three orthogonal markers fixed on a rigid based is attached to the sacrum. The two sets were compared with respect to intra- and inter-session standard deviations of ROM of the pelvis in the sagittal, frontal and transverse planes which used as an intra- and inter-session variability factors. The within- and between-sessions repeatability was measured using coefficient of multiple correlation (within-day and between-day CMC). Data set generated by the Traditional method was discarded as a result of marker occlusion and STA. Therefore, repeatability of the Cluster method only was investigated. Data set from the Cluster method generated and showed high within- and between-session repeatability in all planes (CMC>0.80). None of the previous studies reported the differences in intra- and inter- session variability and repeatability values for different BMI categories such as overweight and obese subjects with relatively large sample size. Hence the Cluster method overcomes a number of theoretical and experimental limitations such as minimising the marker occlusion, and is a reliable alternative to the traditional (the standard) marker set.

The validated Cluster method in this chapter is used in the next two chapters to explore the effect of loaded backpack on pelvic kinematics in adolescents. In the subsequent chapter, a survey on backpack wearing amongst school children is given.

Chapter 6

Survey of backpack use amongst adolescents

Aim The main objective of this chapter is to investigate the use of backpacks amongst schoolchildren through a questionnaire based survey. The information derived from this survey was required to inform the subsequent test protocol and approach to understanding the implications of backpack use on the adolescent spine.

6.1 Introduction

As discussed in Chapter 2, backpacks have become a common and popular method of carrying school related materials amongst school children and adolescents. It is recognized that a loaded backpack can apply a substantial load to the immature adolescent spine (Negrini et al., 2002). However, both the short- and long-term implications to spinal health are as yet unclear. Backpack loads of over 20% BW have been reported in school children creating concerns that such loads may lead to an increased risk of back pain in this young age group (Hong et al., 2003; Negrini et al., 2002). Sheir-Neiss et al. (2003) noted an association between backpack weight and the reporting of back pain, and others have suggested that 80% of school children regard their backpack as being heavy and nearly 50% associate it with back pain (Negrini et al., 2002). While the association between the backpack load and back pain has been acknowledged, the relationship between these two variables remains poorly understood (Negrini et al., 2002). Grimmer et al. (2000) demonstrated that a loaded backpack alters the location of the centre of gravity of the body which results in an accompanying change in the relationship of the centre of gravity to the base of support and causes postural instability. Li et al. (2003) and Hong et al. (2003) investigated range of trunk flexion at backpack loads of more than 10% of BW and they suggested a maximum permissible backpack load of 15% BW based on trunk inclination. However, Chansirinukor et al. (2001) suggested that carrying a 15% BW load was too heavy as prolonged carriage lead to changes in posture. However, these studies only focused on the shoulder and neck posture, gait parameters (cadence and velocity of walking) and trunk forward lean and none of them have investigated the effect of the backpack load on pelvic kinematics. It has been reported that the excessive load on the spine increases the forces and moments about the spine and may cause permanent postural changes and lead to pathological back problems such as degenerative disc disease or disc herniation (Goodgold et al., 2002; Smith et al., 2006). Compensatory pelvic motions due to heavy backpack load might result in gait alteration, additional movement at spine and increased torque and forces on trunk, and lower limbs (Smith et al., 2006; Pascoe et al., 1997) and these changes may contribute to orthopedic and musculoskeletal injuries (Smith et al., 2006). Therefore it is important to assess pelvic movement patterns of adolescents carrying a heavy load.

It was suggested that the daily use of a loaded backpack can cause regular discomfort in children and despite the lack of scientific evidence on the short- and long-term effects of backpacks on adolescents, guidelines for backpack load limits (10-15% BW) have been proposed by different organizations including the American Academy of Orthopedic Surgeons.

During a typical day, school children carry their backpack while they walk to and from the school and whilst waiting for transport to and from the school. They sit down and stand up and ascend and descend the stairs while carrying their backpack. It is important to know the effects of the loaded backpack in such circumstances to inform guidelines on the use of backpacks and recommended loading levels. The literature provides little or no information about the effects of backpacks on school children during the performance of the dynamic activities such as activities of daily living.

Internationally there is great concern with the prevalence of backpack related problems and different surveys have been conducted to address these issues in countries such as United State of America, Italy, France, New Zealand, Spain, Hong Kong, India, Brazil and Poland. In this thesis, a survey is conducted to explore the usage of backpack and its associated problems in the UK.

6.2 Aim and Objectives

The aims of this survey were to:

1. determine the average mass carried by school children in a backpack and to relate this to the body mass of the child
2. determine the type of the backpack and the way in which it is carried (one shoulder, two shoulder)
3. explore any pain presented by children that is believed to be associated with backpack use
4. determine the mean time spent travelling to and from the school and its association to back pain

and finally

5. develop a protocol to investigate the effect of routine backpack loads (as determined from the survey) on the pelvic kinematics of adolescents

6.3 Material and methods

This study was approved by ICREC, and permission was also obtained from the children's school and parents. This study recruited pupils from a single boy's school. The timing of the study was not advertised to the pupils to ensure that they did not modify their usual activities in relation to backpack use.

Sixty boys who were regular backpack users at the time of the study were recruited to complete a questionnaire about their backpack use and perceived pain associated with such use. The questionnaire is provided in Table 6-1.

After completing the questionnaire the subjects were weighed with and without their backpacks by using a set of digital electronic scales. The scales were accurate to 0.01 kg. The students' height was measured in centimeters to one decimal place, with the subject positioned against a wall and instructed to stand straight with their shoulder back, hands by side and eyes looking straight ahead. Table 6-2 summarise the characteristics of the 60 students who participated in the survey.

<table>
<tr><th>No.</th><th colspan="6">Questions</th></tr>
<tr><td>1.</td><td colspan="6">Please circle whether you are a
Girl Boy</td></tr>
<tr><td>2.</td><td colspan="6">How old are you?</td></tr>
<tr><td>3.</td><td colspan="6">What kind of school bag do you use?
Backpack Shoulder bag Trolley bag Sports bag Other-please specify</td></tr>
<tr><td>4.</td><td colspan="6">How long do you carry your school bag per day?
Less than 5 minutes 5 to 30 minutes More than 30 minutes</td></tr>
<tr><td rowspan="5">5.</td><td colspan="6">How do you carry your bag during the day?</td></tr>
<tr><td></td><td>Always (100%)</td><td>usually (80%)</td><td>Sometimes (50%)</td><td>Rarely (10%)</td><td>Never (0%)</td></tr>
<tr><td>Backpack-Both shoulder</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Backpack-One shoulder</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Other-specify</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>6.</td><td colspan="6">How long does it take to go to school?
Less than 5 minutes 5 to 30 minutes More than 30 minutes</td></tr>
<tr><td>7.</td><td colspan="6">How do you get to your school?
Parent’s Car Bus Bike Walk Train</td></tr>
<tr><td>8.</td><td colspan="6">Do you think your school bag is heavy?
Yes No</td></tr>
<tr><td rowspan="5">9.</td><td colspan="6">Please tick the box for each day indicating how heavy your bag is?</td></tr>
<tr><td></td><td>Monday</td><td>Tuesday</td><td>Wednesday</td><td>Thursday</td><td>Friday</td></tr>
<tr><td>Light (example:1-2 books)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Medium (example:2-4 books)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Heavy (example: more than 4 books)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>10.</td><td colspan="6">Does your school provide you with a locker?
Yes No</td></tr>
<tr><td>11.</td><td colspan="6">What do you have in your school bag today? example:4 textbooks, 1 folder</td></tr>
<tr><td>12.</td><td colspan="6">Does any part of your body hurt when you carry your bag?
Yes No</td></tr>
<tr><td>13.</td><td colspan="6">If you answered yes to the previous question can you show on the body map (Figure 6-1) which part of your body hurts?</td></tr>
</table>

Table 6-1 Questionnaire used in this study

Figure 6-1 The body map that was used in the questionnaire, adopted from Mackie et al. (2003)

N=60	Age (years)	Subjects mass (kg)	Subject BMI (kg/m^2)	Backpack mass (kg)	Backpack weight represented by %BW
Mean (±SD)	12.63 (±0.66)	58.00 (±15.94)	21.85 (±4.11)	4.33 (±2.07)	8.14 (±4.35)
Range	12 to 14	33.4 to 123.3	16.28 to 37.80	1.90 to 16.20	3.04 to 25.59

Table 6-2 Subjects data in mean ± standard deviation.

6.4 Results

Subjects were asked 13 questions which included their age, gender and the type of the school bag that they use. The average backpack mass carried by each student was 4.33 kg, but considerably varied from 1.90 kg to 16.20 kg. On average the backpack load represented the 8.14% of student BW, with a maximum of 25.59% BW. Only 2% of students used a trolley bag (backpack with rollers) and 3% carried shoulder bags, with the remainder using a backpack. A third of the students (33%) carried backpacks weighing greater than 10% of their BW. Eighty eight percent of the students made use of school lockers. Students carried an average of 3.92 textbooks, 1.26 folders and 1.12 reading books. Beside the textbooks, folders and reading books, students carried other items in their backpacks including pencil cases, diaries, exercise books, lunch boxes, dictionaries, a calculator, a musical instrument and sport kits (trainers, t-shirt, socks and shorts).

While 44% of the students always carried their backpack on both shoulders, 21% of students had reported that they only sometimes carried their backpack on both shoulders (sometimes was quantified as 50% of time). Participants were also asked if they carried their backpacks only on one shoulder in which 33% and 13% of students said rarely (10% of time) and never (0% of time), respectively (Figure 6-2).

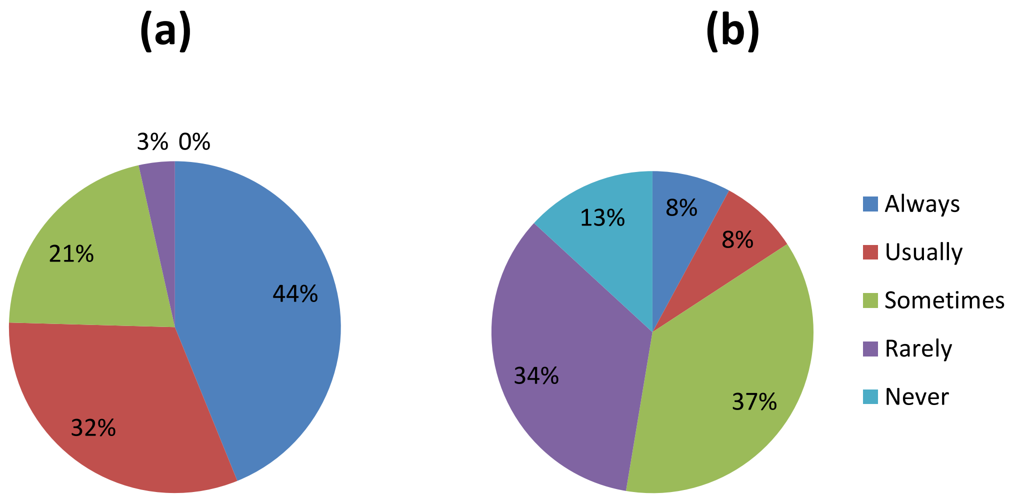


Figure 6-2 **Use of two shoulders (a) or one shoulder (b) in backpack carrying**

The time taken to travel to school and method of commuting was also investigated in which over 70% of the students spend more than 30 minutes traveling to school. The students used different methods to commute to the school, including: bus (43%), train (15%), walking (5%), and parents’ car (3%). Thirty three percent of students used a combination of the above methods to travel to the school, including taking the bus and walking, bus and train, walking and train, car and bus and combinations of walking, taking the bus and train (Figure 6-3).

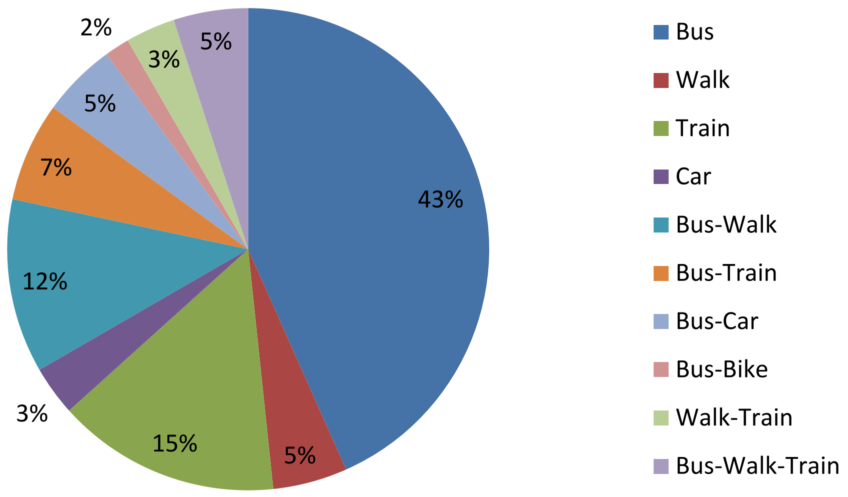


Figure 6-3 School commuting methods

Students were asked how long they carried their school bag; this included carrying their backpack to and from the school as well as the time that the students carried their bag inside the school. Seventy percent of the students reported that they carried their school bag for more than 30 minutes.

To the question “do you think your bag is heavy? “ 68% of the student answered yes and it was noted that 64% of the students ranked their backpack heavy for all five days of the week. Heavy, medium and light were three categories which they were quantified by using the number of books, therefore heavy means carrying more than 4 books while medium and light mean carrying 2-4 books and 1-2 books, respectively (Figure 6-4).

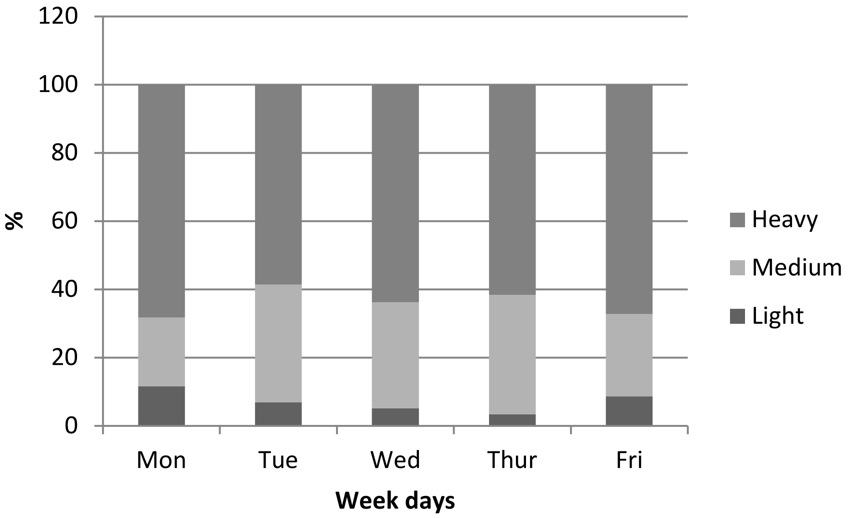


Figure 6-4 **Illustration of how heavy the backpack is during the week**

In order to know if any of students experienced any pain or discomfort associated with carrying their backpacks, a body map was provided and it was asked if they feel pain on any part of their body (Figure 6-1). Of those who answered (58/60), more than half (59%) answered yes.

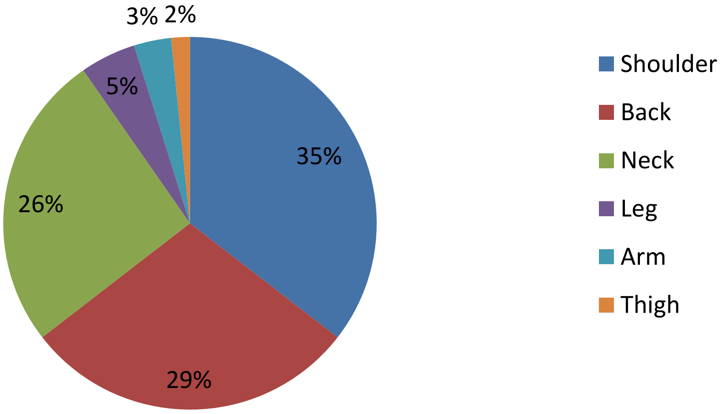


Figure 6-5 **Reported bodily pain associated with carrying the backpack by students**

The shoulders were the body region that was reported by 37% of students to be associated with pains from carrying their backpacks. As shown in Figure 6-5, 27% of the students reported that they suffer from back pain when carrying their bag around. The arms, leg and thigh were rarely reported by the students as being painful following backpack use. It was noted that students who reported body pains, on average, carried a significantly heavier backpack (average mass= 5.29 kg (8.6% BW); range: 2.40 (3.0% BW) to 16.20 (25.59% BW) kg) than those who did not (average mass= 3.39 kg (7.3% BW); range 1.90 (3.8% BW) to 5.40 (11.51% BW) kg; $p<0.05$ using independent t-test). The mean backpack mass carried by students who reported shoulder and back pain were 5.70 (9.4% BW) and 5.75 (9.2% BW) kg, respectively. Around 8% of the students carried a backpack weight of greater 17% of their BW, and these all complained of shoulder, back and neck pain.

Shoulder pain was more prevalent than back pain in 100% of student who carried their backpack on one shoulder and on average they carried 6.2% of their BW in the backpack. Also this study found that 90% of students who complained about back pain, they carried their backpack more than 30 minutes per day and they commute to the school using the bus. Almost all of the students who complained about shoulder and back pain used the school locker.

A regression analysis revealed no significant correlation between the subject's BMI and backpack mass ($R^2=0.039\times10^{-3}$, $Y=0.003X+4.341$ $p=0.481$) which is in agreement with Negrini and colleagues (1999) findings.

6.5 Discussion

The average mass carried by students was 4.33 kg which on average was 8.14% of students' BW. Comparison between the results of this study and the literature is difficult because of differences between the students' age, gender, school and geographical location. The relative mass of the backpack reported in the literature ranged from 10.0% to 46.2% BW (Van Gent et al., 2003; Negrini et al., 2002; Pascoe et al., 1997; Sheir-Neiss et al., 2003; Goodgold et al., 2002; Negrini et al., 1999). Although the average backpack mass obtained in this study is below the weights reported in the literature, a third of the students still carried backpack weighing more than 10% of their BW. The mass of the backpack varied considerably between the students in this study (maximum backpack mass 16.20 kg) which can reflect the great diversity of backpack content between students. The current study noted that 88% of the students used the lockers provided by the school which may explain the lower average backpack mass recorded. The recommended backpack load set by many health professional associations is 10-15% of child's BW (Ontario Chiropractic Association; American Academy of Pediatrics); in this study around 5% of the students carried a backpack load of more than 20% of their BW.

As well as the lockers, the school also has its own special backpack which most of the students use (95%). The backpack was equipped with padded shoulder straps and consisted of two compartments. The different ways of wearing a backpack was investigated in this study in which 76% of students reported that they carry their backpack over two shoulders 80-100% of the time. This figure is similar to that reported in Australia where 72% of students used a proper carrying technique (Grimmer et al., 2000). Conversely, Pascoe et al. (1997) reported that 73.2% of the American students carried their backpack on only one shoulder, with more recent studies in 2002 and 2003 revealing that less than 20% of students used only one strap (Sheir-Neiss et al., 2003; Goodgold et al., 2002). All the students who carried their backpack on one shoulder complained about shoulder pain; since the backpack is designed to be worn over two shoulders to distribute the mass equally across the shoulders, it is very important to educate the students about the consequences that may arise from incorrect use of the backpack (Brackley et al., 2004).

Grimmer et al. (2000) noted that the reporting of low back pain by adolescents (12-18 years of age) is strongly associated with the time spent carrying loaded backpacks (time spent carrying the school bag and time spent sitting, more than 20 minutes). In this study it was shown that 70% of the students spent more than 30 minutes traveling to school and the same proportion of students carried their backpack for more than thirty minutes each day and 90% of these students complained about back pain. This may explain why more than half of the students complained of shoulder, back and neck pain and categorised their backpack as heavy. Body pain associated with carrying a backpack has been previously reported (Pascoe et al., 1997; van Gent et al., 2003; Grimmer et al., 2000; Negrini et al., 2002; Sheir-Neiss et al., 2003). In this study, we have assumed that the presentation of pain was associated with the time and method of commuting and carrying the backpack. Travelling to school by bus was one of the commonest methods of commuting and 90% of the students who complained about back pain used the same method to commute to and from the school. This suggests that students will have to stand, ascend and descend the bus stairs for all or part of their long journey while carrying their loaded backpack. There has been research on the impact of backpack on gait and posture and how the load affects a number of gait parameters. Research has assessed the effect of CoP, trunk forward lean and cervical posture on the kinematics and kinetics of the trunk and lower limbs (Legg et al., 1985; Kinoshita, 1985; Hong et al., 2003; Li et al., 2003; Hong et al., 2001; Li et al., 2001; Hong et al., 2000; Singh et al., 2009; Chansirinukor et al., 2001; Chow et al., 2006; Chow et al., 2005). None of the available studies have looked in detail at the influence of the loaded backpack on pelvic movement and there have not been any studies to look at the effect of the loaded backpack on other activities of daily living such as sit to stand, stair ascending and descending.

In conclusion, although in this small exploratory study there were no correlations between the backpack mass and subjects' BMI, the backpack mass was significantly higher for students who complained about body pain than those who did not. It was alarming that more than half of the students reported complaints of shoulder and/or back and neck pain.

6.6 Future study

Based on the finding of this study two thirds of students carried a backpack load of less than 10% BW. This rate is lower than that previously published and may be attributed to the availability and use of the school lockers. Eight percent of students carried a backpack whose weight ranged, on average, between 17% and 25% of their BW. It is important to know how this level of loads will affect the posture and kinematics of the pelvis as this has not previously been investigated or addressed in the published literature. As discussed in Chapter 3, the pelvis plays an important role in transferring the load between the lower limb and upper limbs. It has been noted that carrying a backpack increases the stress at the lower back and pelvis (Abdrahman et al., 2009). There has not been sufficient research on how the pelvis alters its movement when it is subjected to excessive load.

To this end, a protocol to investigate the influence of the loaded backpack on pelvic kinematics during activities of daily living is developed and presented in Chapter 7. This protocol benefits from the new tracker developed and validated in this thesis and will explore both the mass of the backpack, and the type of the backpack used as both are deemed relevant. It is important to understand whether an ergonomically designed backpack will influence the kinematics of the pelvis in comparison to a non-ergonomic backpack. Mackie et al. (2003) conducted the experiment in which the students were asked to walk on a treadmill for 20 minutes with four different backpack types. Before and after the trial each participant was asked to complete the questionnaire. It was reported that the students chose the more ergonomic backpacks at the end of the experiment but they mainly preferred a backpack for its style and image rather than function and fit. Therefore in the next study two types of backpack will be investigated that reflect the style and image focus as well as the function and fit requirements.

6.7 Summary

Backpacks have become a common method of carrying school related materials. This survey conducted in one school revealed that more than 90% of the students wear backpacks in which 76% of the students carry it on both shoulders for 80 to 100% of the time. The mean mass carried by students was 4.33 kg which was around 8.14% of student's BW. Even though this mean value was less than the recommended limit (10-15% BW), around 8% of the students carried a backpack weight of 17% to 25% of their BW. Eighty percent of the students that carry 17-15% of their BW spend more than 30 minutes each day traveling to school. It has been reported that the time taken to carry the loaded backpack is associated with the reports of body pain for girls and boys (Grimmer et al., 2000). However, this needs further investigation particularly in relation to pelvic kinematics. As well as backpack load, it is important to see how different backpack types could influence on pelvic movements in adolescents, since increasingly a range of styles and designs are available. The findings of this chapter form the basis of further investigations in Chapter 7.

Chapter 7

Kinematics of backpack wearing

Aim The aim of this chapter is to investigate the effect of the backpack load on pelvic kinematics in adolescents during activities of daily living.

7.1 Introduction

As stated in Chapters 2 and 6, backpacks are widely used by adolescents to carry their homework, personal materials and other items for school. Chapter 6 indicated that 8% of students carried a backpack that weighs between 17% and 25% of their BW. Further 29% of these students complained about the back pain as a result of these loads. A review by Mackenzie et al. (2003) suggested that the backpack weight greater than 15% of a child's BW is correlated with back pain symptoms.

Studies have investigated the effect of backpack load on trunk posture and muscle activities (Goh et al., 1998; Li et al., 2003; Hong et al., 2003). They have shown that as the load increases, the centre of gravity is shifted toward the back of the base of support; to compensate for this change subjects naturally move their trunk forward or backward in order to counterbalance the load of the backpack. Pascoe et al. (1997) and other researchers have shown that the trunk forward lean increases as the load is increased (Hong et al., 2003; Singh et al., 2009). The gait parameters have also been measured to investigate the effect of loaded backpack during walking. The results in the literature are not consistent but there is agreement that carrying a load of 20% BW during treadmill walking decreases swing duration and increases double support time (Hong et al., 2001; Li et al., 2001). However, none of the previous studies have investigated the influence of the backpack load on pelvic kinematics of adolescents.

The purpose of this chapter is to assess the compensatory movements of the pelvis as a result of increased load carried by adolescents in a backpack, utilising the pelvic tracker developed and validated in Chapters 4 and 5. According to the survey in Chapter 6, around 8% of students carried a weight between 17% and 25% of their BW, therefore in this chapter the effect of these loads will be investigated for different static and dynamic activities. As well as load effect, the effect of backpack type is also explored in both female and male students between the ages of 12 and 15 years.

7.2 Material and methods

7.2.1 Subject recruitment

As mentioned in Chapter 2, the highest rate of growth occurs during puberty for both boys and girls. In this study 10 schoolchildren with the range of 12-15 years of age were recruited into this study. The exclusion criteria were: surgery to the hip or lower limb, any leg injury (such as fracture or major trauma to the leg), spinal deformities (for example, scoliosis), or any kind of heart or lung problems that would have been exacerbated by the study protocol. This study was approved by ICREC. This sample of children responded to advertisement and flyers displayed on notice boards in local schools. Prior to the recruitment, the parents were given a short description of the experiment and were provided with an information sheet. On the day of testing, the subject attended the Motion Analysis Laboratory at Imperial College London accompanied by his/her parent or legal guardian and additional information regarding the testing procedures was provided. Equipment used in this study such as infrared cameras, force plate, backpacks, load conditions and treadmill were identified and their purposes were explained to ensure that the participants understood the testing procedure and its purposes. Also they were informed both verbally and in writing of their rights to withdraw from the study at any time without providing a reason. Two consent forms were completed and signed by the participants and their parent or legal guardian. The overall anthropometric information of the subjects is given in Table 7-1.

	Age (years) **(SD)**	**Height** (m) **(SD)**	**Weight** (kg) **(SD)**	**BMI** (kg/m^2) **(SD)**	**C7-midPSIS** (m) **(SD)**
Girl (n=5)	13.64(0.61)	1.62(0.06)	49.72(5.71)	18.96(2.55)	0.42(0.01)
Boy (n=5)	13.60(0.85)	1.62(0.06)	52.28(7.12)	19.86(1.60)	0.41(0.02)

Table 7-1 Participant anthropometric data (mean ± standard deviation)

7.2.2 Backpacks and determination of their location

Two backpacks were used in this study: one of standard design and the other ergonomically designed. A JAZZI backpack (Figure 7-1) was used as the standard comfort backpack (COMF). This backpack contained one large main compartment, two front utility pockets, slightly padded shoulder straps and vertically padded back with unpadded outer edges. The COMF backpack was available at a cost of £10.

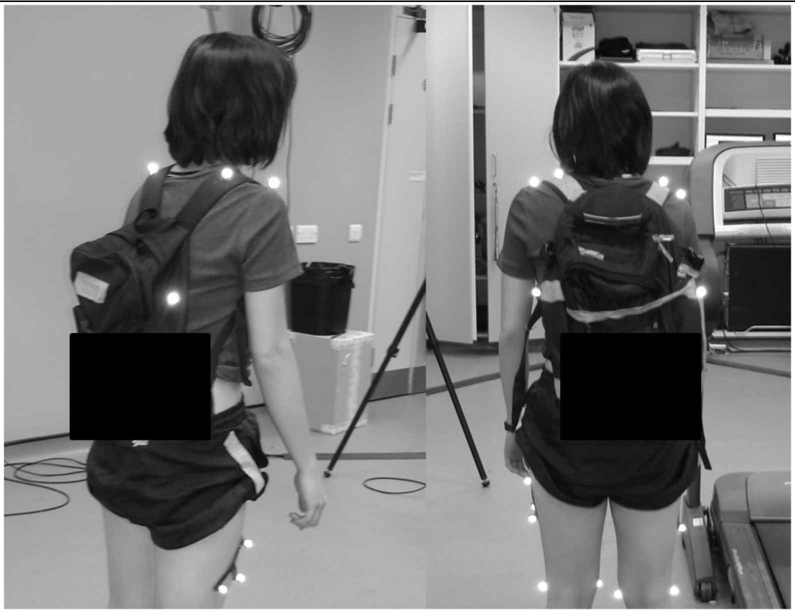
Figure 7-1 The standard comfort backpack (COMF) used in this study to investigate the effect of loaded backpack on pelvic kinematics

The Ergonomic backpack (ERGO) was purchased from BackCare, the charity for healthier backs. It has been designed as an ergonomic backpack (Figure 7-2) and includes an underside curve which is claimed to assist in the distribution of forces thereby promoting an upright standing position (BackCare backpack, 2012). Other ergonomic features of the backpack include wider and heavier padded shoulder straps, slightly curved shoulder straps, a lumbar support, adjustable straps on each side of the backpack, large front zipper pocket, a large padded main compartment and number of small and large cushions on the back panel of the backpack to add an extra padding. The ERGO backpack was available at a cost of £26.

Figure 7-2 The ergonomic backpack (ERGO) used to investigate its effect on pelvic kinematics when it is loaded and compare its performance to the COMF backpack

The weight of the two backpacks was similar and neither of them had an external frame. The two backpacks were in black colour, both closed by zippers and both were anonymised to avoid any manufacturer bias. The same two backpacks were used for the entirety of this study.

As discussed in Chapter 2, previously the effect of backpack height has been assessed there has been study that placed the backpack at waist height and high on the back (Singh et al., 2009). It was reported that positioning the backpack low will affect kinematic parameters in comparison to placing the backpack high. It was shown that for the 20% BW load, the positioning of the backpack low will induce higher joint moments and will result in a higher double support time, lower gait velocity and higher trunk forward lean than the upper configuration. In this thesis the backpacks were positioned as high as possible. In most of the participants the superior aspect of the COMF backpack was positioned near to the inferior angle of the scapula while the superior aspect of the ERGO backpack was positioned approximately at the level of the C7 spinous process. These differences in the location of the two backpacks were due to the fact that the ERGO backpack had to be positioned in relation to its design (lumbar curve and longer straps) whereas for the COMF backpack the best fit approach had to be used to position it as high as possible (shorter straps than the ERGO).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COMF **ERGO**

Figure 7-3 Position of the backpacks on the spine, ERGO backpack was aligned with the spinous process C7 while the COMF backpack was located slightly lower

For each subject, the shoulder straps adjusted to assure the backpack was at the right location. The characteristics of the backpacks are given in Table 7-2.

Backpack	**Manufacturer**	**Dimensions (cm)**			**Mass (kg)**
		Height	**Width**	**Depth**	
JAZZI	Jazzi Gear London	38.0	29.0	13	0.34
BackCare®	William Turner & Son	40.6	30.5	14	0.40

Table 7-2 Characteristics of the COMF (JAZZI) and ERGO (BackCare) backpacks

7.2.3 Subject preparation and lab set up

In this study, an optical motion tracking system (Vicon, Oxford, UK) was used to investigate the influence of a loaded backpack on pelvic kinematics. This system consists of 9 high speed MX-13+ cameras which were running at acquisition rate of 100 Hz. All cameras were calibrated and an accuracy of ±0.2 mm was obtained before conducting the experiment (Figure 4-2). A force plate running at 1000 Hz (Kistler Holding AG, Winterthur, Switzerland) was used to measure postural stability while carrying a loaded backpack.

Prior to data collection, the height and weight of each subject was measured and 17% and 25% of their BW were calculated. Reflective markers (14 mm in diameter) were attached to the bony landmarks on the shoulder, pelvis, left and right femur and left and right foot using double sided tape as shown in Figure 7-4. The sacral cluster was fixed to the sacrum using adhesive spray as well as double sided tape.

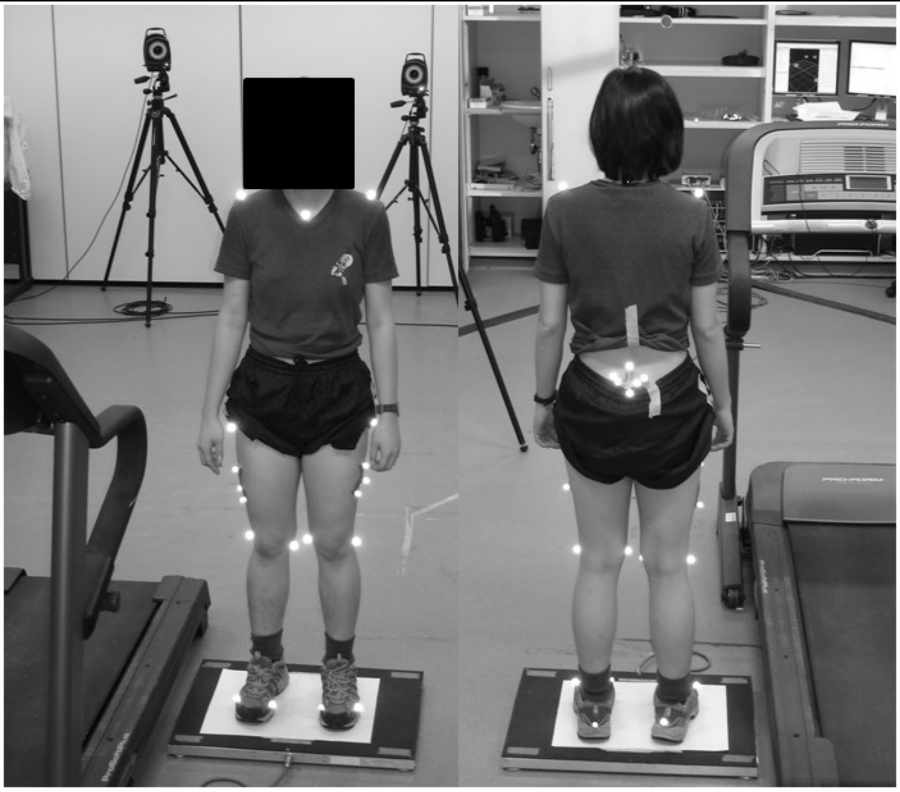
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Figure 7-4 Anterior and posterior location of reflective markers on the participant

Table 7-3 gives a description of the landmarks in each segment that were used to attach the markers in static trials.

Segment	Description	Landmark/marker
Shoulder	acromion joint Clavicle	L/R ACJ CLAV
Pelvis	**Posterior superior iliac spine** Sacrum	**L/R PSIS** Sacral cluster
Femur	Top of greater trochanter Lateral epicondyle Medial epicondyle Femur cluster	L/R GT L/R LE L/R ME L/R FC
Foot	First metatarsal Fifth metatarsal Calcaneus	L/R FM1 L/R FM5 L/R FCC

Table 7-3 Anatomical landmarks used in shoulder, pelvis, femur and foot tracking; the marker listed in blue was removed during the dynamic trials. L/R represents Left/Right.

7.2.4 Experimental protocol

The experimental protocol in this study was similar to the ones describe in Chapter 4 (Study I) and Chapter 5, which includes:

- A static trial of the marker setup

- One static trial to digitise LASIS position (Chapter 4)
- One static trial to digitise RASIS position (Chapter 4)

Following completion of the static trial, the PSIS markers were removed as these were only required to digitise their positions. Subsequently subjects were instructed to complete five different activities under different load and backpack conditions. Both the type of backpack used and its subsequent weight was randomized using combination of permuted blocks, coin tossing and throwing dice. From Chapter 6, it was understood that 8% of the students carried a backpack mass of 17% to 25% of their BW, which was higher than the recommended limits (Ontario Chiropractic Association; American Academy of Pediatrics, 2012). Therefore, in this experiment the participants were asked to carry the two backpacks with two different load conditions: 17% and 25% BW. Soft sandbags were used to provide the weight in the packs, and additional iron bars were added to reach the required weights. The average mass of the backpack in 17% BW and 25% BW were 8.70 kg (range: 7.0 to 10.2 kg, SD: 1.1 kg) and 12.70 kg (range: 10.3 to 15.1 kg, SD: 1.5 kg), respectively.

In this experiment five different activities were completed by each subject to investigate the effect of the backpack load, includes: quiet standing, walking, Sit to stand and Stand to sit, ascending stairs (Stairs-up) and descending stairs (Stairs-down). Each of these activities is discussed below.

7.2.4.1 Quiet standing

During quiet standing subjects were asked to stand still for 90 seconds on a force plate and to minimize any visual distraction which may influence their stability, the participants were asked to look intently at the red circle that was located 4m in front of the subject and adjusted to his/her eye level (Figure 7-5).

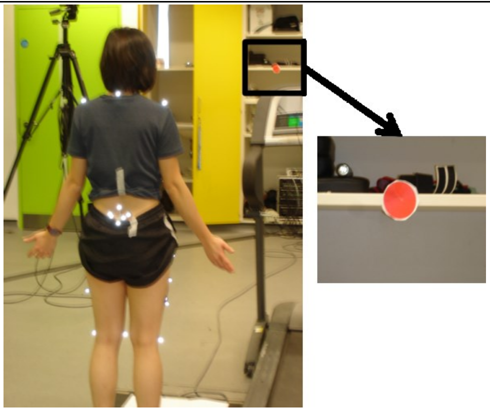

Figure 7-5 The red circle was used to minimize any unwanted movement due to distraction while standing still

Prior to the test, subjects were asked to stand on the force plate and their foot position was outlined on a piece of paper placed on the force plate. For each condition, the subjects were asked to position their feet on the same footprints drawn (Figure 7-6).

Figure 7-6 The position of the feet was marked on a paper and subjects were asked to stand on the same footprints each time to avoid any changes in positioning the feet

During this experiment a force plate (Kistler Holding AG, Winterthur, Switzerland) was used to measure the postural balance and stability of the participants. The force plate consists of four transducers which are located on each corner of the force plate and they measure the three components of force in x, y and z direction (Figure 7-7).

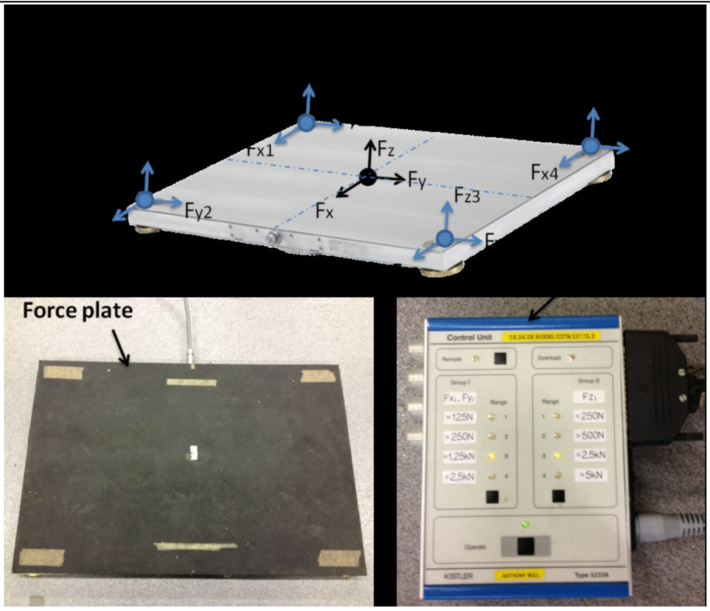

Figure 7-7 Illustration of the force components of each transducer (in blue) and the corresponding resultant force (in black), force plate and amplifier used in this study (Kistler, 2013)

The transducers send a signal proportional to the forces to an amplifier which then is transformed to reaction forces and moments. The location of the action of the resultant force on the force plate which is known as centre of pressure (CoP) is determined from the calculated forces and moments. Detailed calculation of the COP from forces and moments are given in Appendix D.

Each subject completed 5 quiet standing tests, these include: no backpack, ERGO backpack with 17% BW, ERGO backpack with 25% BW, COMF backpack with 17% BW and COMF backpack with 25% BW (Figure 7-8).

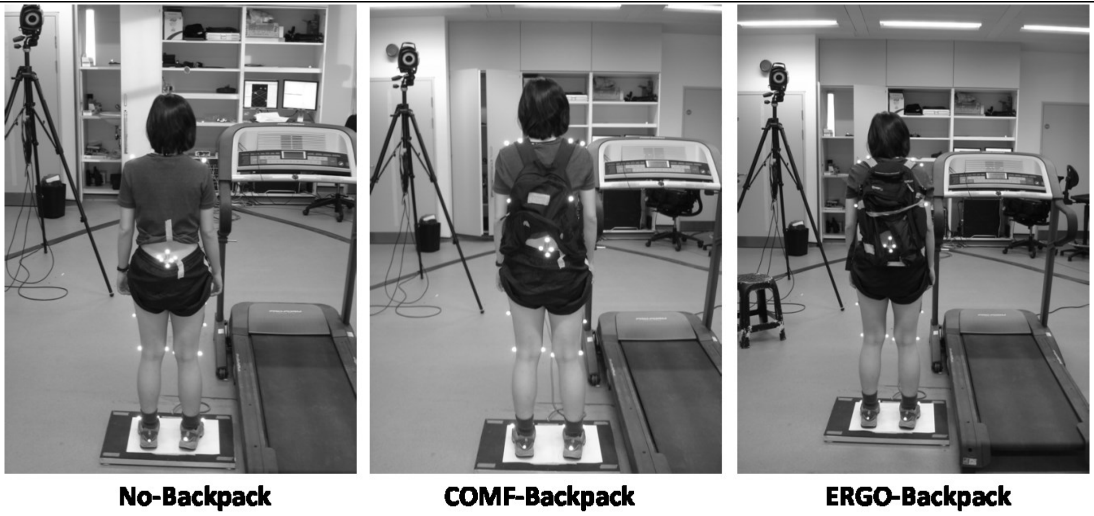
No-Backpack COMF-Backpack ERGO-Backpack

Figure 7-8 **Quiet standing while carrying no backpack, loaded COMF backpack and loaded ERGO backpack**

7.2.4.2 Walking

Each subject was required to walk on the treadmill under the five different load and backpack conditions. While the treadmill offers many advantages such as steady-state speed, concerns have been raised about differences between the gait patterns on the treadmill compared with the over ground walking (White et al. 1998). However some studies have reported that treadmill and over ground locomotion are the same if a constant speed is maintained on the treadmill during the experiment (Basset et al., 1985; Van Ingen Schenau, 1980). Several authors suggest that there is need for treadmill training particularly if the participants are unaccustomed to treadmill walking and the variability in the kinematic data associated with the training process could be common after ten minutes of treadmill walking (Charteris et al., 1978; Wall et al., 1980). Therefore, before collecting the data, subjects were asked to walk on the treadmill for minimum of 15 minutes to familiarize themselves to the treadmill. Only 3 subjects had never used the treadmill before. For each backpack type and load conditions, subjects walked for 2 minutes at a self selected speed and only the final 15 seconds of the trial was recorded. The speed that they chose for one condition was noted and used for the rest of the walking trials. Subjects walked with no backpack, ERGO 17% BW, ERGO 25% BW, COMF 17% BW and COMF 25% BW (Figure 7-9).

No-Backpack **COMF-Backpack** **ERGO-Backpack**

Figure 7-9 Walking while carrying no backpack, COMF backpack and ERGO backpack with different load conditions (17% and 25% BW)

7.2.4.3 Sit-to-stand & Stand-to-sit

Subjects were asked to rise from a seated position and sit on the backless stool (height of 46 cm) from a standing posture while carrying no backpack, Carrying ERGO backpack of 17% and 25% BW and carrying COMF backpack of 17% and 25% BW (Figure 7-10).

Figure 7-10 Sit-to-stand and Stand-to-sit while carrying no backpack, ERGO backpack and COMF backpack

7.2.4.4 Stairs-up & Stairs-down

The participants were also asked to ascend and descend from the bespoke steps while carrying no backpack and carrying the loaded ERGO and COMF backpacks, each time starting with their right foot.

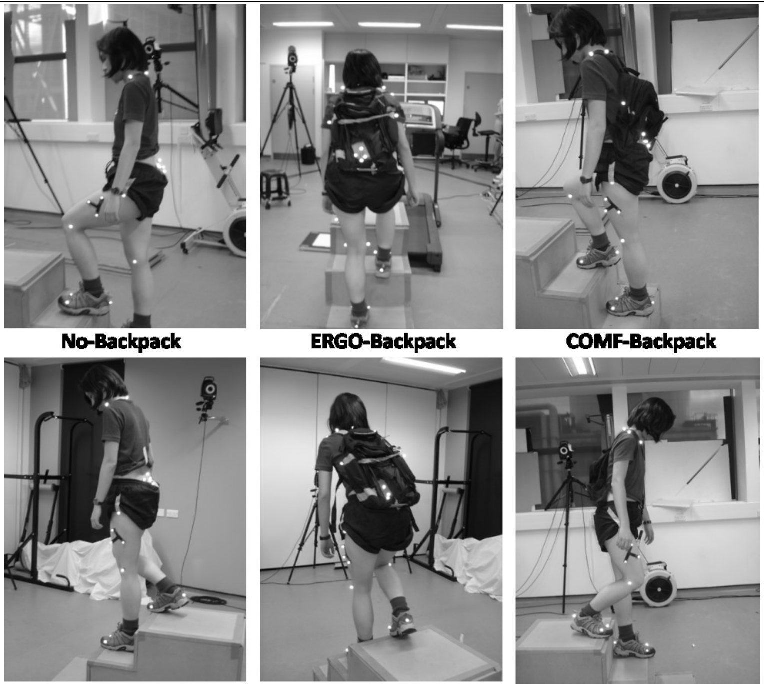

Figure 7-11 Ascending and descending the stairs while carrying no backpack, carrying loaded ERGO and COMF backpack

7.2.5 Data analysis

Data analysis was completed as described in Chapter 4. The digitisation of ASIS positions and definition of anatomical coordinate frames of the pelvis are given in Section 4.5.2.4. The positions of the PSIS markers were also digitised using the static trial as described in Chapter 5 (Section 5.2.4.1). The anatomical coordinate frame for the pelvis was defined according to Cappozzo et al. (1995) description and Table 7-4 provides a summary of this coordinate frame.

Segment	Definition of anatomical coordinate frame
Pelvis	*Origin* Midpoint between ASISs *X-axis* Parallel to the line connecting the ASISs, positive to the RASIS *Z-axis* Orthogonal to the plane defined by ASISs and PSISs, positive superiorly *Y-axis* Orthogonal to the plane defined by X and Z axes, positive anteriorly

Table 7-4 Definition of anatomical coordinate frames for pelvis, the underlined landmarks are the digitised bony landmarks with respect to the cluster.

The kinematic model developed in Chapter 5 (Section 5.2.4.3) was used to measure pelvic kinematics. Therefore, the absolute angle of pelvic tilt, pelvic obliquity and pelvic rotation were measured using Euler angles with X-Y’-Z” Cardan rotation (tilt, obliquity and rotation) relative to the laboratory axes.

Each subject completed five different activities. For each, the subjects carried a load of 0% (no backpack), 17% and 25% of the BW using two types of backpacks, and the order of the backpack and its weight was randomized. The kinematic data for walking, Stairs-Up and Stairs-down were normalised from 0% to 100% of the gait cycle between two successive toe-offs. For these activities, the ROM of the pelvis between the highest and lowest angle was calculated for one stride and the mean angular position for each pelvic motion (tilt, obliquity and rotation) was averaged over one stride for each trial.

In quiet standing, the location of the CoP was tracked for 90 seconds. The total distance traveled by the CoP in each condition was referred to as the sway length and was measured using the equation below (Kim et al. 2009):

$$\text{Sway Length} = \sum_{n=1}^{N} \sqrt{[X_n - X_{n-1}]^2 + [Y_n - Y_{n-1}]^2} \tag{7.1}$$

Where N is the number of data points (80,000). X_n represents the CoP magnitude in anterior-posterior plane (A-P) at point n while the Y_n, represent the CoP magnitude in medio-lateral plane (M-L). The sway length describes the absolute differences between successive CoP positions rather than their individual magnitudes. Another variable used to measure the postural stability in this thesis was through using the sway area. Sway area is the measurement of the area in which the CoP moves during the test (Kim et al., 2009). Therefore the smaller the area, the greater the postural stability. In this thesis the principal component analysis (PCA) method was used to calculate the sway area. PCA is a mathematical procedure that uses an orthogonal transformation to convert a set of possibly correlated variables into a set of values of uncorrelated variables; and it is a common procedure to determine the area of the body sway trajectories which is confined by the PCA of the covariant matrix (Oliveira et al., 1996). Therefore, CoP data points were firstly expressed as polar coordinates using the PCA method and then the body sway area was calculated by the area of the ellipse using the two principal axes of the component analysis. Detailed description of PCA calculations are given in Appendix F. MATLAB (R2013a, Mathworks, Natick, USA) and Microsoft Office Excel (2007) were used to calculate the sway area and sway length.

In addition to the sway length and sway area, the pelvic neutral position was also measured in the sagittal plane and compared for different backpack load conditions. The data recorded for the first 10s of quiet standing was removed to measure for subjects adjustment or any unwanted movement.

In Sit-to-stand and Stand-to-sit, the data was not normalised in order to investigate the effect of the loads on the time spend to complete the task. Also the ROM and mean angular position of the pelvis in the sagittal, frontal and transverse planes were calculated.

Repeated measure ANOVA, student t-test and regression analysis were used to measure the statistical differences between the data. Statistical significant was set for p values <0.05. The statistical tests were carried out using SPSS (version 20.0, Chicago, USA).

7.3 Results

In this section, results obtained for quiet standing, walking, Stairs-up, Stairs-down, Sit-to-stand and Stand-to-sit are presented.

7.3.1 Quiet standing

Sway area significantly increased from 2.30 cm^2 (range: 0.70 cm^2 to 4.48 cm^2) in the unloaded condition to 4.22 cm^2 (range: 2.93 cm^2 to 5.41 cm^2; p=0.000) in 17% BW ERGO, 5.35 cm^2 (range: 3.74 cm^2 to 11.20 cm^2; p=0.007) in 17% BW COMF, 4.97 cm^2 (range: 3.05 cm^2 to 7.96 cm^2; p=0.000) in 25% BW ERGO and 6.91 cm^2 (range: 3.74 cm^2 to 12.45 cm^2; p=0.002) in 25% BW COMF backpack (Figure 7-12).

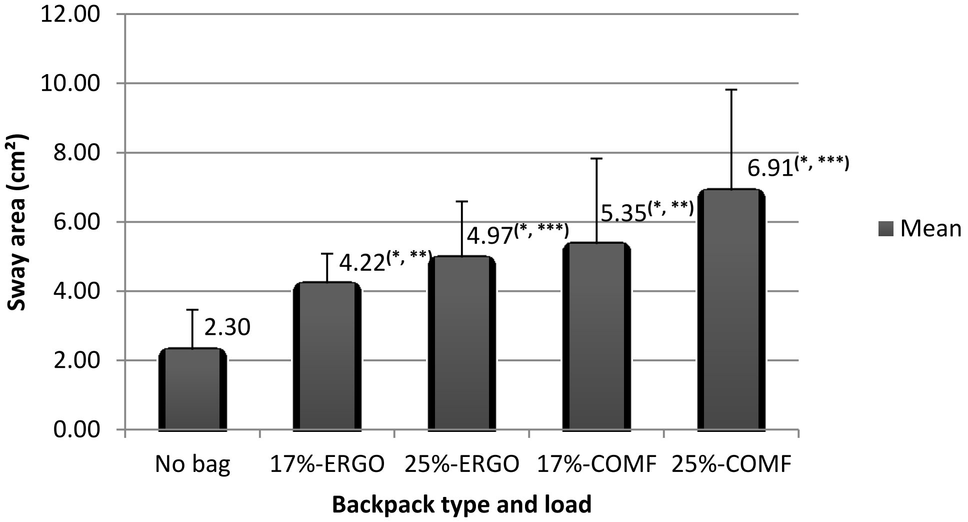

Figure 7-12 Sway area for five conditions with vertical black lines representing the standard deviation for each condition. Significant differences between the unloaded and loaded conditions are shown by *. Significant difference between the two backpacks loaded 17% and 25% BW are shown by ** and ***for p<0.05, respectively.

The mean sway area was significantly different between the two backpacks, with COMF backpack showed greater sway area than the ERGO backpack (p=0.033).

Sway length was also used as a measure of instability (Figure 7-13). The student t-test revealed that the sway length significantly increased from 83.06 cm (range: 40.95 cm to 130.69 cm) in unloaded condition to 108.48 cm (range: 62.99 cm to 198.86 cm; p=0.036) and 127.29 cm (range: 70.46 cm to 269.11 cm; p=0.045) in loaded condition of 17% BW and 25% BW using COMF backpack, respectively. Statistically, there were no significant differences between the unloaded condition and 17% and 25% BW using ERGO backpack (p=0.092 and p=0.066, respectively) which could be due to the sample size and this may be different with a greater sample size.

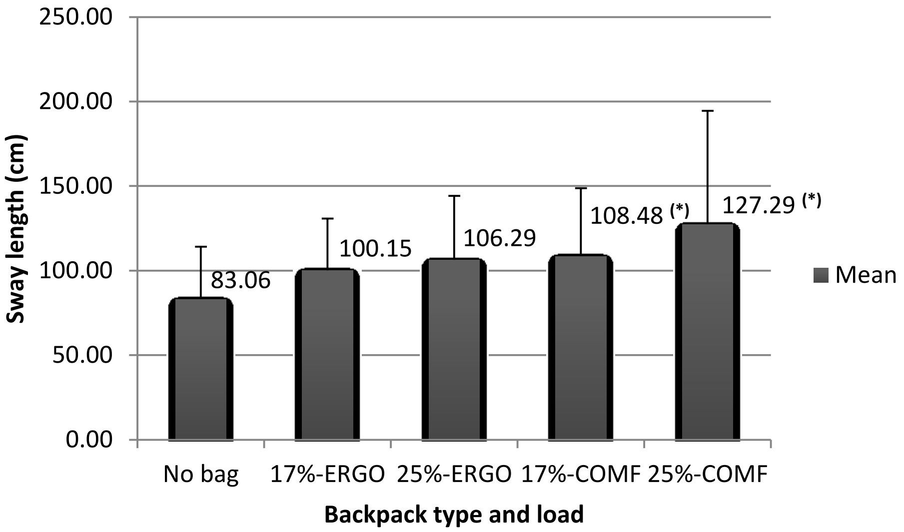

Figure 7-13 Sway length for five conditions with vertical black lines representing the standard deviation for each condition. Significant differences between the unloaded and loaded conditions are shown by * for p<0.05.

Beside sway length and sway area, pelvic tilt was also measured to investigate the effect of the different loaded conditions on the static posture of the pelvis in the sagittal plane. Figure 7-14 shows that as the load increased from 0% to 25% BW the pelvis was tilted more anteriorly.

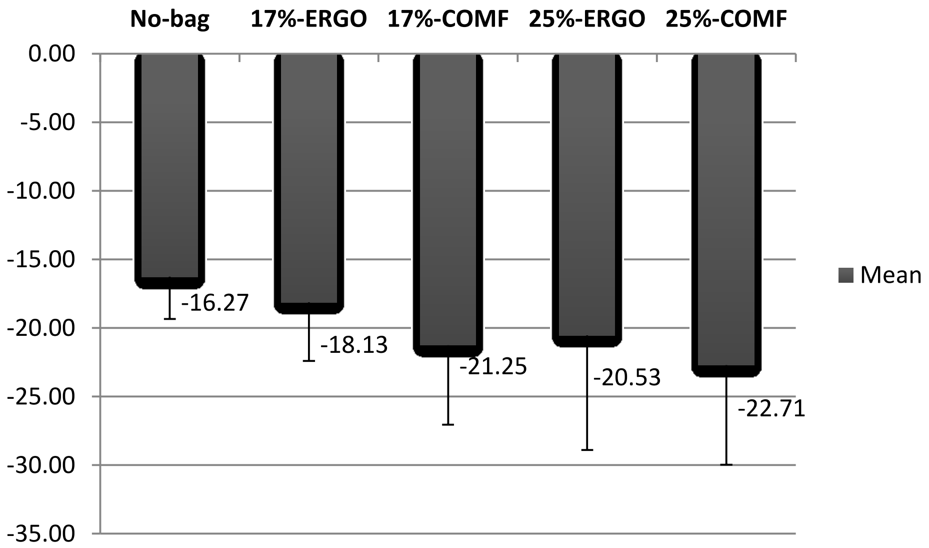

Figure 7-14 Pelvic posture during quiet standing for the two backpack types and load conditions of no backpack, 17% and 25% BW. Solid black vertical lines represent the standard deviations for each bar.

Pelvic tilt was also compared between female and male subjects using a linear regression analysis. Before conducting the regression analysis, pelvic tilt obtained from the loaded conditions was subtracted from unloaded condition for both male and female subjects to investigate their differences in loaded conditions with respect to unloaded condition (Table 7-5). This will allow better visualisation of the differences between the two genders. There were no significant correlations between the pelvic movement of the female and male subjects as load increased from 0% to 17% and 25% using both backpacks, ERGO and COMF.

Pelvic motion	**Carrying conditions**	**Quiet standing**		
		R^2	**Y=aX+b**	**p- value**
Pelvic tilt	**ERGO17%**	0.086	a=-4.0 b=1.97	0.316
	COMF17%	0.102	a=0.21 b=-2.99	0.300
	ERGO25%	0.222	a=0.76 b=-7.97	0.211
	COMF25%	0.007	a=0.05 b=-8.06	0.447

Table 7-5 Coefficient of determination (R^2) of difference of the unloaded and loaded conditions between the pelvic tilt of female and male subjects

Figure 7-15 shows the pelvic tilt of female and male subjects for different load conditions as well as mean differences between the unloaded and loaded conditions for each gender.

The graph of mean differences (Figure 7-15) demonstrates why the pelvic positions of the female and male subjects are not correlated. As load increased from 0% to 25% BW (for COMF) and 17% to 25% BW (for ERGO), the anterior pelvic tilt significantly increased for male subjects (p= 0.041 and p=0.035, respectively; Table 7-6). While for female subjects, statistically there were no significant differences between the values obtained for 17% and 25% BW using ERGO and COMF backpack (p>0.05).

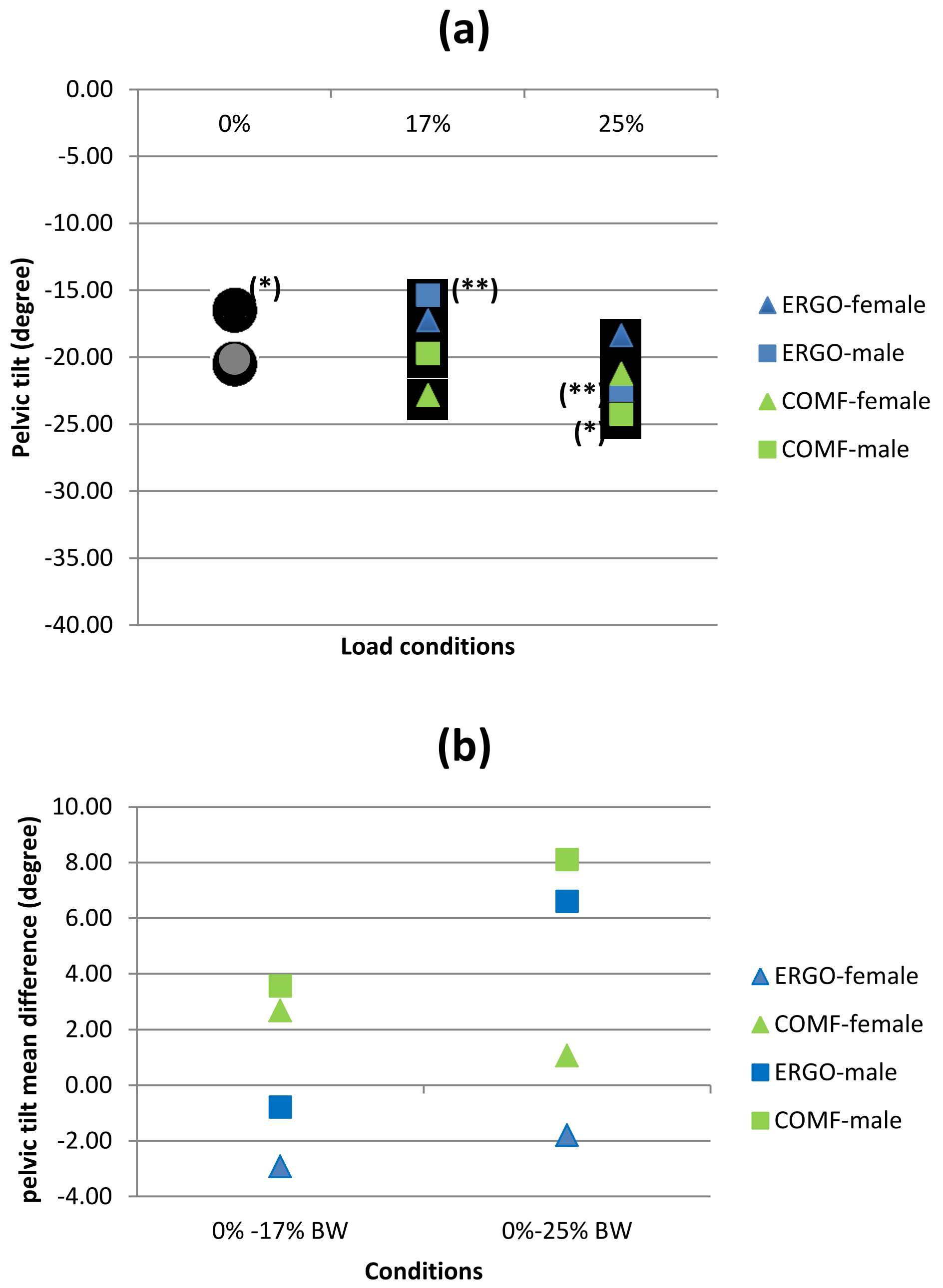

Figure 7-15 **(a) Pelvic tilt in quiet standing for female (triangle) and male (square) subjects using no backpack (black and gray circles represent pelvic static posture for male and female subjects in the sagittal plane, respectively), the ERGO (blue colour) and COMF (green colour) backpacks with load of 17% and 25% BW, (b) the differences between the unloaded and loaded conditions of 17% and 25% BW for female and male subjects (*represents the significant difference between the unloaded and loaded condition of 25% BW for male subject using COMF backpack; and ** represent the significant difference between the loaded condition of 17% and 25% BW for ERGO backpack for male subjects, p<0.05)**

Pelvic tilt	**Paired differences pelvic tilt (in degrees)**					
				%95 Confidence Interval of the difference		
Female	**Mean**	**Std. Deviation**	**Std.Err Mean**	**Upper Bound**	**Lower Bound**	**P-values**
NoBag-ERGO17%	-2.92	6.26	2.80	-10.69	4.85	0.355
NoBag-COMF17%	2.68	6.83	3.05	-5.81	11.16	0.430
NoBag-ERGO25%	-1.79	6.46	2.89	-9.81	6.22	0.568
NoBag-COMF25%	1.06	10.64	4.76	-12.15	14.27	0.834
ERGO17%-25%	1.13	8.56	3.83	-9.50	11.76	0.783
COMF17%-25%	-1.61	6.77	3.03	-10.02	6.79	0.622
ERGO-COMF17%	5.60	7.91	3.54	-4.22	15.42	0.189
ERGO-COMF25%	2.85	4.39	1.96	-2.59	8.30	0.219
Male						
NoBag-ERGO17%	-0.80	8.61	3.85	-11.49	9.90	0.846
NoBag-COMF17%	3.57	4.59	2.05	-2.13	9.26	0.157
NoBag-ERGO25%	6.61	10.39	4.65	-6.30	19.52	0.228
NoBag-COMF25%	8.11	6.10	2.73	0.53	15.68	**0.041**
ERGO17%-25%	7.40	5.26	2.35	0.87	13.94	**0.035**
COMF17%-25%	4.54	4.58	2.05	-1.14	10.23	0.091
ERGO-COMF17%	4.36	7.43	3.32	-4.87	13.59	0.260
ERGO-COMF25%	1.50	9.33	4.17	-10.09	13.09	0.373
Female- male						
NoBag	-4.02	4.12	1.84	-9.13	1.10	0.095
ERGO-17%	-1.89	12.19	5.45	-17.03	13.25	0.746
COMF-17%	-3.13	8.77	3.92	-14.02	7.77	0.470
ERGO-25%	4.38	6.81	3.04	-4.07	12.83	0.223
COMF-25%	3.03	12.93	5.78	-13.02	10.08	0.628

Table 7-6 Paired differences of quiet standing for female and male subjects using the t-test

Although there were no significant differences between the female and male subjects, Table 7-6 demonstrates a trend, indicating that this study might be underpowered.

7.3.2 Walking

With regards to the pelvic tilt, the ROM significantly increased from 5.86° (range: 4.09° to 9.32°) in the unloaded condition to 7.61° (range: 6.26° to 9.98°; p=0.031) and 8.33° (range: 4.83° to 11.88°; p=0.027) in the loaded conditions of 17% and 25% BW while carrying the COMF backpack, respectively (Figure 7-16). There were no significant differences between the ROM of the pelvis in unloaded condition and loaded condition of

17% and 25% BW while carrying the ERGO backpack (p= 0.325 and p=0.146, respectively; Figure 7-16).

The ROM of pelvic rotation significantly decreased from 14.65° (range: 5.36° to 34.57°) in the unloaded condition to 7.46° (range: 3.72° to 11.40°; p=0.019) and 7.65° (range: 4.99° to 13.94°; p= 0.034) in the loaded conditions of 17% and 25% BW while carrying the COMF backpack, respectively. Paired comparisons t-test showed that there were significant differences between the ROM obtained using the ERGO and COMF backpacks when loaded at 17% and 25% of body weight in the transverse plane (p=0.010 and p=0.003, respectively; Figure 7-16).

There were no significant differences in the ROM of pelvic obliquity between the unloaded and loaded conditions and no significant differences between the different type of the backpacks (0.078<p<0.963).

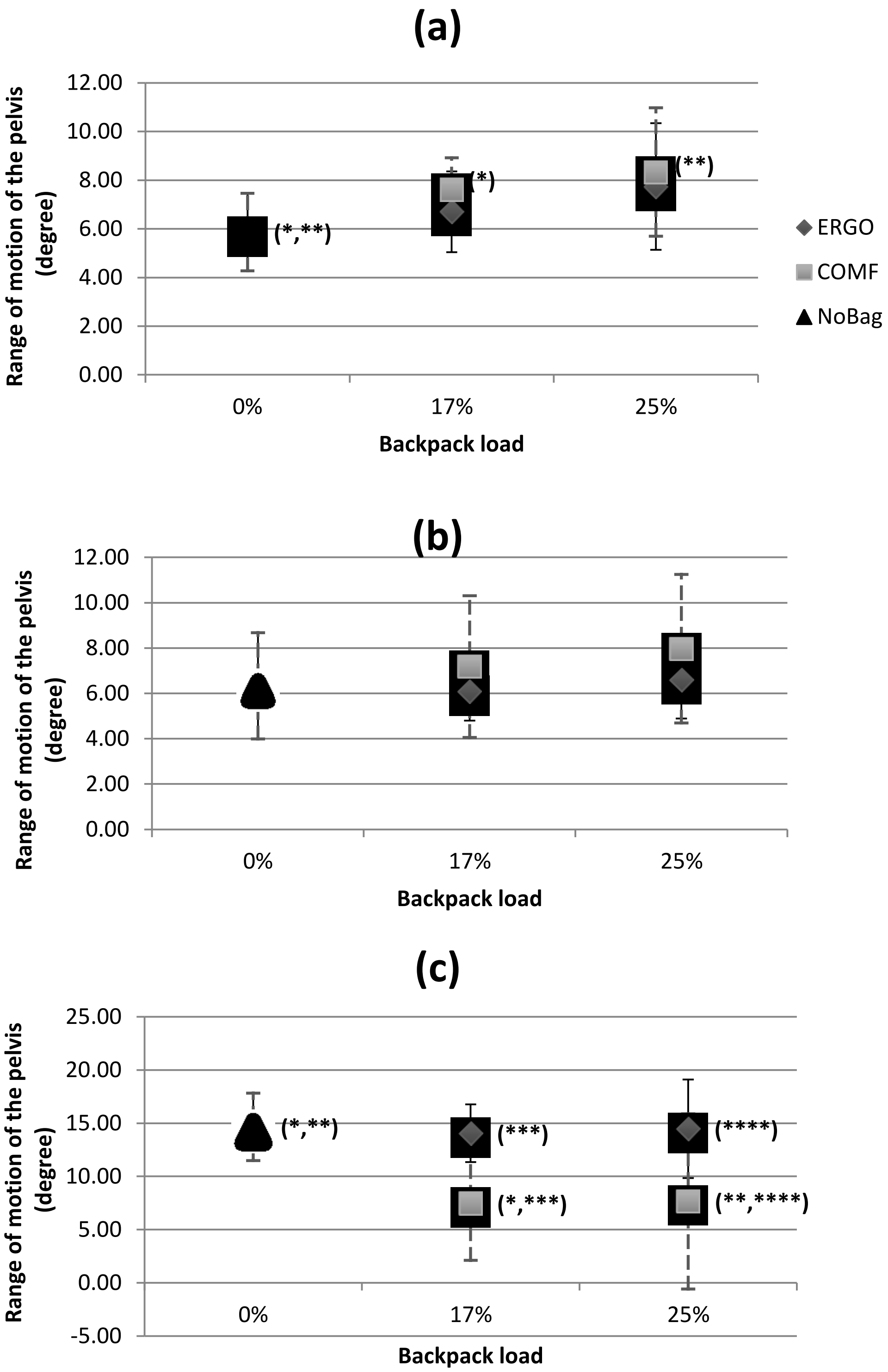

Figure 7-16 ROM of the pelvis in the (a) sagittal, (b) frontal and (c) transverse planes carrying no backpack (0%), ERGO and COMF backpacks loaded with 17% and 25% of subjects' BW. Standard deviations for ERGO and COMF backpacks are shown with solid vertical black line and dotted vertical gray line, respectively (*represents the significant difference between the unloaded and loaded condition of 17% BW for COMF backpack, ** represents the significant difference between the unloaded and loaded condition of 25% BW for COMF backpack, *** and **** represent the significant differences between the ERGO and COMF backpack in 17% and 25% BW conditions respectively, $p<0.05$)

Table 7-7 summarises the paired comparison tests of angular position of the pelvis in all three planes for different load conditions. It was shown that the pelvic tilt significantly decreased from -16.06° (range: -2.79° to -25.03°) for loaded condition of 17% BW to -18.63° (range: -6.01° to -27.57°) for loaded condition of 25% BW using the COMF backpack (p= 0.038; Table 7-7).

	Paired differences angular position (in degrees)					
				%95 Confidence Interval of the difference		
Pelvic tilt	**Mean**	**Std. Deviation**	**Std.Err Mean**	**Upper Bound**	**Lower Bound**	**P-values**
NoBag-ERGO17%	-0.17	3.68	1.16	-3.18	2.85	0.903
NoBag-COMF17%	1.38	4.22	1.33	-1.25	4.01	0.266
NoBag-ERGO25%	2.26	3.70	1.17	-1.02	5.53	0.153
NoBag-COMF25%	2.41	4.58	1.45	-0.23	5.05	0.069
ERGO17%-25%	1.03	1.99	0.63	-0.40	2.45	0.137
COMF17%-25%	2.43	3.15	1.00	0.17	4.68	**0.038**
ERGO-COMF17%	1.55	2.84	0.90	-0.49	3.58	0.119
ERGO-COMF25%	0.15	4.19	1.32	-2.84	3.15	0.912
Pelvic obliquity						
NoBag-ERGO17%	-1.40	1.78	0.56	-0.16	2.39	0.165
NoBag-COMF17%	1.11	2.93	0.93	-3.50	0.70	0.080
NoBag-ERGO25%	-0.05	3.36	1.06	-2.46	2.35	0.963
NoBag-COMF25%	-0.83	4.13	1.31	-3.78	2.12	0.540
ERGO17%-25%	1.35	4.01	1.27	-1.52	4.22	0.314
COMF17%-25%	-1.94	4.04	1.28	-4.84	0.95	0.163
ERGO-COMF17%	2.51	3.69	1.17	-0.13	5.16	0.060
ERGO-COMF25%	-0.78	5.19	1.64	-4.49	2.93	0.646
Pelvic rotation						
NoBag-ERGO17%	-0.65	3.39	1.07	-3.08	1.77	0.557
NoBag-COMF17%	-4.49	4.50	1.42	-7.70	-1.27	**0.012**
NoBag-ERGO25%	0.67	5.93	1.87	-3.57	4.90	0.731
NoBag-COMF25%	-2.42	5.48	1.73	-6.34	1.50	0.196
ERGO17%-25%	-1.76	7.27	2.30	-6.97	3.44	0.463
COMF17%-25%	5.15	5.27	1.67	1.39	8.92	**0.013**
ERGO-COMF17%	3.83	5.83	1.84	-0.34	8.01	0.067
ERGO-COMF25%	-3.08	8.84	2.80	-9.41	3.24	0.299

Table 7-7 Paired comparison between unloaded and loaded conditions during walking

There were also no significant differences in the pelvic obliquity among different conditions (p>0.05; Table 7-7). Paired comparison t-test revealed that pelvic rotation was significantly different among walking conditions which are summarised in Table 7-7.

A linear regression analysis of the pelvic tilt and rotation ROM revealed that there were no significant correlations between the male and female subjects' ROM and angular position of the pelvis in the sagittal and transverse planes (Table 7-8).

Pelvic motion	**Carrying conditions**	**ROM**			**Angular position**		
		R^2	**Y=aX+b**	**p- value**	**R^2**	**Y=aX+b**	**p- value**
Pelvic tilt	**NoBag**	0.422	a=0.33 b=-3.39	0.118	0.771	a=1.98 b=14.85	**0.025**
	ERGO17%	0.014	a=-0.17 b=-8.41	0.425	0.647	a=2.06 b=15.18	**0.050**
	COMF17%	0.210	a=-0.84 b=-14.01	0.219	0.533	a=0.92 b=-1.83	0.081
	ERGO25%	0.023	a=0.42 b=-4.69	0.404	0.493	a=0.73 b=-2.34	0.093
	COMF25%	0.038	a=-0.69 b=-12.15	0.376	0.269	a=0.51 b=-9.70	0.185
Pelvic obliquity	**NoBag**	0.711	a=1.35 b=0.82	**0.036**	0.747	a=0.93 b=-1.03	**0.029**
	ERGO17%	0.621	a=1.24 b=1.00	**0.049**	0.648	a=1.27 b=3.08	**0.050**
	COMF17%	0.701	a=0.60 b=-2.23	**0.039**	0.657	a=0.79 b=5.98	**0.048**
	ERGO25%	0.695	a=0.37 b=-2.57	**0.040**	0.772	a=1.05 b=-1.07	**0.025**
	COMF25%	0.811	a=0.57 b=-2.76	**0.019**	0.900	a=0.66 b=-2.14	**0.007**
Pelvic rotation	**NoBag**	0.007	a=0.04 b=-12.88	0.446	0.124	a=-0.27 b=-0.78	0.280
	ERGO17%	0.593	a=-0.65 b=-22.93	0.064	0.377	a=-0.42 b=5.80	0.135
	COMF17%	0.329	a=0.50 b=-3.28	0.156	0.313	a=-0.47 b=-1.22	0.163
	ERGO25%	0.406	a=0.40 b=-8.67	0.124	0.516	a=-0.86 b=-2.81	0.086
	COMF25%	0.247	a=-0.65 b=-13.17	0.197	0.518	a=1.06 b=-0.64	0.085

Table 7-8 Coefficient of determination (R^2) for every condition across three rotations in walking

7.3.3 Stairs-up

The pelvic ROM was calculated and compared for loaded and unloaded conditions in all three planes (sagittal, frontal and transverse). Figure 7-17 shows the mean ROM of pelvic tilt values while ascending the stairs.

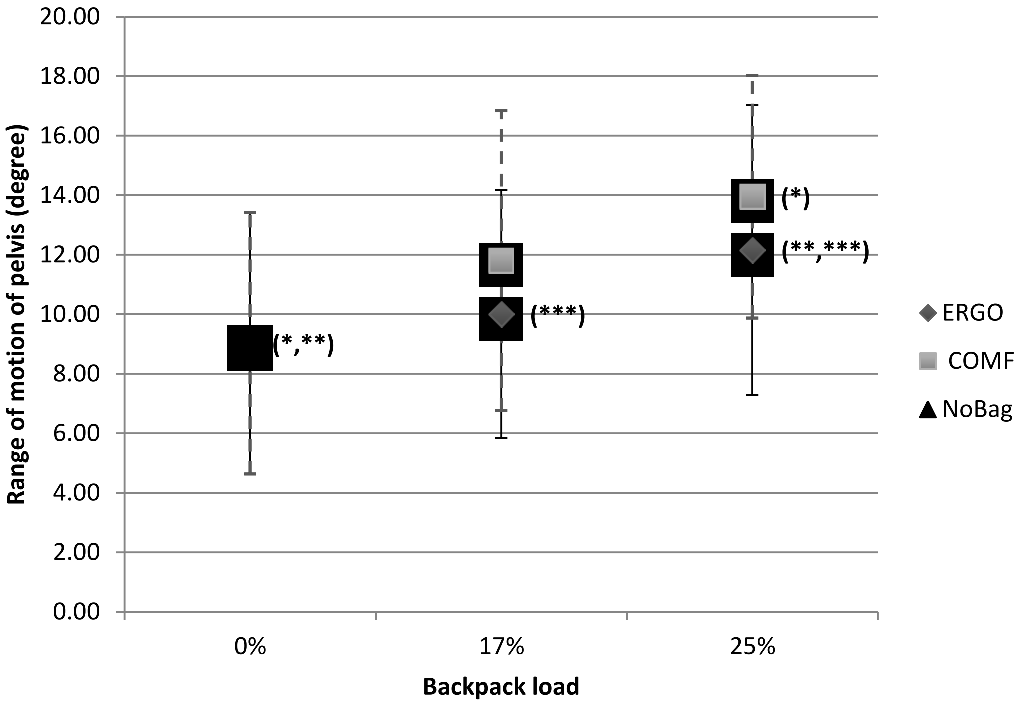

Figure 7-17 ROM of pelvic tilt during ascending the stairs carrying no backpack (0%), ERGO and COMF backpacks loaded with 17% and 25% of BW (vertical solid line and dotted line represent the inter-subject variability for ERGO and COMF backpacks, respectively). * and ** represent the significant differences between the unloaded and loaded condition of 25% BW using COMF and ERGO backpacks respectively, p<0.05. ***represents the significant difference between the 17% and 25% BW conditions using ERGO backpack, p<0.05.

Paired sample student t-test revealed that the ROM of pelvic tilt was significantly increased from 9.03° (range: 5.36° to 20.26°) for the unloaded condition to 12.16° (range: 5.87° to 21.79°; p=0.026) and 13.95° (range: 7.72° to 21.90°; p=0.009) for 25% of BW carrying ERGO and COMF backpack, respectively (Table 7-9).

	Paired differences ROM (in degrees)					
				%95 Confidence Interval of the difference		
Pelvic tilt	**Mean**	**Std. Deviation**	**Std.Err Mean**	**Upper Bound**	**Lower Bound**	**P-values**
NoBag-ERGO17%	-0.98	3.02	0.95	-3.14	1.18	0.331
NoBag-COMF17%	-2.78	6.67	2.11	-7.55	1.99	0.220
NoBag-ERGO25%	-3.14	3.74	1.18	-5.81	-0.46	**0.026**
NoBag-COMF25%	-4.93	4.70	1.49	-8.29	-1.56	**0.009**
ERGO17%-25%	-2.15	1.76	0.56	-3.41	-0.89	**0.004**
COMF17%-25%	-2.15	5.98	1.89	-6.42	2.13	0.285
ERGO-COMF25%	-1.79	4.11	1.30	-4.73	1.15	0.201
ERGO-COMF17%	-1.80	4.58	1.45	-5.07	1.48	0.246
Pelvic obliquity						
NoBag-ERGO17%	-0.04	2.50	0.79	-1.83	1.74	0.957
NoBag-COMF17%	-0.94	3.51	1.11	-3.46	1.57	0.417
NoBag-ERGO25%	-1.78	3.09	0.98	-3.98	0.43	0.102
NoBag-COMF25%	-4.03	5.58	1.76	-8.03	-0.04	**0.048**
ERGO17%-25%	-1.73	2.04	0.64	-3.19	-0.27	0.081
COMF17%-25%	-3.09	4.97	1.57	-6.64	0.47	**0.025**
ERGO-COMF25%	-2.26	3.56	1.13	-4.81	0.29	0.076
ERGO-COMF17%	-0.90	3.57	1.13	-3.46	1.65	0.446
Pelvic rotation						
NoBag-ERGO17%	-0.68	5.86	1.85	-4.87	3.51	0.722
NoBag-COMF17%	-9.43	10.26	3.24	-16.77	-2.09	**0.017**
NoBag-ERGO25%	-1.88	8.50	2.69	-7.96	4.20	0.502
NoBag-COMF25%	-18.37	18.54	5.86	-31.64	-5.22	**0.012**
ERGO17%-25%	-1.20	6.86	2.17	-6.11	3.71	0.593
COMF17%-25%	-8.94	19.76	6.25	-23.08	5.20	0.186
ERGO-COMF25%	-16.49	14.95	4.73	-27.19	-5.79	**0.007**
ERGO-COMF17%	-8.75	11.20	3.54	-16.76	-0.74	**0.035**

Table 7-9 Result of student t-test for the pelvic ROM

Repeated measure ANOVA with two within subject factors (backpack loads and backpack types) revealed a significant difference between the performance of the two backpacks in which the ERGO backpack had less effect on ROM of the pelvis than the COMF backpack (p=0.030).

The result also showed a significant interaction between the gender and load conditions in the sagittal plane (p=0.037). The effect of backpack load on pelvic ROM of the male subjects while carrying a load of 17% BW was 31% higher than the ROM of the pelvis for female subject under the same load condition. The ROM of the pelvis was less affected in female subjects than male subjects. The ROM of the pelvis obtained in the sagittal plane for 17% and 25% BW load conditions in female subjects were 8% and 38% higher than the unloaded condition while the ROM of the pelvis in male subjects for 17% and 25% BW load conditions were 35% and 50% higher than the unloaded condition.

Effect of backpack load was also investigated on pelvic obliquity during ascending the stairs (Figure 7-18).

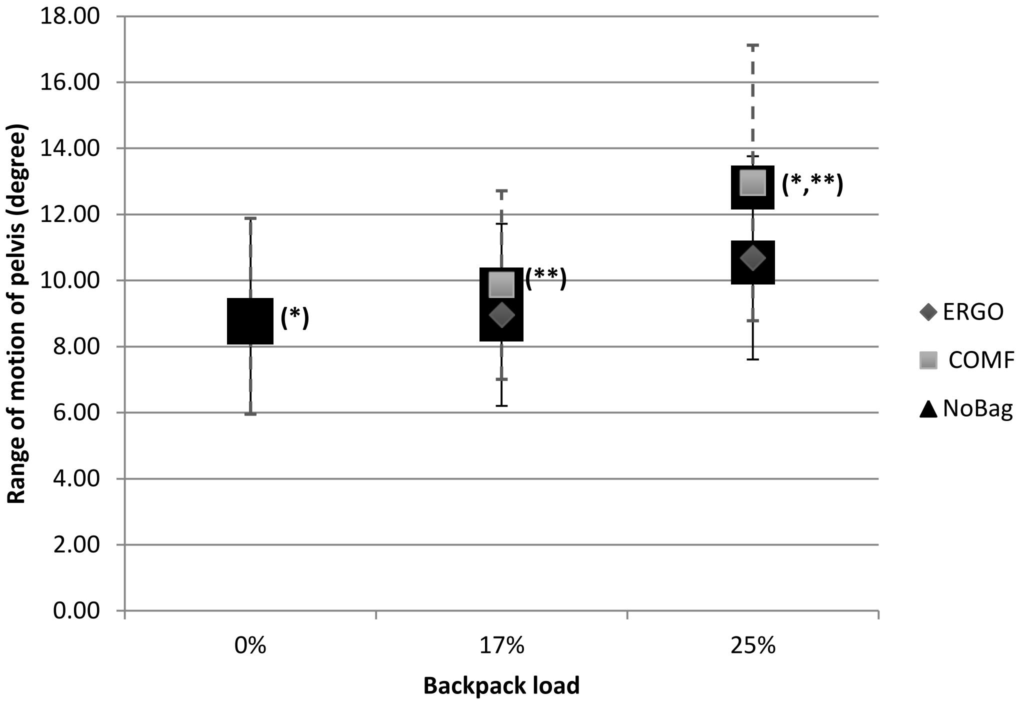

Figure 7-18 ROM of the pelvis in the frontal plane during ascending the stairs carrying no backpack (0%) and carrying ERGO and COMF backpacks with load of 17% and 25% of body weight (vertical solid line and dotted line represent the inter-subject variability (SD) for ERGO and COMF backpacks, respectively). *represents the significant difference between the unloaded and loaded condition of 25% BW using COMF backpack and ** represent the significant difference between the 17% and 25% BW conditions using COMF backpack, p<0.05.

The ROM of pelvic obliquity significantly increased from 8.92° (range: 5.21° to 15.22°) in the unloaded condition to 12.95° (range: 7.55° to 21.94°) in the loaded condition of 25% BW carrying the COMF backpack (p=0.048; Table 7-9). There were no significant differences between the ROM of the pelvis in unloaded condition and loaded condition of 17% BW carrying ERGO and COMF backpacks (p=0.957; p=0.417).

Figure 7-19 shows the result obtained for the ROM of the pelvis in the transverse plane (pelvic rotation).

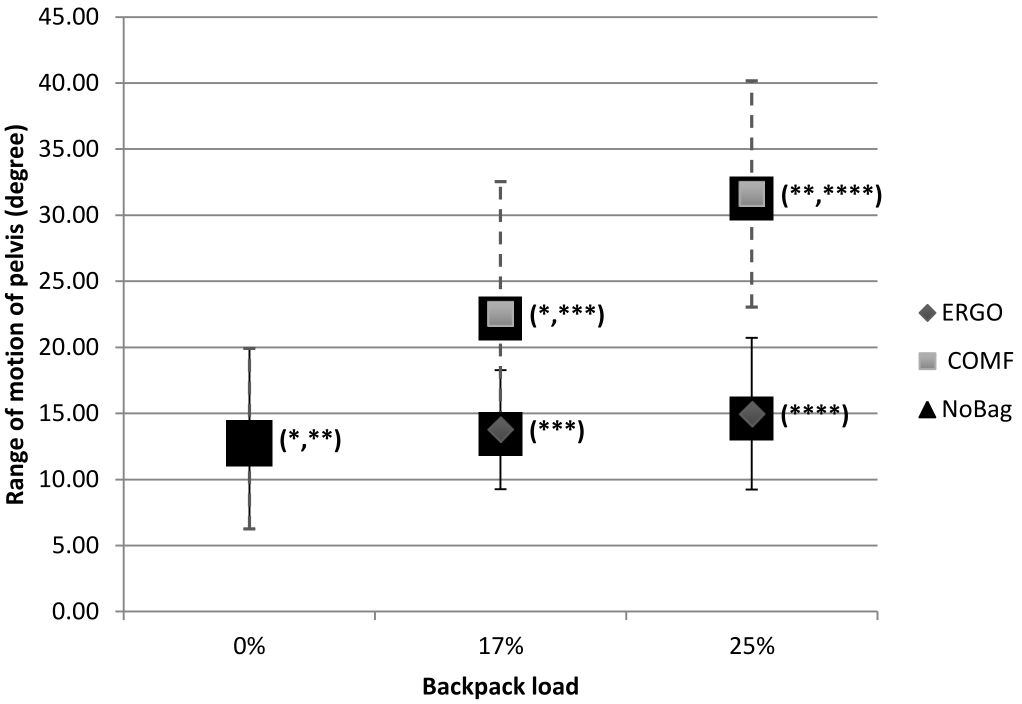

Figure 7-19 ROM of the pelvis in the transverse plane during ascending the stair carrying no backpack (0%), ERGO and COMF backpacks loaded with 17% and 25% of weight of the subjects (vertical solid line and dotted line represent the inter-subject variability (SD) for ERGO and COMF backpacks, respectively). * and **represent the significant differences between unloaded and loaded condition of 17% and 25% BW for COMF backpack respectively, p<0.05. ***and** represent the significant differences between the ERGO and COMF backpack in loaded conditions of 17% and 25% BW respectively, p<0.05.**

The student t-test showed that ROM of pelvic rotation significantly increased from 13.09° (range: 3.49° to 20.06°) in the unloaded condition to 22.53° (range: 13.60° to 47.82°; p=0.017) for COMF backpack with %17 BW and 31.61° (range: 9.03° to 65.57°; p=0.012) for COMF backpack with 25% BW. While the performance of the ERGO backpack for both load conditions was significantly similar to the unloaded condition, it performance was significantly different from COMF backpack in pelvic rotation (p<0.05; Table 7-9).

Regression analysis confirmed a linear correlation between the ROM of the pelvis in female and ROM of the pelvis in male for unloaded condition (p<0.05; Table 7-10). However there were no significant correlations between the ROM of the pelvis for the two genders in loaded conditions which could show that the male and female subjects used different type of mechanism to compensate for the influence of the load carriage while ascending the stair (p>0.05; Table 7-10). Also no significant correlation was found between the mean angular position of the pelvis for female and male subjects for all loaded conditions (p>0.05; Table 7-10).

Pelvic motion	**Carrying conditions**	**ROM**			**Angular position**		
		R^2	**Y=aX+b**	**p- value**	**R^2**	**Y=aX+b**	**p- value**
Pelvic tilt	**NoBag**	0.694	a=2.37 b=-12.27	**0.040**	0.01	a=0.17 b=-15.08	0.434
	ERGO17%	0.562	a=0.63 b=1.01	0.072	0.385	a=0.64 b=-5.95	0.132
	COMF17%	0.206	a=-0.11 b=7.62	0.221	0.243	a=0.53 b=-4.99	0.199
	ERGO25%	0.426	a=0.49 b=3.63	0.116	0.322	a=0.90 b=1.67	0.159
	COMF25%	0.017	a=0.09 b=11.96	0.416	0.142	a=0.39 b=-11.11	0.266
Pelvic obliquity	**NoBag**	0.833	a=0.71 b=-0.73	**0.015**	0.816	a=0.42 b=-8.82	**0.046**
	ERGO17%	0.029	a=0.29 b=3.93	0.393	0.624	a=0.77 b=1.81	0.056
	COMF17%	0.160	a=0.52 b=5.11	0.252	0.542	a=0.61 b=-3.82	0.078
	ERGO25%	0.165	a=-0.33 b=12.86	0.249	0.447	a=0.65 b=-0.82	0.108
	COMF25%	0.202	a=0.35 b=7.34	0.224	0.252	a=0.38 b=-5.54	0.195
Pelvic rotation	**NoBag**	0.834	a=0.83 b=1.01	**0.015**	0.725	a=-0.18 b=-10.64	**0.034**
	ERGO17%	0.471	a=0.38 b=8.65	0.100	0.377	a=-0.28 b=-5.92	0.135
	COMF17%	0.443	a=-2.17 b=65.44	0.110	0.011	a=0.17 b=-15.08	0.434
	ERGO25%	0.367	a=-0.33 b=18.59	0.140	0.013	a=-0.10 b=-10.65	0.427
	COMF25%	0.004	a=0.04 b=32.78	0.460	0.369	a=0.295 b=-3.045	0.139

Table 7-10 Coefficient of determination (R^2) for every condition across three rotations

The mean angular position of the pelvis was measured in the sagittal (pelvic tilt), frontal (pelvic obliquity) and transverse (pelvic rotation) planes. Table 7-11 summarises all the results for mean angular position of the pelvis.

In pelvic tilt, there was only a significant difference between the mean angular position of the pelvis in unloaded and loaded condition of 25% of BW using COMF backpack (p=0.005). However repeated measure analysis of ANOVA showed a significant difference between the angular position of the pelvis in 17% BW and 25% of BW loads for the two backpacks in pelvic tilt (p=0.034).

Carrying conditions	Angular position (degree±SD)		
	Pelvic tilt	Pelvic obliquity	Pelvic rotation
NoBag	-20.81(6.98)[a]	-15.73(3.78)	-1.32(4.30)
ERGO-17%	-22.09(8.86)[c]	-15.90(2.71)	-5.12(5.95)
COMF-17%	-23.30(8.28)[b]	-15.15(5.58)	-9.28(7.66)
ERGO-25%	**-23.44(8.72)**[c]	-16.41(3.23)	-6.43(5.92)
COMF-25%	**-24.56(8.93)**[a,b]	-16.79(6.96)	-8.09(6.22)

Table 7-11 Mean angular position of the pelvis for pelvic tilt, obliquity and rotation for five different carrying conditions, the letters ‘a’, ’b’ and ’c’ represent significant differences (p<0.05) with bold number represent the higher absolute value.

Statistically, there were no significant differences between the mean angular position of the pelvis in unloaded condition and loaded conditions in pelvic obliquity and pelvic rotation (p>0.05).

7.3.4 Stairs-down

The mean angular position of the pelvis in the sagittal plane significantly decreased from -16.09° (range: -6.77° to -22.69°) for the unloaded condition to -19.13° (range: -1.41° to -29.15°; p=0.037) and -19.60° (range:-3.64° to -31.49°; p=0.05) for the loaded condition of 17% and 25% of BW carrying COMF backpack. There were significant differences between the COMF and ERGO backpacks carrying a load of 17% of BW; in which the angular position of the pelvis was less for ERGO backpack (Mean: -16.21°; range: -0.69° to -29.24°; p=0.039) than COMF backpack (Figure 7-20).

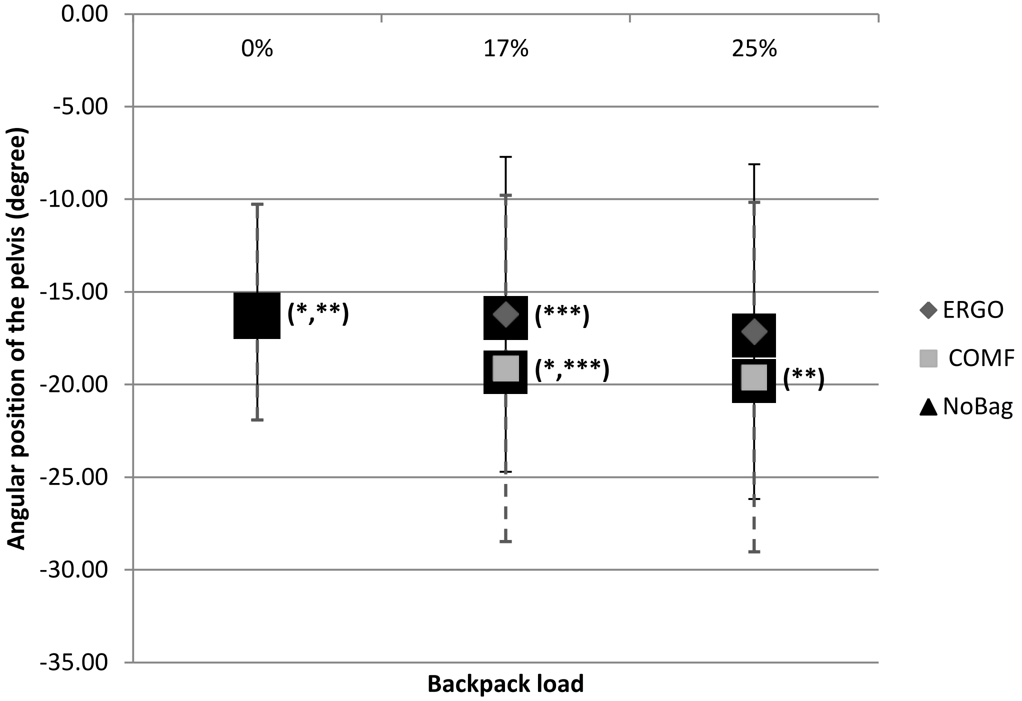

Figure 7-20 Mean angular position of the pelvis in the sagittal plane during descending the stairs for all subjects carrying no backpack, COMF backpack and ERGO backpack loaded with 17% and 25% of body weight of the subjects (vertical lines represent the inter-subject variability (standard deviation) for NoBag, ERGO and COMF conditions). *, and *** represent the significant differences between unloaded and loaded conditions for COMF and ERGO backpacks with $p<0.05$.**

In terms of pelvic obliquity, there were no significant differences between the values obtained for unloaded and loaded conditions during descending the stairs ($p>0.05$; Figure 7-21).

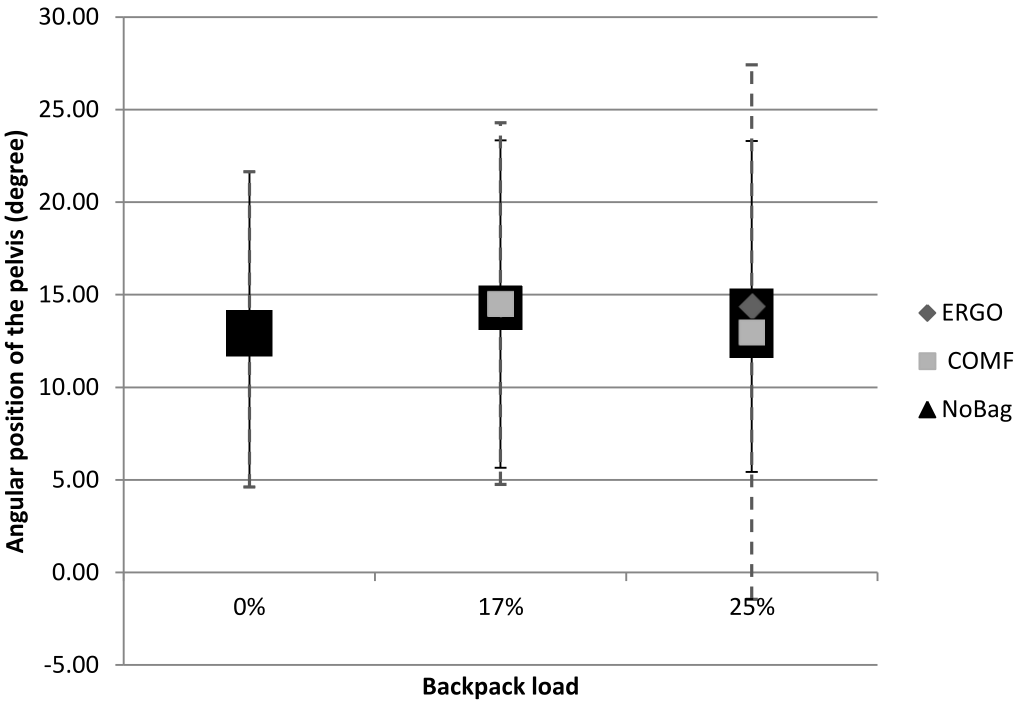

Figure 7-21 Mean angular position of the pelvis in the frontal plane during descending the stairs for 5 different conditions: no backpack, ERGO backpack loaded with 17% and 25% of subjects' body weight and COMF backpack loaded with 17% and 25% of subjects' body weight (vertical lines represent the standard deviations.)

In Pelvic rotation, the mean angular position of the pelvis significantly decreased from 15.33° (range: 7.89° to 29.97°) in the unloaded condition to 5.20° (range: -12.59° to 24.68°; p=0.005) in the loaded condition of 25% BW using COMF backpack (Figure 7-22). There were no significant differences between the angular position of pelvis in unloaded condition and loaded conditions of 17% and 25% of body weight carrying the ERGO backpack. There was a significant difference between the performance of the two backpacks while carrying a load of 25% BW (Mean difference=7.87°, Std. Deviation=12.86°; p=0.049).

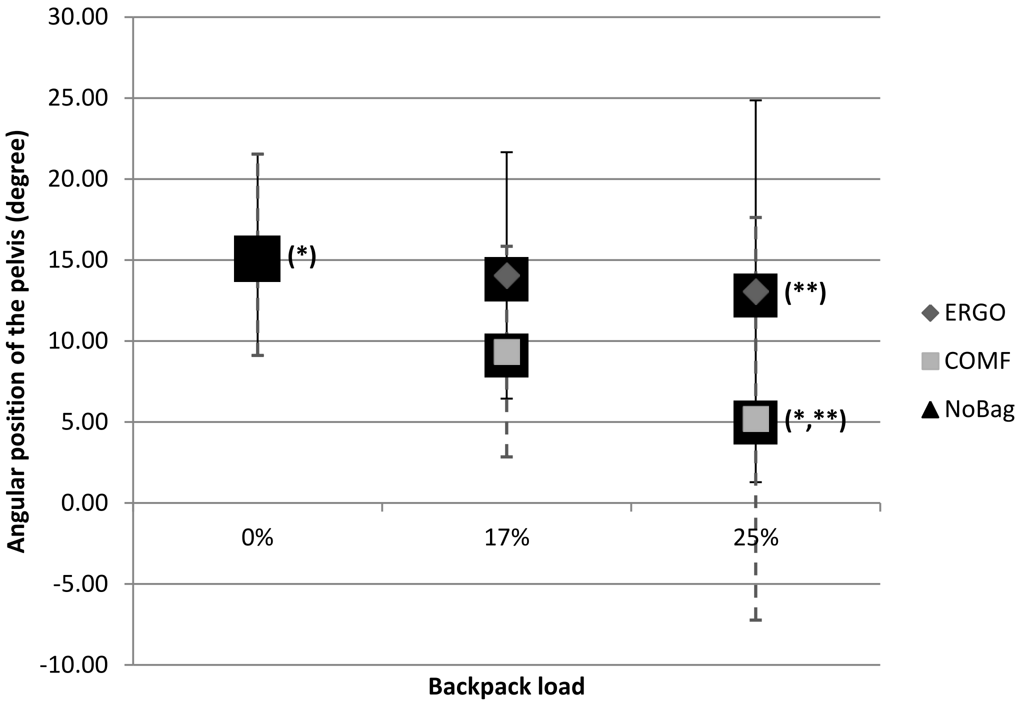

Figure 7-22 Mean angular position of the pelvis in the transverse plane during descending the stairs for different backpack loads and conditions (vertical lines represent the standard deviations). *represents the significant difference between the unloaded and loaded conditions and **represent the significant differences between the backpack types, with p<0.05.

The student t-test revealed that statistically there were no significant differences between the ROM of the pelvis in unloaded condition and loaded conditions in all three planes (Table 7-12). However a significant difference was detected between the obtained ROM using the ERGO backpack and COMF backpack while carrying a load of 17% BW in sagittal plane (pelvic tilt, Table 7-12).

	Paired differences ROM (in degrees)					
				%95 Confidence Interval of the difference		
Pelvic tilt	**Mean**	**Std.Dev**	**Std.Err**	**Lower Bound**	**Upper Bound**	**P-values**
NoBag-Ergo17%	0.33	3.14	0.99	-1.91	2.57	0.747
NoBag-Comf17%	-2.71	4.78	1.51	-6.13	0.71	0.106
NoBag-Ergo25%	-1.10	5.38	1.70	-4.95	2.75	0.535
NoBag-Comf25%	-2.46	4.47	1.41	-5.66	0.74	0.116
ERGO-COMF17%	-3.04	4.21	1.33	-6.05	-0.32	**0.048**
Ergo-Comf25%	-1.36	8.31	2.63	-7.31	4.58	0.617
Ergo17%-25%	-1.43	4.57	1.44	-4.70	1.84	0.349
Comf17%-25%	0.25	7.61	2.41	-5.19	5.70	0.919
Pelvic obliquity						
NoBag-Ergo17%	0.39	1.84	0.58	-0.92	1.70	0.520
NoBag-Comf17%	-1.57	3.50	1.11	-4.07	0.93	0.190
NoBag-Ergo25%	0.061	4.21	1.33	-2.95	3.07	0.964
NoBag-Comf25%	-0.38	5.58	1.77	-4.37	3.62	0.836
Ergo-Comf17%	-1.96	3.09	0.98	-4.17	0.25	0.079
Ergo-Comf25%	-0.44	6.67	2.11	-5.21	4.33	0.840
Ergo17%-25%	-0.33	3.52	1.11	-2.85	2.19	0.775
Comf17%-25%	1.19	6.06	1.92	-3.14	5.53	0.549
Pelvic rotation						
NoBag-Ergo17%	-1.83	6.15	1.94	-6.22	2.57	0.372
NoBag-Comf17%	0.90	4.06	1.28	-2.00	3.80	0.500
NoBag-Ergo25%	-4.27	10.01	3.16	-11.43	2.89	0.210
NoBag-Comf25%	-5.26	13.03	4.12	-14.57	4.06	0.234
Ergo-Comf17%	2.73	4.85	1.53	-0.74	6.20	0.109
Ergo-Comf25%	-0.99	13.29	4.20	-10.50	8.52	0.819
Ergo17%-25%	-2.44	7.98	2.52	-8.15	3.27	0.359
Comf17%-25%	-6.16	11.99	3.79	-14.74	2.42	0.139

Table 7-12 Mean differences of ROM of the pelvis, standard deviation, standard errors, 95% confidence interval of the difference and probability values for each pair of conditions in pelvic tilt, obliquity and rotation during descending the stairs.

Linear regression analysis showed there were no significant correlations between the ROM and angular position of the pelvis of the female and male subjects (Table 7-13).

Pelvic motion	Carrying conditions	ROM			Angular position		
		R^2	Y=aX+b	p- value	R^2	Y=aX+b	p- value
Pelvic tilt	**NoBag**	0.021	a=-0.12 b=9.46	0.408	0.002	a=-0.05 b=-15.18	0.474
	ERGO17%	0.064	a=-0.22 b=9.30	0.341	0.001	a=0.07 b=-14.55	0.477
	COMF17%	0.312	a=-0.43 b=16.61	0.164	0.106	a=0.52 b=-6.03	0.297
	ERGO25%	0.064	a=-0.10 b=8.93	0.341	0.026	a=0.21 b=-10.83	0.397
	COMF25%	0.084	a=-0.16 b=11.69	0.318	0.228	a=0.07 b=1.93	0.208
Pelvic obliquity	**NoBag**	0.108	a=0.22 b=7.19	0.294	0.644	a=0.76 b=1.43	**0.050**
	ERGO17%	0.296	a=0.42 b=5.48	0.172	0.241	a=0.41 b=5.02	0.201
	COMF17%	0.196	a=0.38 b=6.81	0.228	0.056	a=-0.408 b=20.97	0.351
	ERGO25%	0.010	a=0.09 b=8.36	0.436	0.426	a=0.34 b=6.04	0.116
	COMF25%	0.047	a=-0.11 b=10.15	0.363	0.148	a=0.34 b=5.84	0.262
Pelvic rotation	**NoBag**	0.944	a=-0.43 b=19.26	**0.003**	0.658	a=0.44 b=12.07	**0.048**
	ERGO17%	0.016	a=-0.02 b=8.63	0.420	0.452	a=0.33 b=9.41	0.107
	COMF17%	0.314	a=-0.31 b=13.00	0.163	0.372	a=-0.55 b=14.02	0.138
	ERGO25%	0.254	a=0.90 b=7.97	0.194	0.310	a=0.38 b=5.88	0.165
	COMF25%	0.022	a=0.52 b=10.27	0.405	0.122	a=-0.26 b=4.39	0.282

Table 7-13 Coefficient of determination (R^2) for every condition across three rotations

7.3.5 Sit-to-stand and Stand-to-sit

Table 7-14 summarises the result for the mean angular position and ROM of the pelvic tilt, pelvic obliquity and pelvic rotation during the five different load conditions, also the time taken to complete the Sit-to-stand task for five different load conditions are presented.

Pelvic motion	Carrying conditions	Angular position (degree±SD)	ROM (degree±SD)	Duration (seconds±SD)
Pelvic tilt	**NoBag**	-21.33(9.82)^{a,b}	30.75(9.86)	1.17(0.17)^{h}
	ERGO-17%	-23.96(10.74)	30.58(9.68)	1.20(0.12)
	COMF-17%	-24.70(11.33)	26.69(13.15)	1.23(0.18)^{j}
	ERGO-25%	**-27.47(11.82)**^{a}	29.58(7.22)	1.29(0.26)^{i}
	COMF-25%	**-27.50(13.61)**^{b}	27.09(9.01)	**1.44(0.22)**^{h,I,j}
Pelvic obliquity	**NoBag**	0.22(4.88)	12.94(5.52)^{c}	
	ERGO-17%	1.06(5.20)	12.98(3.13)^{d}	
	COMF-17%	1.50(7.18)	**15.55(4.98)**^{d}	
	ERGO-25%	0.52(4.78)	13.13(5.47)^{e}	
	COMF-25%	-1.66(9.49)	**19.55(7.00)**^{c,e}	
Pelvic rotation	**NoBag**	9.15(4.76)	8.79(2.11)^{f}	
	ERGO-17%	8.71(4.51)	8.23(2.49)	
	COMF-17%	11.98(6.32)	15.06(10.44)	
	ERGO-25%	9.14(4.44)	8.61(6.34)^{g}	
	COMF-25%	12.12(5.06)	**17.37(8.16)**^{f,g}	

Table 7-14 Mean angular position and ROM (degree±SD) for pelvic tilt, obliquity and rotation during five carrying conditions during Sit-to-stand. The letters ‘a’,‘b’,’c’,’d’,‘e’,’f’, ‘g’, ‘h’, ‘i’ and ‘j’ represent significant differences ($p<0.05$) with bold numbers represent the higher absolute value.

In Sit-to-stand, the pelvic angular position in the sagittal plane were -21.33° (range: -10.20° to 37.26°; Table 7-14) for the unloaded condition (NoBag). When subjects carried a load of 17% BW, the mean pelvic angular position for ERGO and COMF backpack were -23.96° (range: -7.65° to -39.92°; p=0.113) and -24.70 (range:-2.59° to -37.83°, p=0.243), this change did not reach statistical significance. As the load increased to 25% BW, the mean pelvic angular position significantly decreased to -27.47° (range: -5.95° to -47.47°; p =0.031) for ERGO backpack and -27.50° (range: -7.67° to -42.99°; p =0.041) for COMF backpack. ROM of pelvic obliquity and pelvic rotation were compared between the different conditions. The obtained ROM of pelvic obliquity were 12.94° (range: 5.68° to 21.24°) for no backpack and significantly increased to 19.55° (range: 10.01° to 32.93°; p =0.024) for COMF backpack with 25% BW load. Comparing the performance of the backpacks, the ROM of the pelvic obliquity significantly increased from 12.98° (range: 8.90° to 16.20°) for ERGO 17% BW to 15.55° (range: 8.00° to 22.05°) for COMF 17% BW (p =0.046). The ROM of pelvic obliquity for ERGO 25% of BW significantly increased from 13.13° (range 8.04° to 24.76°) to 19.55° (range: 10.01° to 32.93°) for COMF backpack with 25% of BW (p =0.020).

The ROM of Pelvic rotation significantly increased from 8.79° (range: 5.79° to 11.18°) for the unloaded condition to 17.37° (range: 5.96° to 30.41°) for COMF backpack with 25% of BW (p =0.011). Comparing the performance of the backpacks, the ROM of the pelvic rotation was significantly different between the ERGO backpack and COMF backpack during carrying a 25% of BW (p =0.01).

A repeated measure ANOVA revealed a significant interaction between the gender and the backpack type and loads (Table 7-15). During the unloaded condition, the pelvic ROM for the females and males were 26.53° (±7.25°) and 34.96° (±11.77°), respectively. The values reported for ERGO 17% BW is comparable to the unloaded condition for both genders. The pelvic ROM significantly decreased for boys from the unloaded condition to 25.78° (±10.11°) carrying a COMF with 17% BW, 26.62° (±9.07°) for ERGO 25%BW and 28.53° (±11.97°) for COMF 25% BW.

Load	Backpack type	Gender	Mean pelvic ROM (in degrees)	95% Confidence Interval (in degrees)		P-value Gender*load*Type
				Lower Bound	Upper Bound	
17%BW	**ERGO**	**Girl**	25.68	34.51	16.84	**0.039**
		Boy	35.49	44.33	26.65	
	COMF	**Girl**	27.60	38.42	16.79	
		Boy	25.78	36.60	14.7	
25%BW	**ERGO**	**Girl**	25.66	32.28	19.03	
		Boy	26.62	36.66	16.58	
	COMF	**Girl**	32.55	42.59	22.51	
		Boy	28.53	35.16	21.91	

Table 7-15 Mean ROM of the pelvis in sagittal plane, 95% Confidence Interval, and p-value for the interaction between three conditions (Gender, Backpack type and backpack load) for girls and boys

As well as the ROM and mean angular position of the pelvis, the time taken to complete the task in each condition was also measured. Paired samples t-test revealed that the time taken to complete the task significantly increased from 1.17s for unloaded condition to 1.44s when carrying the COMF 25% BW (p=0.014). The time taken to stand from seated position while carrying a load of 25% BW was significantly increased from 1.29s for ERGO backpack to 1.44s for COMF backpack (p=0.009). When using the same backpack

(COMF), the time taken to complete the task was significantly greater, increasing from 1.23s for 17% BW to 1.44s for 25% BW (p=0.008).

As well as Sit-to-stand, the ROM and angular position of the pelvis were also investigated during Stand-to-sit. Table 7-16 summarises the results for the pelvic ROM and angular position for all three rotations.

Pelvic motion	Carrying conditions	Angular position (degree±SD)	ROM (degree±SD)	Duration (seconds±SD)
Pelvic tilt	**NoBag**	-24.70(7.06)	39.53(13.50)	1.30(0.21)
	ERGO-17%	-25.17(10.17)	40.09(8.07)	1.28(0.19)
	COMF-17%	-25.57(10.45)	**43.09(10.96)**[b]	1.41(0.30)
	ERGO-25%	-26.34(10.34)	42.28(10.87)	1.53(0.24)
	COMF-25%	-27.28(11.22)	37.58(10.53)[b]	1.53(0.38)
Pelvic obliquity	**NoBag**	-18.33(12.05)	12.77(7.29)[c]	
	ERGO-17%	-19.73(13.62)	14.69(5.52)	
	COMF-17%	-20.43(15.29)	15.05(6.64)	
	ERGO-25%	-19.73(12.42)	12.24(7.02)[d]	
	COMF-25%	-23.92(14.61)	**20.09(8.41)**[c,d]	
Pelvic rotation	**NoBag**	**10.68(5.13)**[a]	7.04(2.48)[e,f]	
	ERGO-17%	8.08(6.51)	7.77(1.57)[g]	
	COMF-17%	8.52(5.81)	**13.96(5.79)**[e,g]	
	ERGO-25%	10.93(5.27)	10.03(6.48)	
	COMF-25%	7.55(4.59)[a]	**14.07(4.61)**[f]	

Table 7-16 Mean angular position and ROM (degree±SD) for pelvic tilt, obliquity and rotation during five carrying conditions in Stand-to-sit. The letters 'a', 'b', 'c', 'd', 'e', 'f' and 'g' represent the significant differences (p<0.05) with bold number represents the higher absolute value.

For pelvic tilt, the student t-test revealed that there were no significant differences between the angular positions of the pelvis for different load conditions. A significant difference was noted between the angular rotation of the pelvis (pelvic rotation) when carrying a COMF backpack of 25% BW and the unloaded condition (Table 7-17).

	Paired differences angular position (in degrees)					
				%95 Confidence Interval of the difference		
Pelvic tilt	Mean	Std.Dev	Std.Err	Lower Bound	Upper Bound	P-values
NoBag-Ergo17%	0.97	4.84	1.71	-3.08	5.02	0.590
NoBag-Comf17%	0.87	6.71	2.12	-3.93	5.67	0.692
NoBag-Ergo25%	1.64	8.09	2.56	-4.14	7.42	0.537
NoBag-Comf25%	2.99	8.09	2.70	-3.23	9.21	0.300
Ergo-Comf17%	1.87	2.93	1.04	-0.58	4.32	0.114
Ergo-Comf25%	1.56	7.70	2.57	-4.36	7.48	0.560
Ergo17%-25%	1.66	4.17	1.48	-0.78	6.20	0.109
Comf17%-25%	2.71	8.68	2.89	-5.01	8.33	0.538
Pelvic obliquity						
NoBag-Ergo17%	1.35	6.15	1.94	-3.04	5.75	0.504
NoBag-Comf17%	-0.02	6.43	2.14	-4.96	4.93	0.994
NoBag-Ergo25%	1.35	7.94	2.51	-4.33	7.03	0.603
NoBag-Comf25%	3.47	8.04	2.68	-2.71	9.64	0.232
Ergo-Comf17%	-1.76	2.69	0.90	-3.83	0.31	0.085
Ergo-Comf25%	2.05	7.41	2.47	-3.64	7.74	0.431
Ergo17%-25%	0.00	4.06	1.28	-2.90	2.90	0.999
Comf17%-25%	3.48	7.89	2.63	-2.58	9.55	0.222
Pelvic rotation						
NoBag-Ergo17%	2.60	5.13	1.62	-1.07	6.27	0.143
NoBag-Comf17%	2.16	4.85	1.53	-1.31	5.63	0.192
NoBag-Ergo25%	-0.24	6.03	1.91	-4.56	4.07	0.901
NoBag-Comf25%	3.13	4.20	1.33	0.12	6.13	**0.043**
Ergo-Comf17%	-0.44	5.77	1.83	-4.57	3.69	0.817
Ergo-Comf25%	3.37	6.36	2.01	-1.18	7.92	0.128
Ergo17%-25%	-2.84	8.14	2.57	-8.67	2.98	0.298
Comf17%-25%	0.96	5.99	1.89	-3.32	5.25	0.623

Table 7-17 Mean differences, standard deviation, standard error and 95% confidence interval of the differences plus p-values for each pair for pelvic angular position in all three planes in Stand-to-sit

Repeated measure ANOVA showed that pelvic ROM in the sagittal plane significantly decreased from 43.09 ° (range: 27.81° to 55.43°) for COMF backpack loaded with 17% BW to 37.58° (rang: 19.31° to 55.31°) for COMF backpack with load of 25% BW (p=0.032; Table 7-18).

	Paired differences ROM (in degrees)					
				%95 Confidence Interval of the difference		
Pelvic tilt	Mean	Std.Dev	Std.Err	Upper Bound	Lower Bound	P-values
NoBag-Ergo17%	-0.56	8.42	2.66	-6.58	5.46	0.838
NoBag-Comf17%	-5.17	10.14	3.59	-13.65	3.31	0.193
NoBag-Ergo25%	-2.75	9.17	2.90	-9.30	3.81	0.368
NoBag-Comf25%	0.81	13.08	4.36	-9.24	10.86	0.857
Ergo-Comf17%	-3.75	7.68	2.71	-10.16	2.67	0.210
Ergo-Comf25%	3.94	9.21	3.07	-3.14	11.02	0.235
Ergo17%-25%	-2.19	5.20	1.64	-5.90	1.53	0.216
Comf17%-25%	6.22	6.61	2.34	0.69	11.74	**0.032**
Pelvic obliquity						
NoBag-Ergo17%	-1.92	6.56	2.08	-6.61	2.78	0.379
NoBag-Comf17%	-2.28	4.44	1.40	-5.46	0.90	0.139
NoBag-Ergo25%	0.53	2.53	0.80	-1.28	2.34	0.526
NoBag-Comf25%	-7.32	9.16	2.90	-13.88	-0.77	**0.032**
Ergo-Comf17%	-0.36	7.18	2.27	-5.50	4.77	0.877
Ergo-Comf25%	-7.85	10.77	3.40	-15.55	-0.15	**0.047**
Ergo17%-25%	2.45	6.23	1.97	-2.01	6.91	0.245
Comf17%-25%	-5.04	9.35	2.96	-11.73	1.64	0.122
Pelvic rotation						
NoBag-Ergo17%	-0.73	2.90	0.92	-2.81	1.34	0.444
NoBag-Comf17%	-6.66	6.74	2.25	-11.84	-1.47	**0.018**
NoBag-Ergo25%	-2.99	6.81	2.15	-7.86	1.88	0.198
NoBag-Comf25%	-6.77	4.68	1.56	-10.36	-3.17	**0.002**
Ergo-Comf17%	-6.47	5.68	1.89	-10.83	-2.10	**0.009**
Ergo-Comf25%	-4.33	9.14	3.05	-11.36	2.70	0.193
Ergo17%-25%	-2.25	6.94	2.19	-7.22	2.71	0.331
Comf17%-25%	-0.11	5.38	1.79	-4.24	4.02	0.953

Table 7-18 Mean differences of ROM, standard deviation, standard error, 95% confidence interval of difference and p-values for differences between the two pairs are given for pelvic tilt, pelvic obliquity and pelvic rotation in Stand-to-sit.

Significant differences were found between the unloaded conditions and loaded with 25% BW for COMF backpack in pelvic obliquity and pelvic rotation ROM ($p<0.05$). There were no significant differences between the performance of unloaded and loaded conditions of 17% and 25% BW using ERGO backpack ($p>0.05$). However there were significant differences between the ROM of the pelvis obtained from the two backpacks in the frontal and transverse planes ($p<0.05$; Table 7-18)

7.4 Results summary

Table 7-19 summarises the key results from the Section 7.3.

Activities of daily living		**Pelvic tilt**		**Pelvic obliquity**		**Pelvic rotation**	
		17%	**25%**	**17%**	**25%**	**17%**	**25%**
Stairs-up	**COMF**	↔	↑	↔	↑	↑	↑
	ERGO	↔	↑	↔	↔	↔	↔
Stairs-down	**COMF**	↑[1]	↑	↔	↔	↓	↓
	ERGO	↔	↔	↔	↔	↔	↔
Sit-to-stand	**COMF**	↔	↑	↑[1]	↑[3]	↑[1]	↑[3]
	ERGO	↔	↑	↔	↔	↔	↔
Stand-to-sit	**COMF**	↔	↑[2]	↔	↑	↔	↑
	ERGO	↔	↔	↔	↔	↔	↔
Walking	**COMF**	↑	↑	↔	↔	↓[4]	↓
	ERGO	↔	↔	↔	↔	↔	↔
Quiet standing		**Pelvic tilt**		**Sway length**		**Sway area**	
		17%	**25%**	**17%**	**25%**	**17%**	**25%**
	COMF	↑	↑	↑	↑	↑[1]	↑[3]
	ERGO	↔	↑	↔	↑[1]	↑	↑

Table 7-19 Summary of the results with ↑ represents the significant increases from the unloaded condition to loaded condition while ↓ shows a significant decrease from the unloaded condition to loaded and ↔ shows no significant differences (p<0.05). [1] increased significantly with respect to 17% ERGO, [2] increased significantly with respect to 17% COMF, [3] increased significantly with respect to 25% ERGO, [4] decreased significantly with respect to 17% ERGO.

7.5 Discussion

7.5.1 Quiet standing

Several studies have examined the effect of backpack load on posture but there has been little attention with regards to the effect of backpack load on balance and kinematics. In this thesis the sway area and sway length were derived from the motion of CoP and used as an indirect method to measure adolescent postural stability when carrying a loaded backpack. The results of this study indicate that as the load increased from 0% to 17% and 25% of subjects' BW the sway area and sway length increased. Carrying a loaded backpack alters upright posture and results in postural responses that require a complex interaction of the neuromusculoskeletal system which requires the limb and trunk to adjust to maintain upright equilibrium and accommodate to the new combined COM of the individual and backpack. Changes in the postural sway (area and length) could also be an indication of the physical fitness, as military and fire-fighter personnel who carry loads up to 150% of their BW use the heavy backpack load as a method of training to increase their postural stability. In this study, 90% of the male subjects were semi-professional athletes (Playing and training for Arsenal junior team 5 days a week) and on average the mean differences of sway area and length between male and female subjects were 85.7 and 97.7 cm, respectively. Girls had higher sway area and length than boys. This can be interpreted as physical fitness, in that carrying a heavy backpack load could have had an effect on the postural control. Physical fitness means better muscle strength, control and flexibility therefore addition of an external force on the body (loaded backpack) will have less effect on the postural stability as the subject is more comfortable to compensate for the external force and less time is needed for the body to adjust to the external force. In this study, the subjects had 90s to adjust their posture to 17% and 25% of their BW. From the results, one can speculate that boys adapted to the backpack weight quicker and better than the girls. Therefore there was less body sway. One can assume that if more time and training were given to the girls, their postural stability would have improved. This training can involve strengthening of the abdominal (such as erector spinae, rectus abdominis, trunk extensor/flexor), pelvic, lower back and hip muscles (iliopsoas, rectus femoris, gluteas, femur flexor onto lumbo-pelvic complex) by undertaking core exercises such as sit-ups and push-ups to train the above muscles to work in harmony. This could lead to better balance and stability in daily activities; however, more research is required to investigate this hypothesis. Other factors that can affect the postural stability of the boys and girls are morphological differences between the two genders such that girls have higher soft tissue depositions than boys and boys' muscle flexibility is higher during puberty because of hormone changes (increases in testosterone level) (Burton, 1996; Grimmer et al., 2000; Sheir-Neiss et al., 2003; Negrini et al., 2002; Goodgold et al., 2002; Brackley et al., 2004; Balague et al., 1999). Because of higher muscle flexibility, one can assume it is easier for boys to adjust their pelvis whilst carrying a heavy backpack. Other morphological differences is that girls have a wider pelvis than boys, however these are all speculation and further research is required to investigate the effect of these hypotheses on postural stability.

Results obtained in this chapter corroborates previous research which indicated that sway area and CoP path length increased with load (Schiffman et al., 2006; Heller et al., 2009), however, none of the previous studies indicated the level of fitness of their participants. Therefore one can assume that this instability can be improved if a proper training was provided before conducting the experiment. Further research is required to investigate this hypothesis.

During quiet standing the angular position of the pelvis was measured for each condition, and was noted to tilt more anteriorly as the load increased. When the performance of the two backpacks were compared it was shown that the subjects needed less biomechanical adjustment while wearing the ERGO backpack when compared to the COMF backpack. In Section 7.2.2, the features of the ERGO and COMF backpacks were explained. It was mentioned that the ERGO backpack has a lumbar curvature that helps to position the backpack closer to the body. Therefore the differences between the performance of the two backpacks could be due to the positioning of the ERGO backpack closer to the body which results in the combined COM (body+backpack) to be close to the body. Having the COM closer to the body means that the moment arm of external force is shorter for ERGO backpack therefore less contraction of the back muscles is required to bend the trunk forward or tilt the pelvis anteriorly as a result of heavy backpack load. However, the results of this study did not include any muscle activity and did not measure the joint moment. Future studies should investigate this hypothesis. This work also investigated the gender-related effects of backpack carrying with regards to sway and pelvic static posture and noted that boys and girls control their stability in different ways. The boys tended to tilt their pelvis more anteriorly than the girls when carrying a loaded backpack and the girls' pelvic posture was significantly similar among different loading conditions. These differences between the girls' and boys' performance could be due to different maturation of the nervous system or pelvic anatomy (Pau et al., 2010). It could be suggested that the differences between the boys and girls performance is as a result of the boys being more physically active and therefore stronger than the girls. There are no available studies performed in the past to compare the pelvic kinematics between the girls and boys; therefore further studies must be conducted to carefully evaluate this finding. Looking at the result it can be noted that the inter-subject variability is higher for 25% BW COMF and ERGO backpacks than unloaded or 17% BW ERGO backpack; one should remember that there are other factors such as poor standing posture, type and frequency of physical activities, and generic psychophysical characteristics that affect the compensation mechanism used to maintain the upright posture while carrying a loaded backpack (Pau et al., 2010).

7.5.2 Walking

Under the five different conditions, the result showed the greatest changes in pelvic tilt and pelvic rotation when wearing the COMF backpack. Even when carrying a reduced load of 17% BW, significant biomechanical compensations occurred. Pelvic tilt increased anteriorly when carrying a loaded backpack (COMF) to keep the subjects in a vertical position. Smith et al. (2006) also reported similar changes in pelvic tilt when female college students wore the backpack of 15% of BW on both shoulders. Even though in this study the trunk movement was not investigated, increases in backpack load may result in bending the trunk forward in order to bring the combined COM (body+backpack) forward to maintain the subjects' stability and as a result the pelvis was tilted more anteriorly.

Pelvic rotation ROM significantly decreased as the load increased using the COMF backpack. This finding was similar to previous studies in which the trunk co-contraction increased to continue to provide the static and dynamic stabilities by decreasing pelvic rotation (Kinoshita., 1985; Smith et al., 2006). Chow et al. (2005) also showed reduced pelvic rotation with increasing backpack load. They explained these changes by looking at the increased ROM of the hip in the sagittal plane due to a decreased counter rotation between the upper and lower body. Therefore a greater demand is placed on the hip joint for propulsion, brake and power generation when carrying a heavy backpack.

The mean angular pelvic rotation was not significantly different between the unloaded and loaded condition when using the ERGO backpack while the results were only significant using the COMF backpack. This could indicate that using the ERGO backpack may reduce the effect of high loads on pelvic kinematics.

Pelvic obliquity ROM and mean angular positions did not significantly change with the load conditions. The pelvic obliquity ROM values from Chow et al. (2006) were similar to this study but they reported that the pelvic obliquity was significantly different between 0% and 15% BW. Conversely, Smith et al. (2006) reported no significant difference between the pelvic obliquity of the two conditions (0% and 15%BW with backpack on both shoulders).

Performance of the boys and girls were compared and it was shown that the pelvic tilt and rotation ROM were not significantly correlated between the two genders. These differences could be due to their differences in static posture while carrying no backpack in which the girls tend to tilt more anteriorly than the boys before starting to walk. Other factors that can affect the performance of the girls and boys are their physical fitness, spinal posture and muscle strength. As mentioned before the boys in this study were more physically active than the girls therefore when they carry a loaded backpack they tended to use different technique to keep their upright posture. However, the lack of statistical differences may be due to underpowering.

7.5.3 Stairs-up and Stairs-down

Stair ascending and descending is a challenging task especially carrying a loaded backpack. A number of previous studies had looked at the effect of ascending and descending the stairs on kinematic and kinetic of lower limbs but they only investigated the ankle, knee and hip joint (McFadyen et al., 1988; Riener et al., 2002). In this thesis the effect of loaded backpack on pelvic kinematics was investigated while ascending and descending the stairs. Pelvic tilt ROM significantly increased when carrying a backpack of 25% BW. Mean angular pelvic position was also significantly decreased from unloaded condition to 25% BW and 17% to 25% BW which means the pelvis was more anteriorly tilted during ascending the stair. During stair ascending the trunk moves in both vertical and horizontal directions, therefore as the weight increases the trunk flexion increases to balance the position of COM, therefore the pelvis tilts more anteriorly. Pelvic obliquity and pelvic rotation were also significantly increased during the loaded condition of 25% BW COMF backpack but there were no significant differences between the mean angular position of the pelvis in the frontal and transverse planes. In order to clear one step and move to the next step whilst carrying the heavy backpack, more pelvic obliquity and rotation are needed to clear the steps and move the body forward into an optimal position, therefore increases in pelvic obliquity and rotation are expected.

In stair descent, there were significant changes in the angular position of the pelvis as the load increased to 17% and 25% BW for COMF backpack, with the pelvis becoming increasingly anteriorly tilted. However pelvic rotation only decreased as load increased to 25% BW, this result indicates that the pelvic tilt is more affected while descending the stairs as both 17% and 25% BW load can alter its movement. During stair descent the combined COM of the body is much closer to the base of support than when ascending the stairs.

The ROM of the pelvis was not affected by load conditions as much during descent as during ascent; this could be explained by the work of McFadyen et al. (1988) that ascending the stairs is more a demanding task which consist of a transfer of muscle energy into gravitational (potential) energy of the body, whereas during the descending the potential energy has to be dissipated by the muscles.

The ERGO backpack performed better and was more similar to the unloaded condition than the COMF backpack. This difference is postulated to be due to the fact that the ERGO backpack has lumbar curvature which helps to position the backpack much closer to the body than the COMF backpack. Therefore, if the combined COM (body+backpack) positioned closer to the body less trunk flexion is needed to bring the combined COM position closer to the body and therefore less biomechanical changes are required.

Investigating the effect of the gender on load conditions, it was noted that the compensation mechanism were different among girls and boys during the ascending and descending the stairs when carrying a loaded backpack. As stated before, this could be due to the fact that their pelvic position is dissimilar in upright position or the fact that the physiological maturation of the girls and boys is different. On the other hand, McFayden et al. (1988) investigated the muscle activities during stair climbing and mentioned that the muscular activity is much higher during stair climbing than normal walking. Therefore, the differences between the boys' and girls' performances could be due to the fact that their muscle strength and flexibility is different due to their physical fitness. Therefore the compensation technique that boys used to maintain their posture and balance while stair climbing were different from the girls. This still is inconclusive and further research is needed to address this differences.

The kinematic data in this study obtained on inclination of 42° with step height of 20cm and 22cm deep. The stair inclination angles investigated in this study reflect a typical range of staircases that we encounter in daily life (British Regulation, 2011) however these values are different from the recommended values for public places including schools. The minimum depth of the staircase is 28cm and maximum height of the 18 cm. Therefore it can be assumed that the staircase's inclination in the school is less than the one that was investigate in this study. Increased step depth allows more room for foot placement and toe clearance and decreased step height needs less biomechanical changes to move forward from one step to the next. However further studies are needed to confirm these hypothesis.

7.5.4 Sit-to-stand and Stand-to-sit

Sit-to-stand motion is one of the most frequently executed activities of daily living. During rising from the seated position, the body's centre of mass is transferred from a relatively stable position with a wide base of support to a relatively less table position therefore it is a mechanically demanding motion (Riley et al., 1991). In order to rise from a chair, trunk flexion with associated hip flexion occurs (Richards, 2008). Kinematic results of this study show that the back load of 17% and 25% BW increased the absolute angular position (tilted more anteriorly) of the pelvis to 16% and 29% higher than the unloaded condition in COMF backpack, respectively. From this result, it is evident that more pelvic tilt is required in order to stand-up from a seated position whilst carrying a heavy backpack. Carrying a heavy backpack will result in changing the position of combined COM (body+backpack) therefore more flexion is required in the initiation phase (beginning of the movement) to lift up the body and move the body's COM upward from a sitting position to a standing position without losing balance. In this study subjects used different methods to initiate the Sit-to-stand movement. Whilst carrying a loaded backpack, some of the subjects, mostly girls, stood up by first flexing their trunk and then lifting their buttocks while others (boys) first lifted their buttocks. Therefore, the significant differences between the pelvic ROM and angular positions of the girls and boys in this activity could be due to the body segments that initiate the movement (trunk or buttocks). Because the chair was not equipped with a force plate and the trunk segment was only tracked by one marker (C7) it was not possible to analyse this hypothesis further. However, this difference between the two genders could be also due other factors such as the physical fitness level and muscle flexibility of the boys which allows them to stand up more easily without flexing their trunk. Therefore neuromusculoskeletal changes (e.g. Loss of trunk muscle force, loss of balance, muscle flexibility) may influence the performance of the Sit-to-stand movement for the two genders. More investigation is required to analyse this hypothesis.

The results from the COMF backpack were also compared to the ERGO backpack which indicated that the absolute mean angular position of the COMF backpack loaded with 17% BW was 3% higher than the ERGO backpack. However on average, pelvic ROM was 13% lower for the loaded condition (17% COMF, 25% ERGO and 25% COMF) than the unloaded condition. In general the ERGO backpack performed more closely to the unloaded condition when carrying 17% of body weight, the effect of loaded backpack on pelvic angular position and ROM can be seen for other remaining conditions (COMF 17% BW, ERGO 25% BW and COMF 25% BW). This difference between the two backpacks could be as a result of the differences in their features. The ERGO backpack consisted of the lumbar support which helps to bring the position of combined COM (body+backack) much closer to the body than the COMF backpack, and because of the wider and longer shoulder straps, the ERGO backpack was positioned higher on the spine than the COMF backpack. Therefore fewer biomechanical changes were required for the ERGO backpack to lift the body and move the combined COM upward, however for the COMF backpack the need for generation of momentum was increased as it was positioned low on the spine. More analysis is required to investigate the effect of backpack types and positions on the horizontal momentum of the body during Sit-to-stand.

The current study revealed that school children of age 12-15 with no backpack load, took on average 1.17 seconds to complete the Sit-to-stand motion. No previous studies have described the Sit-to-stand movement in children age 12-15 years however Cahill et al. (1999) reported that children of age of 4-5 year and 9-10 year completed Sit-to-stand in 1.2 seconds and 1.4 seconds, respectively. These values are similar to this study.

It was also noticed that inter-subject variability increased as back load increased to 25% BW, especially for the COMF backpack. This could be due to the fact children use different method to stabilise their COM as discussed before. Cahill et al. also suggested that the greater variability in the children may be due to the child's inability to control the horizontal momentum of the COM. Also it was reported that the height of the chair seat and foot position influence the Sit-to-stand movement (Janssen et al. 2002; Riley et al. 1991). Shepherd and Koh (1996) examined the effect of three foot placements (back, preferred and forward) on the kinematics of the hip joint for young women during Sit-to-stand. They concluded that a forward foot placement would affect the ease of standing up for individual with leg muscle weakness (Shepherd et al. 1996). In this thesis the subjects were allowed to select their own foot positions and speed (while keeping arms next to their body) in order to address a natural motion pattern. The foot position was not controlled within subjects for each load condition and neither was controlled between the subjects and therefore this great variability between the subjects could be due to this fact.

As well as Sit-to-stand, the Stand-to-sit movement was also investigated, which has not previously been examined. The results of this study revealed that statistically there were no significant differences between the ROM of the pelvis during unloaded and loaded conditions for both backpack types in the sagittal plane, however there were significant differences between the ERGO and COMF backpacks in the frontal and transverse planes. The angular position of the pelvis was 10% higher in loaded condition of 25% BW using COMF backpack than the unloaded condition in the transverse plane. Kinematic changes in these two planes could be due to the fact that the subjects rotated and bent their trunk laterally to determine the position of the chair in order to avoid falling. As Stand-to-sit is less mechanical demanding therefore less mechanical changes were required in the sagittal plane.

Time taken to complete the Stand-to-sit activity was significantly higher than the time taken to complete the Sit-to-stand (p=0.005) which could be due to the fact that subjects were trying to sit down with caution to avoid falling.

To conclude, there are many factors that influence the Sit-to-stand movement and more thorough investigation is required to determine the influence of each factor on the pelvic kinematics of the adolescents. These include the chair-related determinants such as seat height, armrests, chair type (ergonomically designed) and backrest. There are some strategy related determinants that need further research such as speed of movement, foot positioning, trunk positioning, training and arm movement.

7.6 Summary

The purpose of this study was to investigate the influence of a loaded backpack on pelvic kinematics. The pelvic kinematics of 10 adolescents were measured whilst carrying a loaded backpack of 17% and 25% of their BW during different activities of daily living such as: walking, quiet standing, Sit-to-stand, Stand-to-sit, ascending and descending the stairs. The results showed that, as the load increased to 25% of the body weight, the instability in postural control increased. As the load increased to 25% BW, the ROM of the pelvis increased and the pelvis tended to tilt more anteriorly in activities such as walking, quiet standing, ascending and descending the stairs. The ROM of the pelvic tilt was decreased during the Sit-to-stand activity. Significant changes in pelvic rotation and pelvic angular position were noted in almost all the activities whilst the pelvic obliquity was only altered during Sit-to-stand, Stand-to-sit and stair ascent. The performance of the two backpacks, ergonomic and non-ergonomic, was compared among all activities and it was noted that the biomechanical compensation of the pelvis was significantly greater when using a non-ergonomic backpack than the ergonomic. These differences could be due to the ergonomic features of the ERGO backpack such as lumbar curve support, and wide and long straps. There were no significant correlations between the two genders when they carried different backpack load which shows that male and female subjects used different mechanism to compensate for the effect of the loaded backpack. These could be due to the hypothesis that the two genders have different neuromusculoskeletal development at the same age as well as different level of physical fitness and muscle flexibility and perhaps different skeletal structure. In conclusion, it is evident that carriage of loaded backpack results in alteration of the movement of the pelvis in adolescents.

In Chapter 8, the overall discussion and conclusion of the thesis including discussion of the results of this chapter will be presented.

Chapter 8

Discussion and recommendations for future work

Aim The aim of this chapter is to summarise the work described in this thesis, discuss the outcomes of each study, place them in a wider context and provide recommendations for future work.

8.1 Summary of results

Recent concern for the amount of weight that children carry to, from and around school has promoted several studies to investigate the effect of backpack load on posture, trunk inclination and gait parameters. Previous research has focused on male subjects or mixed populations with no consideration of gender, demonstrating a significant change in posture and gait parameters depending on weight and position in which the backpack was carried (Pascoe et al., 1997; Bloom et al., 1987; Kinoshita, 1985). None of the previous studies have analysed the biomechanical compensation of pelvic motion during activities of daily living whilst using backpacks with loads similar to those carried by school children on a daily basis. One of the main limitations of analysing the pelvic motion has been the displacement of the reflective markers around the pelvis when using motion capture systems.

Many difficulties are encountered when measuring pelvic motion, especially under dynamic movements such as walking, sit-to-stand, and ascending and descending the stairs. These difficulties (such as, STA and marker occlusion) have led to different laboratories employing different measurement techniques, such as pin insertion, radiographic imaging, electromagnetic motion tracking and optical motion tracking, to analyse pelvic kinematics. However, none of these methods produces a reliable non-invasive measurement technique that can be used to investigate the pelvic kinematics when carrying a backpack.

In this work, a thorough study of the available pelvic measurement techniques and the technical obstacles in accurately measuring pelvic kinematics has led to the development and validation of a pelvic tracker. The pelvic tracker was used to measure the effect of loaded backpacks on pelvic kinematics in adolescents. Not only was the effect of different loads investigated, but also the effects of different types of backpack. The results from the development and application of pelvic tracker are presented here.

8.1.1 Development of a pelvic tracker

The first step in investigating compensatory movement of the pelvis due to carried loads was to design and develop a new marker set capable of measuring a full pelvic range of motion, as well as improving the practical and theoretical characteristic of recording pelvic motion. One of the limitations of skin-mounted markers for measuring kinematics is the error introduced by skin motion or inadequate fixation of the markers to the skin (Clark et al., 1989). Therefore, a custom-designed cluster was developed using three reflective markers which were attached to the end of three plastic rods and fixed to a plastic base. This cluster of markers was then attached to the sacrum to measure the pelvic movement, as there is less soft tissue over the sacrum than the ASIS (Lalonde et al., 2003; Clark et al., 1989). A kinematic model using the new marker set was developed to measure pelvic kinematics during the execution of a motor task, and its sensitivity to different landmark calibrations was tested during different studies.

Study I: Defining a pelvic kinematic model using a sacral cluster

A kinematic model was developed using the developed sacral cluster to measure pelvic kinematics using a skeleton. In this study, positions of the ASIS were digitised with respect to the sacral cluster, as proposed by Cappozzo et al. (2006) and discussed in Chapter 4. This study did not address STA or skin movement and the digitised positions of the ASIS were similar to their positions during the static trial. The main reasons for this study were: firstly to develop a mathematical model for digitisation of the bony landmarks and calculation of segment and joint kinematics, and secondly to measure the instrumental and experimental error. The RMSE of the results were on average 0.58°.

Study II: The effect of digitising the PSIS positions and size of the digitising pointer on pelvic kinematics

The objectives of this study were to (1) investigate the effect of calibrating the PSIS positions using different methods, namely calibrating using a calibration wand and calibrating using the markers directly, and (2) determine if the repeatability or precision of manual palpation procedures for the position of ASIS could be improved by using a smaller calibration pointer (V-Pointer, S-Pointer). Kinematic parameters were used to quantify the differences. The results indicated high repeatability and reliability between the methods of digitising the positions of PSIS and ASIS, and there were no significant differences between them. It was noted that the size of the pointer did not have any effect on the repeatability or reproducibility of the kinematic data. Even though both methods led to similar results, a smaller calibration pointer allowed more natural palpation than the larger pointer, since the finger-tip did not leave the surface of palpated anatomical landmarks and also it was both lighter and smaller; therefore unwanted movement was minimised when using the smaller pointer. In a study conducted by Cappozzo et al. (1996), it was noted that during knee flexion there was a misplacement of up to 40 mm of a marker on the lateral epicondyle of the femur, and this caused errors in the estimation of bone orientation of up to 28°. Although there have not been enough studies to quantify the amount of the errors introduced by the PSIS markers' positioning, the result of this study showed that using different methods of digitisation does not influence the repeatability and reproducibility of the kinematic data.

Study III: The effect of pelvic orientation in digitising the ASIS positions

The objective of this study was to investigate the effect that pelvic orientation during calibration has on the measurement of pelvic kinematics. The mean maximum anterior pelvic tilt, obliquity and rotation were compared for five different pelvic positions during the task of lifting a light box. Results showed that digitising the ASIS positions while the subject is standing upright or with the pelvis tilted posteriorly by flexing the femur are the most reproducible methods for digitising the ASIS positions. These two positions were found to measure significantly less anterior pelvic tilt than the other three positions during the movement of pure pelvic tilt suggesting that the relative movements between the cluster and underlying bone significantly affects the digitised landmarks and consequently the kinematics data at these three positions. It was also revealed that calibrating the ASIS positions in the neutral position and with the femur flexed led to less variability in measures of pelvic tilt and pelvic obliquity. With respect to pelvic rotation, the kinematic model measured less pelvic rotation when the ASIS positions were calibrated in a neutral position. The effect of skin motion in different pelvic orientations was also investigated and it was shown that the cluster position in PII, PIV and PV was more affected by skin motion than in PI and PIII. The skin movement over the sacrum can be used to explain the over- and under-estimation of maximum pelvic tilt in PII, PIV and PV. Errors in calibrating the ASIS positions can also propagate to the kinematic data; the vertical off-sets between the waveforms represent the errors in anatomical landmarks palpation as well as skin movement over the sacrum. Therefore it was decided that calibrating the landmarks in the neutral position gives more promising results, especially when measuring changes in the frontal and transverse planes, as the propagation of STA mainly affects the joints characterised by a small range of motion (Cappozzo et al., 1995).

Study IV: Single and double anatomical landmark calibration

The aim of this study was to compare the effect of single and double calibrations of anatomical landmarks on pelvic kinematics. The results showed that there were no significant differences between the methods for the pelvic range of motion. As discussed in Study II of Chapter 4, the neutral pelvic orientation was shown to have better repeatability and less variability than the other positions. Therefore, in this study two double calibrations were performed between the neutral position of the pelvis and pelvis fully tilted anteriorly (trunked flexed), and the neutral position of the pelvis and pelvis fully rotated to the left. Even though no significant differences were found between the single and double calibration methods, the results obtained from double calibration have less variability than the single calibration in positions other than the neutral. Although single calibration of the pelvis in the neutral position was performed in this thesis, one can note that, by choosing the double calibration process, the variability and repeatability of kinematic data could be improved. The double anatomical landmark calibration could be also used to improve the reliability of the kinematic data for inexperienced researchers who have problems in identifying bony landmarks (Stagni et al., 2006).

Chapter 5: Pelvic tracker validation

The developed kinematic model of the pelvic tracker was investigated in Chapter 5. The aim of this study was to validate the pelvic tracker by determining its repeatability, reproducibility and reliability, and it was compared to the most relevant previous method. Therefore the performance of the pelvic tracker (‘Cluster’) was compared to the Helen Hayes marker set (HH, ‘Traditional’) proposed by Kadaba et al. (1990), which consists of four separate markers on bony landmarks of the pelvis. In this study, thirty subjects participated and were divided into three equal groups according to their BMI (normal, overweight and obese). The result showed that for activities that required full ROM, the Cluster method measured more pelvic ROM in the sagittal plane than the Traditional method, especially for obese subjects. On average the Cluster method measured similar values of pelvic movement to those of the Traditional method in all three planes for activities where the pelvis rotates in all three planes, such as walking.

The repeatability and reproducibility of the two marker sets were also compared using the within-day and between-day CMC. The results of this study showed that both methods had high within-day (CMC=0.90) and between-day (CMC=0.80) repeatability in the sagittal plane. The waveform of kinematic data of the two methods showed moderate similarity for the activities that required full ROM of the pelvis in only one plane. Comparing the performance of the two methods between the different BMI groups demonstrated that the within-day and between-day CMC values for overweight and obese subjects on average showed higher repeatability for the Cluster method than for the Traditional method in all planes. This result may indicate the influence of marker occlusion on repeatability and reproducibility of the kinematic data during data collection. The intra- and inter-session variability of the two marker sets (cluster and traditional) were compared with respect to intra- and inter-session standard deviation of ROM of the pelvic tilt, obliquity and rotation during different activities of daily living among different BMI groups. The results revealed that the intra- and inter- session variability of the Cluster method are lower than those of the Traditional method, especially for overweight and obese subjects. For activities that require a full range of movement in the sagittal plane, the variability of the kinematic data for overweight and obese subjects was greater for the Traditional method than for the Cluster method; while for activities such as walking, where the pelvis moves in all three planes, the variability of the two methods was similar. Therefore, from these findings it was concluded that there was higher variability and less repeatability in kinematic data obtained using the Traditional method than with the Cluster method. This may arise from STA and marker occlusion during data collection due to the excess soft tissue (obese). By introducing the technical frame and the concept of anatomical landmark calibration, the effect of STA and occlusion of the markers was minimized with the Cluster method.

The study concluded that the Cluster method overcame a number of theoretical and experimental limitations, such as minimising the effect of movement of markers relative to each other as well as to the underlying bone, minimising the effect of STA especially for overweight and obese subjects, fewer cameras required to track the Cluster and less time needed for post processing of the data as there is no marker occlusion. And finally, the result of this study (Chapter 5) was compared to some of the previous studies (Table 5-

23), and showed a great improvement in repeatability of the kinematic waveform obtained using the Cluster method. As shown and discussed in Chapter 5, 76% and 100% of the data for overweight and obese subjects were interpolated because of marker occlusion, however, none of the data obtained using the Cluster method needed to be interpolated. Because of marker occlusion the vital part of the trial obtained from the Traditional method needs interpolation (Figure 5-20), which makes the data less reliable than the Cluster method. Therefore, in future studies the Cluster method should be used.

8.1.2 Application of the pelvic tracker

Compensatory movement of the pelvis due to the loaded backpack results in alterations in gait, trunk forward lean, spinal deformities (such as scoliosis and kyphosis) as well as increased torque and linear forces on the body, which may contribute to orthopedic, musculoskeletal or soft tissue injuries (Pascoe et al., 1997; Bloom et al., 1987; Smith et al., 2006). Recently, concerns about school children carrying heavy backpacks has grown and it is important to investigate the effect of a loaded backpack on pelvic biomechanics and kinematics. One of the main limitations of studying the kinematics of the pelvis is the displacement of the marker set around the pelvis. It was noted that none of the available studies analysed the influence of the loaded backpacks similar to those carried by school children.

The new pelvic tracker allowed the investigation of the effects of a loaded backpack on pelvic kinematics of adolescents during different activities of daily living. Therefore, the purpose of this study was to investigate the effect of backpack loads, backpack types and gender on pelvic kinematics.

Chapter 6: Survey of backpack wearing

The aim of this study was to investigate the result of the survey conducted in one of the schools in the UK. In this study, 60 boys, aged 12-14, participated. The result of the survey showed that more than 90% of the students wear a backpack and 76% of them carry it on both shoulders. The average mass carried by students to school was 4.33 kg, which was approximately 8.14% of their BW. Even though the carried weight on average was less than the recommended weight limit (10-15%), around 8% of the students carried a backpack weight of 17-25% of their BW and spent more than 30 minutes each day travelling to school. It was noted that students who reported body pains, on average, carried a significantly heavier backpack than those who did not. It has been reported that the time taken to carry the loaded backpack is associated with reports of body pain (Grimmer et al., 2002). One of the most common methods of commuting was travelling to school by bus, which suggests that students will have to stand, ascend and descend the bus stairs for all or part of their long journey while carrying a heavy backpack. Different studies have looked at the effect of loaded backpacks on gait parameters, CoP and posture, but none have looked at the effect of loaded backpacks on pelvic kinematics during different activities of daily living; therefore, this needs further investigation, especially with regard to the impact on the pelvis.

Chapter 7: Kinematics of backpack wearing

The objectives of this study were to develop a protocol using the outcomes of the survey in Chapter 6 to investigate the influence of backpack loads, backpack types and gender on pelvic kinematics in adolescents during different activities of daily living. The loads included in this study were 17% and 25% of subjects' BW (based on the questionnaire on Chapter 6) and their effect on pelvic kinematics was investigated during different activities such as walking, quiet standing, Sit-to-stand, Stand-to-sit, and ascending and descending stairs. The results showed that as the load increased to 25% BW, the instability in postural control increased. During quiet standing, the sway length and area in the loaded condition of 25% BW was on average 127% higher than the unloaded condition, especially for non-ergonomic backpacks. Increases in sway length and area can be interpreted as a compensation mechanism to stabilise the body while standing with a heavy backpack. However subjects' training and physical fitness play an important role in postural stability. The pelvic tilt ROM increased and was tilted more anteriorly when carrying a heavy backpack load of 17% and 25% BW during quiet standing, walking and ascending and descending stairs activities. Pascoe et al. (1997) and Smith et al. (2006) also found increases in pelvic tilt when subjects carried unframed backpacks of 17% and 15% BW and this was postulated to be a result of leaning forward to counterbalance the back load. Other researchers found significant forward lean in subjects who wore loaded backpacks of 20% to 40% of their BW (Bloom et al., 1987; Kinoshita, 1985). Therefore subjects lean forward to bring the position of combined COM (body+backpack) to its natural position which will result in trunk flexion and consequently increase in pelvic tilt. During the Sit-to-stand task, the absolute mean angular position of the pelvic tilt increased as the subject started the trial while seating on a chair. In order to stand up from a seated position and bring the position of body's COM upward the trunk flexed forward and pelvic tilted more to allow the body to move upward whilst carrying a heavy backpack. As discussed in Chapter 7, subjects used different standing-up strategies. These include flexing the trunk or lifting the buttocks as an initiation strategy to stand up from the seated position.

The pelvic rotation ROM and angular position changed significantly as the load increased in almost all of the activities that required pelvic movement in the transverse plane. It was predicted that the pelvic rotation decreases when a loaded backpack was carried. Kinoshita (1985) suggested that carrying a heavy loaded backpack minimises the shoulder rotation as both shoulders are pulled backwards by the shoulder straps, which will then contribute to a reduction in pelvic rotation. Smith et al. (2006) explained that walking with a heavy backpack increases forward lean in which the simultaneous contraction of the agonist and antagonist muscles increases in order to provide both static and dynamic stability. Therefore, as a result, the pelvic rotation decreases.

The pelvic obliquity ROM and angular position did not change with load conditions during walking; this was also confirmed by other studies that investigated the effect of loaded backpacks of 0% and 15% BW (Chow et al., 2006; Smith et al., 2006). However, in stair climbing the ROM of pelvic obliquity increased for a loaded condition of 25% BW and it did not change during descending the stairs. The differences between the stair ascending and descending were expected because stair climbing is more physiologically demanding than descending. In order to clear the step and create an optimal position and to lift the body against the gravitational force, greater amounts of hip and trunk flexion are needed, which will result in changes in pelvic tilt, obliquity and rotation (Andriacchi et al., 1980; Protopapadaki et al., 2007; Hicks-Little et al., 2010). The results of this study showed that whilst carrying a heavy backpack, greater amount of pelvic obliquity is required to clear the steps and move the body upward against the gravitational force. On stair descent, however, more eccentric control is needed, due to the effect that gravity has on the body in accelerating it downward and therefore smaller hip flexion is needed. Consequently, the effect of a loaded backpack will be less on pelvic kinematics when descending rather than ascending the stairs (Hicks-Little et al., 2010). The same fact can also explain the differences between the obtained pelvic kinematics in Sit-to-stand and Stand-to-sit while carrying a loaded backpack.

Another objective of this study was to investigate the effect of ergonomic and non-ergonomic backpacks on pelvic kinematics when carrying a loaded backpack. The result of the study showed that there was a significant difference between the two backpacks, especially when the subject carried a backpack load of 25% BW. It was noted that the performance of the ergonomic backpack was more similar to the unloaded condition, and the biomechanical compensation of the pelvis was significantly greater when using the non-ergonomic backpack. The greater performance of the ERGO backpack could be due to its ergonomical features such as wider and longer shoulder straps compared to the COMF backpack which resulted in positioning the ERGO backpack higher on the spine that COMF backpack. Another factor is due to the lumbar support curve which allows the ERGO backpack to be positioned closer to the body (horizontally) than the COMF backpack which minimizes the moment arm therefore as a result less biomechanical changes required.

The effect of gender on pelvic kinematics whilst carrying a loaded backpack was also investigated in Chapter 7. The results showed that there was no significant correlation between the pelvic kinematics of the two genders when carrying different backpack loads. The result during quiet standing showed that the male subjects tended to tilt their pelvis more anteriorly than the females when carrying a loaded backpack and that the females' pelvic tilt when carrying a heavy backpack was similar to the unloaded condition. Among all activities, the boys' pelvic kinematics were more affected by the loaded backpack than the girls'. The girls' performance was very similar to the unloaded condition, especially when they carried the ergonomic backpack. These differences could be explained by the fact that girls' musculoskeletal and nervous systems mature earlier than those of boys of the same age (Pau et al., 2010); however, the boys participating in this study were all high level athletes. Therefore, their ability to flex their pelvis more than the girls could be due to their muscle flexibility, strength and physical fitness. These findings are inconclusive and further research is needed to investigate the changes in the pelvic kinematics and its effect on other segments.

To conclude, it is evident that carriage of a loaded backpack will result in alteration of the movement of the pelvis by increasing the pelvic tilt and limiting the pelvic rotation and obliquity; even small changes in pelvic movement as a result of loaded backpack may in future promote postural deviation and trunk lean which may lead chronic lumbar pain disorders (Pascoe et al., 1997; Smith et al., 2006). Even though the effect of backpack load on pelvic kinematics was investigated, one should remember these changes on the pelvic movement could be as a result of low level of physical fitness or lack of knowledge on proper backpack usage. No doubt some adolescents will experience problems in carrying their backpack, but there is also a training opportunity here. If the children were trained on how to carry their backpack safely this problematic task would become an appropriate training/strengthening program for the spine, and back and core muscles. Therefore, it is vital for schools, teachers, parents and physiotherapist to teach the children how to adjust and carry their backpack correctly and safely and as a result changing a perceived danger into training for better health and performance (Section 8.3).

8.2 Errors and limitations

The studies conducted in this thesis suffer from some errors and limitations. The errors, related mainly to the measurement of the pelvic motion, such as STA, anatomical landmark calibration and calibrating the bony landmarks using a calibration wand, have been addressed in Chapter 4. However, there are other errors which may affect the quality of the outcomes and these include:

- **Systematic error:** Systematic errors are directly related to the optical motion tracking system used to capture the pelvic motion and ranges between 0.1 to 0.4 mm. The system calibration errors increase when the subject moves away from the centre of the capturing volume. In the studies presented here, the calibration error obtained was 0.2 mm and the cameras were strategically placed in a circle (umbrella camera configuration) that ensures that at least three cameras track the data for each marker during dynamic activities such as walking, ascending and descending the stairs.

- **Joint simplification:** In this study, the pelvis was considered as a single rigid body and the limited movement of the sacroiliac joint (SIJ) was considered negligible as mostly normal subjects with no history of back pain or any related SIJ dysfunction were recruited. As discussed in details in Chapter 3 (Table 3-1), different studies have suggested that the rotational and translational movements available at the SIJ in a normal group are limited and negligible; as a result, in most of the kinematic studies the pelvis is considered as a single rigid body (Smidt et al., 1997; Jacob et al., 1995; Sturesson et al., 2000; Collins et al., 2009; Vogt et al., 2003; Fukuchi et al., 2010).

- **Accessing repeatability and reliability of the two methods in-vivo:** The studies presented have explored the repeatability and reliability of the pelvic tracker in-vivo and were compared to the HH marker set, since there is no invasive gold standard to compare the accuracy of these methods. Using an indirect measurement technique, such as a motion analysis system, has provided an experimental framework to answer the variety of problems related to gait, segment and joint kinematics. However, a direct measurement technique is needed to report the actual movement of the markers with respect to the underlying bony landmarks, which have not been looked at within this work but can form the basis of future studies.

- **Inter-subject errors:** Within this thesis, different types of subject participated and the inter-subject variation were great. These are caused by the differences in the subjects' bone morphology and geometry, as well as muscle strength, neuromuscular control, level of physical fitness and poor posture. These variations challenge the standardization of data collection and analysis.

- **Body mass index (BMI):** In this thesis the BMI was used as a factor to distinguish between the subjects' obesity level. BMI is based on a measurement of total mass and height, irrespective of the location of the mass. There are some limitations associated with BMI, such as overestimates of adiposity in those with high muscle mass (athletes), and it does not account for body frame sizes. Using BMI combined with waist circumference or waist-hip ratio may have given more accurate results than BMI alone. However, in this study BMI only used to classify individuals into three discrete groups and was not used as a continuous variable. There was no overlap between groups, and so the method was deemed suitable.

- **Number of subjects:** The study conducted to investigate the effect of loaded backpack on pelvic kinematics involved a limited number of school children. This work could have benefited from greater participation of more schools and children from a larger age range.
- **Palpation and landmark calibration error between sessions:** In validating the pelvic tracker, the between-session variability was higher than the within-session variability. Between-session variability includes changes in subjects' performance patterns from day to day as well as differences due to the investigator placing the markers in different locations. However, these differences were very low in magnitude compared with the within-session variability.
- **Backpack weight:** In this thesis, sand and iron bars were used to load the backpacks rather than books, which may have had an effect on the mass distribution in the backpack, and they did not imitate the real-life situation. However, a standardized distribution allowed for more consistency in the experimental protocol.
- **Detection of gait events:** The determination of the gait events' timings is usually done by using the force plate. In this study the gait events were detected manually. This could have affected the repeatability of kinematics data during activities such as walking, ascending and descending stairs, and Sit-to-stand. The effect that only one frame may have on the average pelvic movements was investigated and results showed that there were no significant differences in the repeatability of the data ($p=0.092$), and the RMSE of mean angular position of the pelvis in the sagittal, frontal and transverse planes with one frame out were 0.0001°, 0.123° and 0.023°, respectively (walking task).

8.3 Future work and recommendations

This study has proposed some suggestions for further study; these include the points below:

- This research investigated the effect of wearing a loaded backpack on pelvic kinematics; however, the implications of such a load on muscle activity was not investigated and has key implications with respect to spinal loading, and as such required consideration in future work. Combining the kinematic with kinetic and electromyography data (EMG) will provide a greater insight to the effect of a loaded backpack on the spine, pelvis and lower limbs. Kinetic data will provide us with forces exerted on the pelvis, spine and lumbosacral joint as a result of the heavy backpack.
- In this study, the effect of backpack loading on the Sit-to-stand (STS) movement of children was investigated. The experiment was conducted using a seat set at a constant height and children selected their own speed and feet positions to address a natural motion pattern. However, it has been debated that changing the seat height leads to different kinematic and kinetic mechanisms for the STS motion. Therefore, it is important to investigate how the seat height affects the compensatory movement of the pelvis when carrying a loaded backpack. A study using two extra force plates is needed to investigate the important role of buttocks in preparing for standing up during an STS task.
- It is important to evaluate the effect of time spent carrying a loaded backpack on changes in pelvic kinematics, and how long it takes for normal kinematics to return. Therefore, further research is needed to investigate these changes over a longer period of time and observe the time taken to recover from the changes.
- It is vital to know if training the subject on some of the tasks such as quiet standing and Sit-to-stand will result in better postural control.
- There have been debates on the vertical position of the backpack, therefore future studies should examine postural stability, pelvic kinematics and muscle activation patterns according to backpack position in order to estimate the optimal position for the backpack. Also the effects of a balanced load medio-laterally in the backpack and the centre of mass of the contents of the backpack on postural stability and pelvis kinematics should be investigated.

- In this study, the effects of only two backpacks on the pelvic kinematics of 10 school children were investigated. To enable the results to be generalized for the whole population of children, the number of subjects should be increased and other ergonomic backpacks with different features (e.g. waist belt) should be tested.
- In this thesis, a marker set was developed to measure the pelvic movement non-invasively and more repeatably and reliably than the previous methods. However, the accuracy of the developed method is questionable; therefore it is important to compare the findings of this study to a direct measurement of motion. Further research is needed.

As was discussed in Chapter 7, pelvic motion was altered when carrying a loaded backpack of more than 17% BW. Therefore students, parents and teachers should become more aware of backpack weights and work together to reduce the weight carried. In order to minimise problems associated with carrying a heavy backpack, some suggestions can be made:

- Schools should understand the extent of the problems caused by carrying heavy backpacks and should try to educate children and their parents on how to use their backpack. Schools can integrate a programme into the maths or science curriculums by incorporating the calculation of the backpack percentage of BW and work and energy expenditure into existing learning modules. Schools can also place posters of pictures of students, wearing their backpack properly and improperly on school walls.
- A national school backpack awareness day is set by the American Occupational Therapy Association (AOTA) on the third Wednesday of each September. Hosting a backpack safety day with different competitions for school children (e.g. poster competition) can assist teachers and schools to help students to learn to recognize when their backpack is too heavy and how to arrange the contents of their backpacks.
- Goodgold et al. (2002) found that education about proper backpack usage and weight is more effective for children if it is given by a physiotherapist in

collaboration with their teachers. Physiotherapists play an important role in preventing musculoskeletal pain associated with carrying heavy school backpacks. They can teach students the key signs that are associated with wearing a heavy backpack, such as if the child struggles to put on or take off the backpack, postural mal-alignment (head flexion, forward trunk lean or laterally bending) and pain or lack of sensation in their arms when wearing the backpack. Physiotherapists can help students with musculoskeletal problems associated with heavy backpack carriage by introducing them to physical therapy, including exercises that strengthen abdominal and back musculature, improve posture, and increase flexibility of hamstring muscles and low back musculature. Goodgold et al. (2002) suggested that these training techniques may enhance the child's ability to maintain good postural alignment when wearing a backpack.

- Parents are the best advocates for safety promotion and they can reduce backpack-related injuries by checking backpack weights and contents. Forjuoh et al. (2003) and Negrini et al. (2002) showed that parents can play a vital role in reducing the number of backpack injuries associated with carrying a heavy backpack by exercising care when purchasing backpacks and school materials for children, and also they can check the weight of the backpack and its contents to make sure that children are only taking items relevant to that day's activity.

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Appendix A

This appendix contains calculation of pelvic rotation using Euler angle. For the description of the three dimensional movement of pelvis two coordinate frames are introduced. The I, J, K system is fixed and represents the unit base vectors of the global coordinate frame while the i, j, k system represents the unit base vectors of the anatomical coordinate frame of the pelvis.

The sequence of the pelvis rotations is to rotate anatomical coordinate frame of the pelvis about the three global axes in the following succession: first rotate about the X-axis which is pelvic tilt by an angle θ_1, then about the Y-axis which is pelvic obliquity by an angle θ_2, and finally rotate around the Z-axis which is pelvic rotation by an angle θ_3.

The rotation matrix of θ_1, θ_2, and θ_3 about X, Y, and Z axes, respectively, are given as:

$$R_X(\theta_1)=\begin{bmatrix}1 & 0 & 0\\ 0 & cos(\Theta_1) & -sin(\Theta_1)\\ 0 & sin(\Theta_1) & cos(\Theta_1)\end{bmatrix} \qquad \text{B.1}$$

$$R_Y(\theta_2)=\begin{bmatrix}cos(\Theta_2) & 0 & sin(\Theta_2)\\ 0 & 1 & 0\\ -sin(\Theta_2) & 0 & cos(\Theta_2)\end{bmatrix}$$

B.2

$$R_Z(\theta_3)=\begin{bmatrix}cos(\Theta_3) & -sin(\Theta_3) & 0\\ sin(\Theta_3) & cos(\Theta_3) & 0\\ 0 & 0 & 1\end{bmatrix}$$

B.3

Combining these equations give us the rotation matrix $[R_{XY'Z''}]$ (c refers to cosine and s to sine).

$$R= [R_{XY'Z''}] = R_X(\theta_1)\, R_Y(\theta_2)\, R_Z(\theta_3)$$

B.4

$$=\begin{bmatrix}1 & 0 & 0\\ 0 & cos(\Theta_1) & -sin(\Theta_1)\\ 0 & sin(\Theta_1) & cos(\Theta_1)\end{bmatrix}\begin{bmatrix}cos(\Theta_2) & 0 & sin(\Theta_2)\\ 0 & 1 & 0\\ -sin(\Theta_2) & 0 & cos(\Theta_2)\end{bmatrix}\begin{bmatrix}cos(\Theta_3) & -sin(\Theta_3) & 0\\ sin(\Theta_3) & cos(\Theta_3) & 0\\ 0 & 0 & 1\end{bmatrix}=$$

$$\begin{bmatrix} c(\Theta_2).c(\Theta_3) & -c(\Theta_2).s(\Theta_3) & s(\Theta_2) \\ s(\Theta_1).s(\Theta_2).c(\Theta_3)+c(\Theta_1).s(\Theta_3) & -s(\Theta_1).s(\Theta_2).s(\Theta_3)+c(\Theta_1).c(\Theta_3) & -s(\Theta_1).c(\Theta_2) \\ -c(\Theta_1).s(\Theta_2).c(\Theta_3)+s(\Theta_1).s(\Theta_3) & c(\Theta_1).s(\Theta_2).s(\Theta_3)+s(\Theta_1).c(\Theta_3) & c(\Theta_1).c(\Theta_2) \end{bmatrix}$$

Considering the general form of rotation matrix:

$$R= \begin{bmatrix} r_{1,1} & r_{1,2} & r_{1,3} \\ r_{2,1} & r_{2,2} & r_{2,3} \\ r_{3,1} & r_{3,2} & r_{3,3} \end{bmatrix} \qquad \text{B.5}$$

We can now extract the Euler angles from Equation B.4, using BodyBuilder or MATLAB software. The rotation angles are as follow:

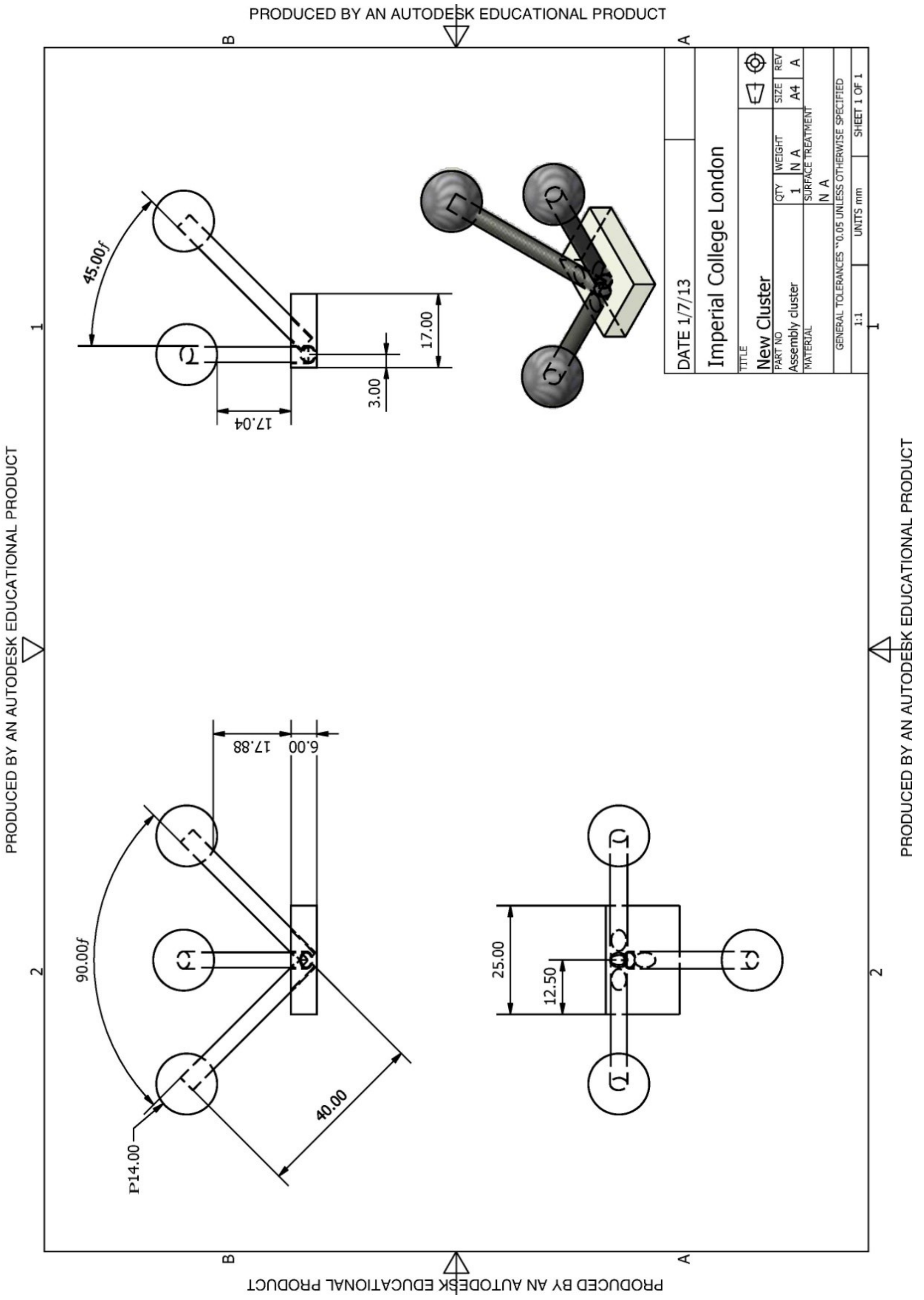
$$\theta_2 = \sin^{-1}(r_{1,3}) = \sin^{-1}(s\theta_2) \qquad \text{B.6}$$

$$\theta_3 = \text{atan2}\left(\frac{r_{1,1}}{c(\theta_2)}, \frac{-r_{1,2}}{c(\theta_2)}\right) = \text{atan2}\left(\frac{c(\Theta_2).c(\Theta_3)}{c(\theta_2)}, \frac{c(\Theta_2).s(\Theta_3)}{c(\theta_2)}\right) \qquad \text{B.7}$$

$$\theta_1 = \text{atan2}\left(\frac{-r_{2,3}}{c(\theta_2)}, \frac{r_{3,3}}{c(\theta_2)}\right) = \text{atan2}\left(\frac{s(\Theta_1).c(\Theta_2)}{c(\theta_2)}, \frac{c(\Theta_2).c(\Theta_2)}{c(\theta_2)}\right) \qquad \text{B.8}$$

Atan2 (a,b) is a function available in many computer languages, that computes the arc tangent ($\tan^{-1}$) utilizing the sings of both the a and b components to calculate the quadrant of the resultant angle.

Appendix B


PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT
A
B
1
2
45.00°
17.00
3.00
17.04
90.00°
17.88
6.00
40.00
⌀14.00
25.00
12.50
DATE 1/7/13
Imperial College London
TITLE
New Cluster
PART NO
Assembly cluster
MATERIAL
QTY
1
WEIGHT
N A
SIZE
A4
REV
A
SURFACE TREATMENT
N A
GENERAL TOLERANCES ±0.05 UNLESS OTHERWISE SPECIFIED
1:1
UNITS mm
SHEET 1 OF 1

Appendix C

```
% Written by Maedeh Borhani, 21-10-2011 (version 1)

% Input:  filtered kinematic data (Text file exported from Nexus)
% Output: For Left & Right gait cycles: Walking, Stairs-up, Stairs-down and Time up
% three sessions for Normal, Overweight and Obese subjects, five trials per sesion.

% Fule selection: five trials
[filename1, pathname] = uigetfile('*.txt', 'Select txt file');
[filename2, pathname] = uigetfile('*.txt', 'Select txt file');
[filename3, pathname] = uigetfile('*.txt', 'Select txt file');
[filename4, pathname] = uigetfile('*.txt', 'Select txt file');
[filename5, pathname] = uigetfile('*.txt', 'Select txt file');

% Make variable File
FILE1=[pathname,filename1];
FILE2=[pathname,filename2];
FILE3=[pathname,filename3];
FILE4=[pathname,filename4];
FILE5=[pathname,filename5];

% Set rows and columns you want to read in
row=6;
column=0;

Data1=dlmread(FILE1,  '\t', row, column);
Data2=dlmread(FILE2,  '\t', row, column);
Data3=dlmread(FILE3,  '\t', row, column);
Data4=dlmread(FILE4,  '\t', row, column);
Data5=dlmread(FILE5,  '\t', row, column);

% Constants
% Sample freq
Sample_freq=150;
%timsestamp
dt=1/Sample_freq;
%Time steps for normalised data
steps=1;
 % Read in TO times data 1
 fid = fopen([pathname,filename1]);
% function file to get times
TO_Times1=GetTimes(fid);
fclose(fid);
% Read in TO times data 2
fid = fopen([pathname,filename2]);
% function file to get times, this command is written by Jeroen Bergmann and modified by
Maedeh Borhani. This command will help to take gait event from Nexus to Matlab.
TO_Times2=GetTimes(fid);
fclose(fid);
 % Read in TO times data 3
 fid = fopen([pathname,filename3]);
% function file to get times
```

```
TO_Times3=GetTimes(fid);
fclose(fid);
% Read in TO times data 4
fid = fopen([pathname,filename4]);
% function file to get times
TO_Times4=GetTimes(fid);
fclose(fid);
% Read in TO times data 5
fid = fopen([pathname,filename5]);
% function file to get times
TO_Times5=GetTimes(fid);
fclose(fid);

%Find rows containing Right & Left Gait cycles (TO-TO)
 First_sample1=Data1(1,1);
First_sample2=Data2(1,1);
First_sample3=Data3(1,1);
First_sample4=Data4(1,1);
First_sample5=Data5(1,1);
TO_Times1=TO_Times1*Sample_freq+1;
TO_Times2=TO_Times2*Sample_freq+1;
TO_Times3=TO_Times3*Sample_freq+1;
TO_Times4=TO_Times4*Sample_freq+1;
TO_Times5=TO_Times5*Sample_freq+1;

% For Data 1
 S_RightTO1=TO_Times1(4,1); % Toe off1 FP2
S_LeftTO1=TO_Times1(1,1); % Toe off1 FP1
S_RightTO2=TO_Times1(5,1); % Toe off2 FP2
S_LeftTO2=TO_Times1(2,1); % Toe off2 FP1

RightTO1=(S_RightTO1-First_sample1)+1; % Toe off1 FP2
LeftTO1=(S_LeftTO1-First_sample1)+1; % Toe off1 FP1
RightTO2=(S_RightTO2-First_sample1)+1; % Toe off2 FP2
LeftTO2=(S_LeftTO2-First_sample1)+1; % Toe off2 FP1

RSample_No1=Data1(RightTO1:RightTO2,1);
LSample_No1=Data1(LeftTO1:LeftTO2,1);
RPelvisAngle1_X=Data1(RightTO1:RightTO2,3);
RPelvisAngle1_Y=Data1(RightTO1:RightTO2,4);
RPelvisAngle1_Z=Data1(RightTO1:RightTO2,5);
RPelvisAngle1TRAD_X=Data1(RightTO1:RightTO2,6);
RPelvisAngle1TRAD_Y=Data1(RightTO1:RightTO2,7);
RPelvisAngle1TRAD_Z=Data1(RightTO1:RightTO2,8);
LPelvisAngle1_X=Data1(LeftTO1:LeftTO2,3);
LPelvisAngle1_Y=Data1(LeftTO1:LeftTO2,4);
LPelvisAngle1_Z=Data1(LeftTO1:LeftTO2,5);
LPelvisAngle1TRAD_X=Data1(LeftTO1:LeftTO2,6);
LPelvisAngle1TRAD_Y=Data1(LeftTO1:LeftTO2,7);
LPelvisAngle1TRAD_Z=Data1(LeftTO1:LeftTO2,8);

% For Data 2
S_RightTO1=TO_Times2(4,1); % Toe off1 FP2
S_LeftTO1=TO_Times2(1,1); % Toe off1 FP1
S_RightTO2=TO_Times2(5,1); % Toe off2 FP2
S_LeftTO2=TO_Times2(2,1); % Toe off2 FP1
```

```
RightTO1=(S_RightTO1-First_sample1)+1; % Toe off1 FP2
LeftTO1=(S_LeftTO1-First_sample1)+1; % Toe off1 FP1
RightTO2=(S_RightTO2-First_sample1)+1; % Toe off2 FP2
LeftTO2=(S_LeftTO2-First_sample1)+1; % Toe off2 FP1

RSample_No2=Data2(RightTO1:RightTO2,1);
LSample_No2=Data2(LeftTO1:LeftTO2,1);  RPelvisAngle2_X=Data2(RightTO1:RightTO2,3);
RPelvisAngle2_Y=Data2(RightTO1:RightTO2,4);
RPelvisAngle2_Z=Data2(RightTO1:RightTO2,5);
RPelvisAngle2TRAD_X=Data2(RightTO1:RightTO2,6);
RPelvisAngle2TRAD_Y=Data2(RightTO1:RightTO2,7);
RPelvisAngle2TRAD_Z=Data2(RightTO1:RightTO2,8);
LPelvisAngle2_X=Data2(LeftTO1:LeftTO2,3);
LPelvisAngle2_Y=Data2(LeftTO1:LeftTO2,4);
LPelvisAngle2_Z=Data2(LeftTO1:LeftTO2,5);
LPelvisAngle2TRAD_X=Data2(LeftTO1:LeftTO2,6);
LPelvisAngle2TRAD_Y=Data2(LeftTO1:LeftTO2,7);
LPelvisAngle2TRAD_Z=Data2(LeftTO1:LeftTO2,8);

% For Data 3
S_RightTO1=TO_Times3(4,1); % Toe off1 FP2
S_LeftTO1=TO_Times3(1,1); % Toe off1 FP1
S_RightTO2=TO_Times3(5,1); % Toe off2 FP2
S_LeftTO2=TO_Times3(2,1); % Toe off2 FP1
RightTO1=(S_RightTO1-First_sample1)+1; % Toe off1 FP2
LeftTO1=(S_LeftTO1-First_sample1)+1; % Toe off1 FP1
RightTO2=(S_RightTO2-First_sample1)+1; % Toe off2 FP2
LeftTO2=(S_LeftTO2-First_sample1)+1; % Toe off2 FP1
RSample_No3=Data3(RightTO1:RightTO2,1);
LSample_No3=Data3(LeftTO1:LeftTO2,1);

RPelvisAngle3_X=Data3(RightTO1:RightTO2,3);
RPelvisAngle3_Y=Data3(RightTO1:RightTO2,4);
RPelvisAngle3_Z=Data3(RightTO1:RightTO2,5);
RPelvisAngle3TRAD_X=Data3(RightTO1:RightTO2,6);
RPelvisAngle3TRAD_Y=Data3(RightTO1:RightTO2,7);
RPelvisAngle3TRAD_Z=Data3(RightTO1:RightTO2,8);
LPelvisAngle3_X=Data3(LeftTO1:LeftTO2,3);
LPelvisAngle3_Y=Data3(LeftTO1:LeftTO2,4);
LPelvisAngle3_Z=Data3(LeftTO1:LeftTO2,5);
LPelvisAngle3TRAD_X=Data3(LeftTO1:LeftTO2,6);
LPelvisAngle3TRAD_Y=Data3(LeftTO1:LeftTO2,7);
LPelvisAngle3TRAD_Z=Data3(LeftTO1:LeftTO2,8);

% For Data 4
S_RightTO1=TO_Times4(4,1); % Toe off1 FP2
S_LeftTO1=TO_Times4(1,1); % Toe off1 FP1
S_RightTO2=TO_Times4(5,1); % Toe off2 FP2
S_LeftTO2=TO_Times4(2,1); % Toe off2 FP1
RightTO1=(S_RightTO1-First_sample1)+1; % Toe off1 FP2
LeftTO1=(S_LeftTO1-First_sample1)+1; % Toe off1 FP1
RightTO2=(S_RightTO2-First_sample1)+1; % Toe off2 FP2
LeftTO2=(S_LeftTO2-First_sample1)+1; % Toe off2 FP1
RSample_No4=Data4(RightTO1:RightTO2,1);
LSample_No4=Data4(LeftTO1:LeftTO2,1);
```

```
RPelvisAngle4_X=Data4(RightTO1:RightTO2,3);
RPelvisAngle4_Y=Data4(RightTO1:RightTO2,4);
RPelvisAngle4_Z=Data4(RightTO1:RightTO2,5);
RPelvisAngle4TRAD_X=Data4(RightTO1:RightTO2,6);
RPelvisAngle4TRAD_Y=Data4(RightTO1:RightTO2,7);
RPelvisAngle4TRAD_Z=Data4(RightTO1:RightTO2,8);
LPelvisAngle4_X=Data4(LeftTO1:LeftTO2,3);
LPelvisAngle4_Y=Data4(LeftTO1:LeftTO2,4);
LPelvisAngle4_Z=Data4(LeftTO1:LeftTO2,5);
LPelvisAngle4TRAD_X=Data4(LeftTO1:LeftTO2,6);
LPelvisAngle4TRAD_Y=Data4(LeftTO1:LeftTO2,7);
LPelvisAngle4TRAD_Z=Data4(LeftTO1:LeftTO2,8);

% For Data 5
S_RightTO1=TO_Times5(4,1); % Toe off1 FP2
S_LeftTO1=TO_Times5(1,1); % Toe off1 FP1
S_RightTO2=TO_Times5(5,1); % Toe off2 FP2
S_LeftTO2=TO_Times5(2,1); % Toe off2 FP1
RightTO1=(S_RightTO1-First_sample1)+1; % Toe off1 FP2
LeftTO1=(S_LeftTO1-First_sample1)+1; % Toe off1 FP1
RightTO2=(S_RightTO2-First_sample1)+1; % Toe off2 FP2
LeftTO2=(S_LeftTO2-First_sample1)+1; % Toe off2 FP1
RSample_No5=Data5(RightTO1:RightTO2,1);
LSample_No5=Data5(LeftTO1:LeftTO2,1);

RPelvisAngle5_X=Data5(RightTO1:RightTO2,3);
RPelvisAngle5_Y=Data5(RightTO1:RightTO2,4);
RPelvisAngle5_Z=Data5(RightTO1:RightTO2,5);
RPelvisAngle5TRAD_X=Data5(RightTO1:RightTO2,6);
RPelvisAngle5TRAD_Y=Data5(RightTO1:RightTO2,7);
RPelvisAngle5TRAD_Z=Data5(RightTO1:RightTO2,8);
LPelvisAngle5_X=Data5(LeftTO1:LeftTO2,3);
LPelvisAngle5_Y=Data5(LeftTO1:LeftTO2,4);
LPelvisAngle5_Z=Data5(LeftTO1:LeftTO2,5);
LPelvisAngle5TRAD_X=Data5(LeftTO1:LeftTO2,6);
LPelvisAngle5TRAD_Y=Data5(LeftTO1:LeftTO2,7);
LPelvisAngle5TRAD_Z=Data5(LeftTO1:LeftTO2,8);

Left_Data_1 = {LPelvisAngle1_X LPelvisAngle1_Y LPelvisAngle1_Z LPelvisAngle1TRAD_X
LPelvisAngle1TRAD_Y LPelvisAngle1TRAD_Z};
Right_Data_1 = {RPelvisAngle1_X RPelvisAngle1_Y RPelvisAngle1_Z RPelvisAngle1TRAD_X
RPelvisAngle1TRAD_Y RPelvisAngle1TRAD_Z};
Left_Data_2 = {LPelvisAngle2_X LPelvisAngle2_Y LPelvisAngle2_Z LPelvisAngle2TRAD_X
LPelvisAngle2TRAD_Y LPelvisAngle2TRAD_Z};
Right_Data_2 = {RPelvisAngle2_X RPelvisAngle2_Y RPelvisAngle2_Z RPelvisAngle2TRAD_X
RPelvisAngle2TRAD_Y RPelvisAngle2TRAD_Z};
Left_Data_3 = {LPelvisAngle3_X LPelvisAngle3_Y LPelvisAngle3_Z LPelvisAngle3TRAD_X
LPelvisAngle3TRAD_Y LPelvisAngle3TRAD_Z};
Right_Data_3 = {RPelvisAngle3_X RPelvisAngle3_Y RPelvisAngle3_Z RPelvisAngle3TRAD_X
RPelvisAngle3TRAD_Y RPelvisAngle3TRAD_Z};
Left_Data_4 = {LPelvisAngle4_X LPelvisAngle4_Y LPelvisAngle4_Z LPelvisAngle4TRAD_X
LPelvisAngle4TRAD_Y LPelvisAngle4TRAD_Z};
Right_Data_4 = {RPelvisAngle4_X RPelvisAngle4_Y RPelvisAngle4_Z RPelvisAngle4TRAD_X
RPelvisAngle4TRAD_Y RPelvisAngle4TRAD_Z};
Left_Data_5 = {LPelvisAngle5_X LPelvisAngle5_Y LPelvisAngle5_Z LPelvisAngle5TRAD_X
LPelvisAngle5TRAD_Y LPelvisAngle5TRAD_Z};
```

```
Right_Data_5 = {RPelvisAngle5_X RPelvisAngle5_Y RPelvisAngle5_Z RPelvisAngle5TRAD_X
RPelvisAngle5TRAD_Y RPelvisAngle5TRAD_Z};

Left_Data1 = cell2mat(Left_Data_1);
Right_Data1 = cell2mat(Right_Data_1);
Left_Data2 = cell2mat(Left_Data_2);
Right_Data2 = cell2mat(Right_Data_2);
Left_Data3 = cell2mat(Left_Data_3);
Right_Data3 = cell2mat(Right_Data_3);
Left_Data4 = cell2mat(Left_Data_4);
Right_Data4 = cell2mat(Right_Data_4);
Left_Data5 = cell2mat(Left_Data_5);
Right_Data5 = cell2mat(Right_Data_5);

index_steps=0:steps:100;
% FOR Left_Data1
% Get size of the Data1
SIZELeft_Data1=size(Left_Data1);
for i=1:SIZELeft_Data1(2)
   % make time variables
    TimeLeft_Data1=(0:length(Left_Data1)-1)*(100/(length(Left_Data1)-1));
     for h=1:length(index_steps)-1
        indexLeft_Data1=find(TimeLeft_Data1>=index_steps(h)&
TimeLeft_Data1<index_steps(h+1));
        New_Left_Data1(h,i)=mean(Left_Data1(indexLeft_Data1,i));
    end
end

% FOR Left_Data2
 % Get size of the Data2
SIZELeft_Data2=size(Left_Data2);
 for i=1:SIZELeft_Data2(2)
   % make time variables
    TimeLeft_Data2=(0:length(Left_Data2)-1)*(100/(length(Left_Data2)-1));
    for h=1:length(index_steps)-1
        indexLeft_Data2=find(TimeLeft_Data2>=index_steps(h)&
TimeLeft_Data2<index_steps(h+1));
        New_Left_Data2(h,i)=mean(Left_Data2(indexLeft_Data2,i));
    end
end

% FOR Left_Data3
% Get size of the Data3
SIZELeft_Data3=size(Left_Data3);
for i=1:SIZELeft_Data3(2)
  % make time variables
    TimeLeft_Data3=(0:length(Left_Data3)-1)*(100/(length(Left_Data3)-1));
    for h=1:length(index_steps)-1
        indexLeft_Data3=find(TimeLeft_Data3>=index_steps(h)&
TimeLeft_Data3<index_steps(h+1));
        New_Left_Data3(h,i)=mean(Left_Data3(indexLeft_Data3,i));
    end
end

% FOR Left_Data4
% Get size of the Data4
```

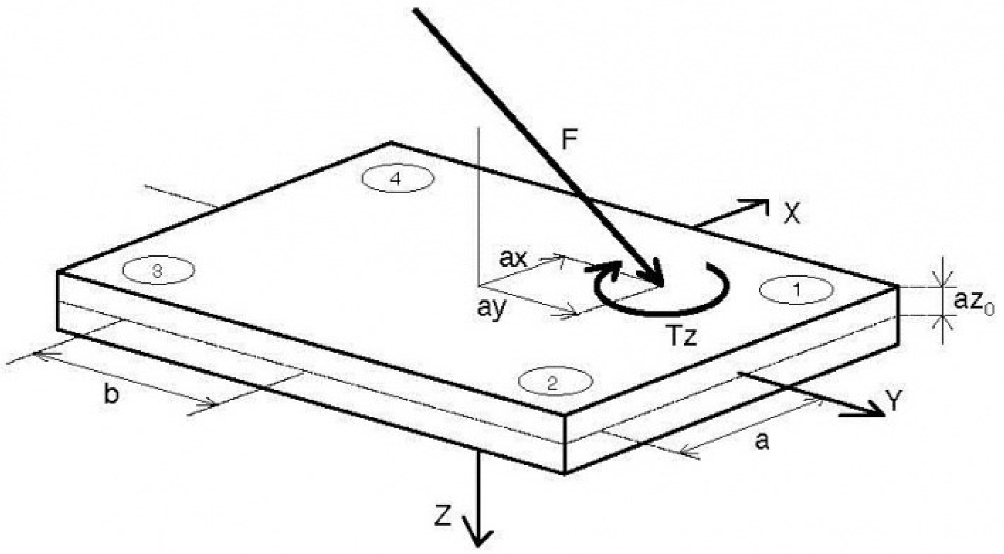
```
SIZELeft_Data4=size(Left_Data4);
for i=1:SIZELeft_Data4(2)
  % make time variables
   TimeLeft_Data4=(0:length(Left_Data4)-1)*(100/(length(Left_Data4)-1));
    for h=1:length(index_steps)-1
      indexLeft_Data4=find(TimeLeft_Data4>=index_steps(h)&
TimeLeft_Data4<index_steps(h+1));
      New_Left_Data4(h,i)=mean(Left_Data4(indexLeft_Data4,i));
   end
end

% FOR Left_Data5
 % Get size of the Data5
SIZELeft_Data5=size(Left_Data5);
 for i=1:SIZELeft_Data5(2)
   % make time variables
   TimeLeft_Data5=(0:length(Left_Data5)-1)*(100/(length(Left_Data5)-1));
    for h=1:length(index_steps)-1
      indexLeft_Data5=find(TimeLeft_Data5>=index_steps(h)&
TimeLeft_Data5<index_steps(h+1));
      New_Left_Data5(h,i)=mean(Left_Data5(indexLeft_Data5,i));
   end
end

%% After timing
New_LPelvisAngle1_X=New_Left_Data1(:,1);
New_LPelvisAngle1_Y=New_Left_Data1(:,2);
New_LPelvisAngle1_Z=New_Left_Data1(:,3);
New_LPelvisAngle1TRAD_X=New_Left_Data1(:,4);
New_LPelvisAngle1TRAD_Y=New_Left_Data1(:,5);
New_LPelvisAngle1TRAD_Z=New_Left_Data1(:,6);
New_LPelvisAngle2_X=New_Left_Data2(:,1);
New_LPelvisAngle2_Y=New_Left_Data2(:,2);
New_LPelvisAngle2_Z=New_Left_Data2(:,3);
New_LPelvisAngle2TRAD_X=New_Left_Data2(:,4);
New_LPelvisAngle2TRAD_Y=New_Left_Data2(:,5);
New_LPelvisAngle2TRAD_Z=New_Left_Data2(:,6);
New_LPelvisAngle3_X=New_Left_Data3(:,1);
New_LPelvisAngle3_Y=New_Left_Data3(:,2);
New_LPelvisAngle3_Z=New_Left_Data3(:,3);
New_LPelvisAngle3TRAD_X=New_Left_Data3(:,4);
New_LPelvisAngle3TRAD_Y=New_Left_Data3(:,5);
New_LPelvisAngle3TRAD_Z=New_Left_Data3(:,6);
New_LPelvisAngle4_X=New_Left_Data4(:,1);
New_LPelvisAngle4_Y=New_Left_Data4(:,2);
New_LPelvisAngle4_Z=New_Left_Data4(:,3);
New_LPelvisAngle4TRAD_X=New_Left_Data4(:,4);
New_LPelvisAngle4TRAD_Y=New_Left_Data4(:,5);
New_LPelvisAngle4TRAD_Z=New_Left_Data4(:,6);
New_LPelvisAngle5_X=New_Left_Data5(:,1);
New_LPelvisAngle5_Y=New_Left_Data5(:,2);
New_LPelvisAngle5_Z=New_Left_Data5(:,3);
New_LPelvisAngle5TRAD_X=New_Left_Data5(:,4);
New_LPelvisAngle5TRAD_Y=New_Left_Data5(:,5);
New_LPelvisAngle5TRAD_Z=New_Left_Data5(:,6);
 % defining the output matrix
```

```
New_Left_Data1 = {New_LPelvisAngle1_X New_LPelvisAngle2_X New_LPelvisAngle3_X
New_LPelvisAngle4_X New_LPelvisAngle5_X  New_LPelvisAngle1_Y New_LPelvisAngle2_Y
New_LPelvisAngle3_Y New_LPelvisAngle4_Y New_LPelvisAngle5_Y New_LPelvisAngle1_Z
New_LPelvisAngle2_Z New_LPelvisAngle3_Z New_LPelvisAngle4_Z New_LPelvisAngle5_Z
New_LPelvisAngle1TRAD_X New_LPelvisAngle2TRAD_X New_LPelvisAngle3TRAD_X
New_LPelvisAngle4TRAD_X New_LPelvisAngle5TRAD_X  New_LPelvisAngle1TRAD_Y
New_LPelvisAngle2TRAD_Y New_LPelvisAngle3TRAD_Y New_LPelvisAngle4TRAD_Y
New_LPelvisAngle5TRAD_Y  New_LPelvisAngle1TRAD_Z New_LPelvisAngle2TRAD_Z
New_LPelvisAngle3TRAD_Z New_LPelvisAngle4TRAD_Z New_LPelvisAngle5TRAD_Z };
New_Left_Data = cell2mat(New_Left_Data1);

% write data to excel
 GROUP=input('GROUP: ', 's'); % normal, overweight and obese
 CELL=input('Cell: ', 's');

% make new file name
pathname_new='F:\Black Drive\Result.Study 1\';
OUTPUT=[pathname_new, GROUP '.xlsx'];
 ARRAY=[New_Left_Data];
[SUCCESS,MESSAGE]=XLSWRITE(OUTPUT,ARRAY,'Session1',CELL); %session 1,2,3
```

Appendix D

Force plate is a measuring instrument that measures the ground reaction forces generated by a body standing or moving across it. The force plate is used to quantify postural stability, gait parameters and other parameters of biomechanics. The force plate measures the three dimensional components of a single equivalent force applied to the surface and its point of application, called centre of pressure, as well as the vertical moment of force. Data gathered in the anterior-posterior direction, the medio-lateral direction, and the vertical direction as well as moments about all 3 axes are used together to calculate the position of the centre of pressure relative to the origin of the force plate.

Figure below represents the Kistler force plate.



The analogue signals that are collected from four transducers on the corners of the force plate (1-4) are used to compute several parameters that calculates the position of the centre of position.

Force plate output signals

Output signal	Channel	Description
fx12	1	Force in X-direction measured by sensor 1 + sensor 2
fx34	2	Force in X-direction measured by sensor 3 + sensor 4

fy14	3	Force in Y-direction measured by sensor 1 + sensor 4
fy23	4	Force in Y-direction measured by sensor 2 + sensor 3
fz1 ... fz4	**5 ... 8**	Force in Z direction measured by sensor 1 ... 4

Calculated parameters

Parameter	**Calculation Description**
Fx = fx12 + fx34	Medio-lateral force 1)
Fy = fy14 + fy23	Anterior-posterior force 1)
Fz = fz1 + fz2 + fz3 + fz4	Vertical force
Mx = b * (fz1 + fz2 - fz3 - fz4)	Plate moment about X-axis 3)
My = a * (-fz1 + fz2 + fz3 - fz4)	Plate moment about Y-axis 3)
Mz = b * (-fx12 + fx34) + a * (fy14 - fy23)	Plate moment about Z-axis 3)
Mx' = Mx + Fy*az0	Plate moment about top plate surface 2)
My' = My - Fx*az0	Plate moment about top plate surface 2)
ax = -My' / Fz	X-Coordinate of force application point (COP) 2)
ay = Mx' / Fz	Y-Coordinate of force application point (COP) 2)
Tz = Mz - Fy * ax + Fx * ay	Free moment, Vertical torque, Frictional torque
COFx = Fx/Fz	Coefficient of Friction x-component
COFy = Fy/Fz	Coefficient of Friction y-component
COFxy = sqrt (COFx^2 + COFy^2)	Coefficient of Friction absolute

All formulae are in Kistler coordinate system.

1) Walking direction is positive Y-axis

2) az0 = top plane offset (negative value)

3) a, b = sensor offset (positive values)

Appendix E

1. Walking

1.1Variability:

BMI	Method	ROM Mean(±SD)	Max. movement Mean(±SD)	Intra-Session Variability	Inter-Session Variability
Pelvic tilt(X) (in degrees)					
Normal	**Cluster**	9.44(3.94)*	-18.80(5.63)	1.64(0.73)	3.00(2.09)
	Traditional	5.51(2.26)	-15.69(4.99)	1.43(0.66)	3.15(2.10)
Over Weight	**Cluster**	8.37(4.17)*	-18.68(5.17)	1.19(0.50)	2.10(1.65)
	Traditional	4.38(2.07)	-16.63(3.88)	1.30(0.29)	3.30(2.09)*
Obese	**Cluster**	10.4(5.57)*	-18.20(9.12)	1.30(0.36)	1.47(0.97)
	Traditional	5.34(2.26)	-16.66(6.95)	1.20(0.33)	3.20(1.50)*
Pelvic obliquity(Y') (in degrees)					
Normal	**Cluster**	11.59(2.62)	-3.36(3.95)	0.71(0.19)	0.81(0.38)
	Traditional	10.41(2.39)	-3.67(1.30)	0.99(0.44)*	2.63(1.79)*
Over Weight	**Cluster**	9.85(2.99)	-3.28(3.39)	0.75(0.30)	0.96(0.70)
	Traditional	10.27(2.57)	-3.34(1.91)	0.96(0.34)*	2.24(1.23)*
Obese	**Cluster**	9.21(3.11)	-3.64(3.24)	0.66(0.19)	0.71(0.51)
	Traditional	8.33(3.19)	-3.07(2.05)	0.70(0.21)	1.98(1.23)*
Pelvic rotation(Z") (in degrees)					
Normal	**Cluster**	16.63(6.75)*	-6.11(4.06)	1.68(0.45)	1.69(0.84)
	Traditional	12.39(5.06)	-4.98(3.59)	2.57(1.05)*	2.22(0.90)*
Over Weight	**Cluster**	15.93(8.20)*	-6.86(4.85)	1.69(0.51)	1.61(0.45)
	Traditional	11.49(5.24)	-5.97(3.40)	2.50(0.95)*	2.26(1.30)*
Obese	**Cluster**	13.82(3.97)*	-4.32(4.36)	1.55(0.39)	1.07(0.57)
	Traditional	9.91(3.29)	-4.83(3.06)	1.55(0.20)	2.27(1.84)*

Illustrate the mean values of the ROM, maximum pelvic movement, intra-session and inter-session variability for normal, overweight and obese subjects for all three range of motion during walking (*represents the significant difference between the two methods, p<0.05).

1.2 Repeatability:

BMI	Method	Within-day CMC (SD)	Between-day CMC(SD)	CMD(SD)
Pelvic tilt(X)				
Normal	Cluster	0.923(0.070)*	0.821(0.198)*	0.547(0.439)*
	Traditional	0.722(0.139)	0.534(0.207)	
Over Weight	Cluster	0.922(0.082)*	0.838(0.126)	-0.038(0.362)
	Traditional	0.827(0.119)	0.825(0.189)	
Obese	Cluster	0.955(0.069)*	0.942(0.097)*	-0.082(0.339)*
	Traditional	0.823(0.092)	0.851(0.095)	
Pelvic obliquity(Y')				
Normal	Cluster	0.904(0.108)	0.956(0.047)*	0.594(0.335)*
	Traditional	0.957(0.042)	0.811(0.216)	
Over Weight	Cluster	0.963(0.038)*	0.907(0.047)	0.460(0.297)
	Traditional	0.880(0.127)	0.949(0.054)	
Obese	Cluster	0.936(0.043)	0.956(0.041)*	0.366(0.370)*
	Traditional	0.945(0.050)	0.854(0.103)	
Pelvic rotation(Z")				
Normal	Cluster	0.823(0.125)	0.865(0.094)	0.776(0.132)*
	Traditional	0.862(0.110)	0.873(0.082)	
Over Weight	Cluster	0.855(0.105)	0.887(0.097)	0.692(0.257)
	Traditional	0.876(0.092)	0.799(0.142)	
Obese	Cluster	0.858(0.110)	0.859(0.119)	0.554(0.262)*
	Traditional	0.870(0.102)	0.896(0.081)	

The within-day CMC, between-day CMC and CMD values of the kinematic waveforms obtained from both the Cluster and Traditional methods during walking are given for all three range of motion of the pelvis. The inter subject standard deviation is given inside the parentheses (*represents the significant difference between the two methods, $p<0.05$).

2. Toe

2.1 variability:

BMI	Method	ROM Mean(±SD)	Max. movement Mean(±SD)	Intra-Session Variability	Inter-Session Variability
Pelvic tilt(X) (in degrees)					
Normal	**Cluster**	54.40(13.42)*	-73.27(13.24)	1.62(0.65)	4.86(2.88)
	Traditional	50.68(10.48)	-66.98(9.35)	2.26(1.24)*	6.49(3.44)*
Over Weight	**Cluster**	51.17(8.82)*	-70.71(11.39)	1.56(0.57)	3.90(2.75)
	Traditional	46.24(15.36)	-65.69(15.12)	2.47(1.30)*	5.73(3.63)*
Obese	**Cluster**	39.01(15.50)*	-58.71(15.85)	1.49(0.51)	2.95(2.32)
	Traditional	38.09(11.16)	-57.22(7.52)	2.23(1.28)*	5.31(4.24)*
Pelvic obliquity(Y’) (in degrees)					
Normal	**Cluster**	4.83(1.77)	-1.09(4.39)	0.84(0.31)	2.76(2.49)
	Traditional	6.45(5.46)*	-3.87(5.09)	1.30(0.57)*	3.61(3.41)
Over Weight	**Cluster**	4.22(1.72)	-0.91(4.01)	0.92(0.34)	2.80(2.01)
	Traditional	7.44(4.62)*	-1.73(4.76)	1.13(0.64)*	2.61(2.50)
Obese	**Cluster**	3.90(1.43)	-1.30(3.45)	0.68(0.21)	2.19(1.13)
	Traditional	7.35(6.80)*	-2.49(3.51)	1.04(0.61)*	1.35(0.94)
Pelvic rotation(Z”) (in degrees)					
Normal	**Cluster**	4.21(1.77)	0.47(4.16)	0.99(0.63)	1.57(0.93)
	Traditional	6.94(4.12)*	-0.09(2.88)	1.29(0.90)	2.84(1.56)
Over Weight	**Cluster**	3.70(1.61)	-0.65(3.20)	1.05(0.58)	1.91(0.75)
	Traditional	5.41(2.41)*	-1.74(2.66)	0.91(0.44)	1.54(0.96)
Obese	**Cluster**	3.58(1.49)	1.23(3.60)	0.69(0.38)	1.20(0.33)
	Traditional	4.71(2.25)*	-1.85(2.90)	0.70(0.27)	2.04(1.19)

Illustrate the mean values of the ROM, maximum pelvic movement, intra-session and inter-session variability for normal, overweight and obese subjects for all three range of motion during Toe (*represents the significant difference between the two methods, p<0.05).

2.2 Repeatability:

BMI	**Method**	**Within-day CMC (SD)**	**Between-day CMC(SD)**	**CMD(SD)**
Pelvic tilt(X)				
Normal	**Cluster**	0.938(0.051)	0.900(0.088)	0.858(0.207)*
	Traditional	0.943(0.059)	0.900(0.088)	
Over Weight	**Cluster**	0.962(0.022)	0.947(0.057)	0.794(0.273)
	Traditional	0.953(0.073)	0.951(0.063)	
Obese	**Cluster**	0.960(0.024)	0.903(0.120)	0.632(0.313)*
	Traditional	0.961(0.047)	0.962(0.045)	
Pelvic obliquity(Y')				
Normal	**Cluster**	0.872(0.141)*	0.721(0.229)*	0.020(0.478)
	Traditional	0.625(0.178)	0.474(0.264)	
Over Weight	**Cluster**	0.857(0.169)	0.874(0.145)	0.001(0.380)
	Traditional	0.761(0.178)	0.794(0.196)	
Obese	**Cluster**	0.874(0.145)*	0.874(0.128)	-0.105(0.393)
	Traditional	0.684(0.201)	0.836(0.192)	
Pelvic rotation(Z")				
Normal	**Cluster**	0.871(0.097)*	0.636(0.228)*	0.244(0.437)
	Traditional	0.678(0.163)	0.437(0.206)	
Over Weight	**Cluster**	0.836(0.183)*	0.847(0.160)	0.157(0.471)
	Traditional	0.709(0.208)	0.723(0.167)	
Obese	**Cluster**	0.905(0.121)*	0.836(0.139)	-0.098(0.478)
	Traditional	0.670(0.156)	0.759(0.247)	

The within-day CMC, between-day CMC and CMD values of the kinematic waveforms obtained from both the Cluster and Traditional methods during Toe are given for all three range of motion of the pelvis. The inter subject standard deviation is given inside the parentheses (*represents the significant differences between the two methods, p<0.05).

3. STS

3.1 Variability:

BMI	Method	ROM Mean(±SD)	Max. movement Mean(±SD)	Intra-Session Variability	Inter-Session Variability
Pelvic tilt(X) (in degrees)					
Normal	**Cluster**	38.54(6.95)*	-35.88(8.53)	1.69(0.64)	3.69(1.82)
	Traditional	35.95(5.73)	-30.39(5.82)	2.08(0.95)	5.38(2.77)*
Over Weight	**Cluster**	37.67(8.01)*	-35.50(9.56)	1.64(0.41)	3.16(3.16)
	Traditional	34.60(8.69)	-35.47(7.85)	2.02(0.78)	5.42(4.18)*
Obese	**Cluster**	36.13(8.53)*	-33.22(12.66)	1.98(0.93)	3.36(2.95)
	Traditional	33.09(11.25)	-33.37(8.85)	3.04(3.06)	4.77(1.64)*
Pelvic obliquity(Y’) (in degrees)					
Normal	**Cluster**	6.71(8.10)	-1.16(6.69)	0.85(0.33)	2.79(3.94)
	Traditional	8.13(8.84)*	-2.51(4.93)	0.82(0.22)	4.47(4.42)*
Over Weight	**Cluster**	5.54(4.85)	-2.16(4.04)	0.91(0.36)	1.39(1.34)
	Traditional	6.25(3.82)*	-2.17(3.86)	1.56(2.65)	2.56(1.85)*
Obese	**Cluster**	5.60(4.64)	-1.91(3.00)	0.69(0.27)	1.08(1.32)
	Traditional	6.13(1.96)*	-2.54(3.78)	1.41(1.84)	2.00(1.39)*
Pelvic rotation(Z”) (in degrees)					
Normal	**Cluster**	2.83(7.22)	0.64(3.94)	1.36(0.58)	2.46(1.62)
	Traditional	3.76(3.44)*	-1.39(10.66)	2.89(5.83)	3.52(5.34)
Over Weight	**Cluster**	5.94(8.05)	-0.61(3.87)	1.15(0.43)	1.96(1.18)
	Traditional	7.83(3.95)*	-1.59(2.27)	1.07(0.44)	1.25(0.58)
Obese	**Cluster**	5.73(3.81)	0.40(3.72)	1.13(0.51)	1.26(1.06)
	Traditional	7.88(2.75)*	-2.65(3.52)	1.39(1.18)	2.22(1.04)

Illustrate the mean values of the ROM, maximum pelvic movement, intra-session and inter-session variability for normal, overweight and obese subjects for all three range of motion during STS (*represents the significant difference between the two methods, p<0.05).

3.2 Repeatability:

BMI	Method	Within-day CMC (SD)	Between-day CMC(SD)	CMD(SD)
Pelvic tilt(X)				
Normal	**Cluster**	0.934(0.030)	0.940(0.041)	0.858(0.109)*
	Traditional	0.954(0.022)	0.890(0.050)	
Over Weight	**Cluster**	0.911(0.045)	0.933(0.039)*	0.647(0.287)
	Traditional	0.905(0.065)	0.862(0.105)	
Obese	**Cluster**	0.896(0.054)	0.871(0.115)	0.459(0.252)*
	Traditional	0.867(0.122)	0.883(0.113)	
Pelvic obliquity(Y’)				
Normal	**Cluster**	0.932(0.064)*	0.746(0.246)*	0.186(0.478)
	Traditional	0.790(0.125)	0.503(0.226)	
Over Weight	**Cluster**	0.889(0.139)*	0.856(0.105)	0.026(0.346)
	Traditional	0.769(0.152)	0.880(0.093)	
Obese	**Cluster**	0.873(0.097)*	0.854(0.092)	0.178(0.297)
	Traditional	0.843(0.135)	0.857(0.137)	
Pelvic rotation(Z”)				
Normal	**Cluster**	0.812(0.176)*	0.694(0.253)*	0.264(0.447)
	Traditional	0.657(0.138)	0.496(0.211)	
Over Weight	**Cluster**	0.824(0.121)*	0.788(0.131)	0.308(0.379)
	Traditional	0.680(0.154)	0.807(0.134)	
Obese	**Cluster**	0.874(0.136)*	0.874(0.101)*	0.102(0.434)
	Traditional	0.702(0.157)	0.725(0.234)	

The within-day CMC, between-day CMC and CMD values of the kinematic waveforms obtained from both the Cluster and Traditional methods during STS are given for all three range of motion of the pelvis. The inter subject standard deviation is given inside the parentheses (*represents the significant difference between the two methods, $p<0.05$).

4. Squat

4.1 Variability:

BMI	Method	ROM Mean(±SD)	Max. movement Mean(±SD)	Intra-Session Variability	Inter-Session Variability
Pelvic tilt(X) (in degrees)					
Normal	**Cluster**	24.40(8.22)*	-37.70(9.72)	1.83(0.53)	3.33(2.08)
	Traditional	18.78(7.05)	-30.75(7.47)	2.16(0.59)*	5.04(2.81)*
Over Weight	**Cluster**	24.88(8.07)*	-40.26(11.51)	1.31(0.46)	3.37(2.85)
	Traditional	22.14(7.87)	-37.93(9.79)	1.66(0.48)	4.77(4.76)*
Obese	**Cluster**	25.86(8.63)*	-39.96(14.11)	1.50(0.75)	2.96(1.54)
	Traditional	22.47(5.24)	-36.71(6.86)	2.06(0.98)*	4.69(2.39)*
Pelvic obliquity(Y’) (in degrees)					
Normal	**Cluster**	4.98(2.22)	-1.29(6.37)	0.71(0.24)	2.29(3.57)
	Traditional	3.83(1.88)	-2.32(4.45)	1.02(0.31)*	3.74(4.22)*
Over Weight	**Cluster**	4.59(2.21)	-1.74(3.56)	0.84(0.35)	1.25(0.47)
	Traditional	5.24(15.12)	-1.54(1.91)	0.95(0.42)	2.60(1.46)*
Obese	**Cluster**	3.71(1.40)	-1.15(3.18)	0.62(0.29)	0.80(0.41)
	Traditional	5.23(4.20)	-1.19(1.70)	0.65(0.25)*	2.25(1.46)*
Pelvic rotation(Z”) (in degrees)					
Normal	**Cluster**	4.65(1.74)	1.55(3.41)	1.41(0.51)	1.89(1.00)
	Traditional	6.70(3.11)*	0.33(2.78)	1.27(0.28)	2.42(1.24)*
Over Weight	**Cluster**	4.44(2.09)	0.19(3.82)	1.40(0.61)	1.66(0.93)
	Traditional	6.17(3.16)*	-0.91(2.53)	1.20(0.40)	1.91(1.26)*
Obese	**Cluster**	4.72(2.24)	1.84(3.70)	0.85(0.25)	1.34(0.62)
	Traditional	6.21(2.32)*	-1.96(2.58)	1.10(0.47)	2.40(1.52)*

Illustrate the mean values of the ROM, maximum pelvic movement, intra-session and inter-session variability for normal, overweight and obese subjects for all three range of motion during squat (*represents the significant difference between the two methods, p<0.05).

4.2 Repeatability:

BMI	Method	Within-day CMC (SD)	Between-day CMC(SD)	CMD(SD)
Pelvic tilt(X)				
Normal	**Cluster**	0.917(0.066)	0.844(0.150)	0.696(0.278)
	Traditional	0.935(0.058)	0.891(0.077)	
Over Weight	**Cluster**	0.953(0.031)	0.906(0.094)	0.648(0.361)^1
	Traditional	0.940(0.099)	0.920(0.078)	
Obese	**Cluster**	0.937(0.049)	0.941(0.047)	0.494(0.329)^1
	Traditional	0.919(0.130)	0.849(0.121)	
Pelvic obliquity(Y')				
Normal	**Cluster**	0.891(0.099)*	0.758(0.232)*	0.187(0.533)
	Traditional	0.709(0.176)	0.526(0.305)	
Over Weight	**Cluster**	0.866(0.144)*	0.767(0.162)	0.014(0.475)
	Traditional	0.727(0.222)	0.771(0.158)	
Obese	**Cluster**	0.868(0.145)*	0.834(0.175)	-0.098(0.312)
	Traditional	0.717(0.145)	0.826(0.234)	
Pelvic rotation(Z")				
Normal	**Cluster**	0.793(0.137)*	0.670(0.199)*	0.357(0.356)
	Traditional	0.610(0.157)	0.585(0.173)	
Over Weight	**Cluster**	0.751(0.215)*	0.830(0.132)*	0.315(0.428)
	Traditional	0.687(0.158)	0.660(0.192)	
Obese	**Cluster**	0.895(0.095)*	0.894(0.085)*	0.065(0.473)
	Traditional	0.712(0.163)	0.725(0.151)	

The within-day CMC, between-day CMC and CMD values of the kinematic waveforms obtained from both the Cluster and Traditional methods during squat are given for all three range of motion of the pelvis. The inter subject standard deviation is given inside the parentheses (*represents the significant difference between the two methods, $p<0.05$ and ^{1}represents the significant difference between overweight and obese subjects with $p<0.05$).

5. Box lifting

5.1 Variability:

BMI	Method	ROM Mean(±SD)	Max. movement Mean(±SD)	Intra-Session Variability	Inter-Session Variability
Pelvic Tilt(X) (in degrees)					
Normal	**Cluster**	25.21(10.07)*	-40.22(11.28)	2.97(1.29)	5.57(3.98)
	Traditional	22.05(10.85)	-34.58(10.56)	3.50(2.11)*	6.51(2.54)*
Over Weight	**Cluster**	25.45(9.93)*	-40.36(13.21)	2.27(1.15)	4.25(2.93)
	Traditional	22.99(8.84)	-39.33(9.24)	2.78(0.75)*	6.13(3.13)*
Obese	**Cluster**	25.72(13.55)*	-44.72(18.39)	2.04(1.14)	2.60(1.48)
	Traditional	24.68(8.04)	-40.18(9.46)	2.81(1.32)*	6.16(4.22)*
Pelvic Obliquity(Y’) (in degrees)					
Normal	**Cluster**	5.11(1.72)	-0.76(4.46)	0.88(0.29)	1.15(1.14)
	Traditional	4.55(3.55)	-1.84(2.11)	0.90(0.40)	3.04(1.57)*
Over Weight	**Cluster**	4.42(1.84)	-1.12(3.54)	0.98(0.25)	0.87(0.54)
	Traditional	4.35(2.15)	-1.32(2.21)	1.13(0.58)	2.25(1.91)*
Obese	**Cluster**	3.51(1.64)	-1.23(2.88)	0.63(0.12)	1.08(0.49)
	Traditional	6.44(5.99)	-1.93(1.90)	0.98(0.64)	2.01(0.95)*
Pelvic Rotation(Z”) (in degrees)					
Normal	**Cluster**	5.95(4.63)	-0.16(3.98)	1.69(0.81)	1.76(0.79)
	Traditional	7.84(3.63)*	-1.06(2.78)	1.44(0.48)	2.55(1.83)*
Over Weight	**Cluster**	5.23(2.71)	0.33(2.83)	1.46(0.47)	1.23(0.59)
	Traditional	6.76(3.51)*	-1.21(2.14)	1.30(0.64)	1.58(0.89)*
Obese	**Cluster**	5.09(2.26)	0.02(3.56)	1.40(0.31)	0.83(0.44)
	Traditional	6.10(2.24)*	-3.18(2.64)	1.31(0.64)	1.99(1.35)*

Illustrate the mean values of the ROM, maximum pelvic movement, intra-session and inter-session variability for normal, overweight and obese subjects for all three range of motion during Box (*represents the significant difference between the two methods, p<0.05).

5.2 Repeatability:

BMI	Method	Within-day CMC (SD)	Between-day CMC(SD)	CMD(SD)
Pelvic tilt(X)				
Normal	**Cluster**	0.908(0.103)	0.875(0.047)	0.681(0.264)[1,2]
	Traditional	0.888(0.111)	0.831(0.105)	
Over Weight	**Cluster**	0.910(0.093)	0.940(0.044)*	0.561(0.406)[1]
	Traditional	0.881(0.116)	0.890(0.073)	
Obese	**Cluster**	0.909(0.086)	0.975(0.017)*	0.544(0.325)[2]
	Traditional	0.939(0.069)	0.852(0.082)	
Pelvic obliquity(Y')				
Normal	**Cluster**	0.880(0.116)*	0.787(0.229)	0.195(0.513)
	Traditional	0.711(0.188)	0.582(0.255)	
Over Weight	**Cluster**	0.844(0.185)*	0.811(0.155)	0.050(0.451)
	Traditional	0.729(0.187)	0.817(0.169)	
Obese	**Cluster**	0.847(0.143)*	0.831(0.106)	-0.044(0.337)
	Traditional	0.700(0.152)	0.885(0.147)	
Pelvic rotation(Z")				
Normal	**Cluster**	0.795(0.143)*	0.729(0.184)	0.456(0.344)
	Traditional	0.639(0.164)	0.568(0.190)	
Over Weight	**Cluster**	0.736(0.146)	0.813(0.149)	0.346(0.377)
	Traditional	0.785(0.170)	0.845(0.076)	
Obese	**Cluster**	0.870(0.114)*	0.924(0.055)*	0.205(0.452)
	Traditional	0.690(0.142)	0.724(0.174)	

The within-day CMC, between-day CMC and CMD values of the kinematic waveforms obtained from both the Cluster and Traditional methods during Box are given for all three range of motion of the pelvis. The inter subject standard deviation is given inside the parentheses (*, [1] and [2] represent the significant difference between the two methods, $p<0.05$).

6. Stairs-up

6.1 Variability:

BMI	Method	ROM Mean(±SD)	Max. movement Mean(±SD)	Intra-Session Variability	Inter-Session Variability
Pelvic tilt(X) (in degrees)					
Normal	**Cluster**	8.85(3.43)	-25.51(6.63)	1.858(0.70)	3.82(3.76)
	Traditional	8.47(8.03)	-22.57(8.00)	2.67(3.19)	3.94(1.68)*
Over Weight	**Cluster**	9.31(4.18)*	-25.56(7.71)	0.97(0.18)	2.89(2.44)
	Traditional	6.02(2.86)	-24.60(5.76)	1.30(0.55)	5.58(2.93)*
Obese	**Cluster**	9.91(3.42)*	-25.77(11.52)	1.08(0.37)	1.46(1.08)
	Traditional	7.40(4.42)	-23.98(7.31)	1.27(0.48)	4.79(3.47)*
Pelvic obliquity(Y') (in degrees)					
Normal	**Cluster**	15.90(4.79)	-10.21(5.65)	2.75(2.00)	2.62(1.57)
	Traditional	18.78(4.83)	-11.13(5.30)	3.11(2.62)*	2.95(2.09)*
Over Weight	**Cluster**	14.81(3.50)	-9.48(5.04)	2.12(0.67)	2.01(1.08)
	Traditional	18.80(4.33)	-12.51(5.04)	2.44(1.05)*	3.19(1.74)*
Obese	**Cluster**	14.46(3.11)	-7.17(4.15)	1.52(0.51)	1.71(1.43)
	Traditional	17.85(4.36)	-9.87(3.50)	2.16(1.26)*	2.44(1.39)*
Pelvic rotation(Z") (in degrees)					
Normal	**Cluster**	20.63(17.18)	12.02(13.59)	8.24(5.83)	4.67(5.17)
	Traditional	18.32(15.41)	12.09(15.16)	8.77(7.29)*	5.59(3.38)
Over Weight	**Cluster**	17.83(9.80)	-13.85(23.83)	3.60(1.13)	5.57(2.87)
	Traditional	18.72(13.13)	-18.60(28.93)	6.53(3.84)*	6.70(5.58)
Obese	**Cluster**	15.82(6.76)	10.75(15.08)	3.13(1.32)	3.48(2.08)
	Traditional	22.21(23.96)	10.70(15.66)	4.99(2.28)*	4.31(4.50)

Illustrate the mean values of the ROM, maximum pelvic movement, intra-session and inter-session variability for normal, overweight and obese subjects for all three range of motion during Stairs-up (*represents the significant difference between the two methods, $p<0.05$).

6.2 Repeatability:

BMI	Method	Within-day CMC (SD)	Between-day CMC(SD)	CMD(SD)
Pelvic tilt(X)				
Normal	**Cluster**	0.847(0.164)*	0.929(0.066)	0.138(0.381)
	Traditional	0.647(0.183)	0.831(0.110)	
Over Weight	**Cluster**	0.922(0.116)*	0.824(0.136)	-0.070(0.456)
	Traditional	0.855(0.138)	0.800(0.174)	
Obese	**Cluster**	0.851(0.194)*	0.752(0.169)*	-0.132(0.320)
	Traditional	0.746(0.144)	0.546(0.248)	
Pelvic obliquity(Y')				
Normal	**Cluster**	0.890(0.071)	0.942(0.034)	0.758(0.208)
	Traditional	0.887(0.131)	0.881(0.061)	
Over Weight	**Cluster**	0.954(0.036)*	0.935(0.102)	0.726(0.181)
	Traditional	0.907(0.081)	0.887(0.068)	
Obese	**Cluster**	0.909(0.080)	0.930(0.096)	0.646(0.259)
	Traditional	0.867(0.214)	0.896(0.124)	
Pelvic rotation(Z")				
Normal	**Cluster**	0.554(0.206)	0.621(0.160)*	0.454(0.493)
	Traditional	0.627(0.250)	0.541(0.147)	
Over Weight	**Cluster**	0.776(0.189)	0.729(0.184)*	0.432(0.491)
	Traditional	0.724(0.189)	0.641(0.188)	
Obese	**Cluster**	0.667(0.255)	0.825(0.164)*	0.273(0.407)
	Traditional	0.542(0.223)	0.694(0.149)	

The within-day CMC, between-day CMC and CMD values of the kinematic waveforms obtained from both the Cluster and Traditional methods during Stairs-up are given for all three range of motion of the pelvis. The inter subject standard deviation is given inside the parentheses (*represent the significant difference between the two methods, $p<0.05$).

7. Stairs-down:

7.1 Variability:

BMI	Method	ROM Mean(±SD)	Max. movement Mean(±SD)	Intra-Session Variability	Inter-Session Variability
Pelvic tilt(X) (in degrees)					
Normal	Cluster	7.27(2.76)*	-16.45(6.24)	1.57(0.56)	3.30(2.24)
	Traditional	5.40(2.09)	-13.48(4.70)	1.88(0.70)	4.42(2.07)*
Over Weight	Cluster	7.83(2.77)*	-16.46(6.59)	1.03(0.31)	2.47(2.05)
	Traditional	6.04(2.14)	-16.69(5.42)	1.66(0.59)	4.64(1.71)*
Obese	Cluster	8.50(3.62)*	-17.86(12.84)	1.20(0.39)	1.69(1.29)
	Traditional	8.03(6.73)	-16.71(11.06)	2.06(1.91)	4.99(3.44)*
Pelvic obliquity(Y’) (in degrees)					
Normal	Cluster	10.84(3.35)*	-3.73(5.03)	1.34(0.28)	1.39(0.72)
	Traditional	9.79(3.42)	-4.06(2.85)	1.18(0.17)	3.35(2.31)*
Over Weight	Cluster	12.84(4.15)*	-4.45(2.92)	1.18(0.63)	1.13(0.59)
	Traditional	11.60(3.76)	-3.90(2.25)	1.34(0.70)	2.13(1.25)*
Obese	Cluster	14.26(6.15)*	-7.13(4.51)	1.62(1.48)	1.17(0.26)
	Traditional	11.97(4.32)	-5.91(3.77)	2.13(1.93)	3.05(2.61)*
Pelvic rotation(Z”) (in degrees)					
Normal	Cluster	14.25(6.49)	-5.21(4.98)	3.14(1.39)	2.41(1.32)
	Traditional	14.14(5.88)	-6.27(4.65)	3.01(1.28)	1.93(1.19)
Over Weight	Cluster	17.95(8.17)	-11.39(8.22)	2.94(1.47)	3.41(2.90)
	Traditional	17.82(9.14)	-12.89(9.51)	3.83(2.09)*	2.68(3.84)
Obese	Cluster	19.63(10.20)	-8.35(8.21)	3.61(1.81)	3.52(1.74)
	Traditional	20.89(11.51)	-11.60(9.74)	4.66(2.44)*	3.08(2.07)

Illustrate the mean values of the ROM, maximum pelvic movement, intra-session and inter-session variability for normal, overweight and obese subjects for all three range of motion during Stairs-down (*represent the significant differences between the two methods, p<0.05).

7.2 Repeatability:

BMI	Method	Within-day CMC (SD)	Between-day CMC(SD)	CMD(SD)
Pelvic tilt(X)				
Normal	**Cluster**	0.866(0.148)*	0.703(0.197)*	-0.038(0.404)
	Traditional	0.573(0.174)	0.391(0.225)	
Over Weight	**Cluster**	0.879(0.074)	0.850(0.122)	-0.093(0.451)
	Traditional	0.891(0.129)	0.873(0.143)	
Obese	**Cluster**	0.863(0.137)*	0.944(0.070)	-0.126(0.324)
	Traditional	0.690(0.150)	0.899(0.071)	
Pelvic obliquity(Y’)				
Normal	**Cluster**	0.924(0.065)*	0.933(0.069)*	0.588(0.328)
	Traditional	0.844(0.138)	0.773(0.172)	
Over Weight	**Cluster**	0.921(0.087)	0.947(0.036)	0.601(0.288)
	Traditional	0.897(0.093)	0.855(0.083)	
Obese	**Cluster**	0.864(0.107)	0.951(0.034)*	0.555(0.258)
	Traditional	0.876(0.111)	0.845(0.117)	
Pelvic rotation(Z”)				
Normal	**Cluster**	0.791(0.141)*	0.831(0.122)*	0.585(0.534)
	Traditional	0.691(0.174)	0.676(0.175)	
Over Weight	**Cluster**	0.843(0.123)	0.826(0.151)	0.737(0.309)
	Traditional	0.828(0.156)	0.752(0.309)	
Obese	**Cluster**	0.780(0.126)	0.805(0.150)	0.700(0.208)
	Traditional	0.782(0.116)	0.827(0.173)	

The within-day CMC, between-day CMC and CMD values of the kinematic waveforms obtained from both the Cluster and Traditional methods during Stairs-down are given for all three range of motion of the pelvis. The inter subject standard deviation is given inside the parentheses (*represent the significant differences between the two methods, p<0.05).

8. Time-up

8.1 Variability:

BMI	Method	ROM Mean(±SD)	Max. movement Mean(±SD)	Intra-Session Variability	Inter-Session Variability
Pelvic tilt(X) (in degrees)					
Normal	Cluster	38.71(9.33)*	-33.27(9.73)	3.62(1.38)	4.84(3.72)
	Traditional	36.32(11.8)	-29.09(10.21)	5.03(2.81)*	5.51(1.81)*
Over Weight	Cluster	40.40(8.37)*	-34.88(10.44)	2.48(1.08)	2.96(3.21)
	Traditional	35.57(9.98)	-32.42(9.18)	2.86(1.25)*	5.57(3.54)*
Obese	Cluster	33.69(12.1)*	-31.14(14.81)	2.14(0.65)	3.51(3.03)
	Traditional	28.36(13.6)	-29.92(12.28)	4.60(4.31)*	4.76(1.75)
Pelvic obliquity(Y’) (in degrees)					
Normal	Cluster	57.20(23.25)*	-31.39(11.48)	3.85(1.79)	4.81(3.35)
	Traditional	47.36(13.3)	-26.55(9.13)	3.84(1.57)	5.62(2.93)*
Over Weight	Cluster	57.62(15.6)*	-34.08(10.83)	2.96(1.22)	2.96(3.20)
	Traditional	53.92(13.5)	-31.79(9.57)	3.72(1.87)	5.72(3.58)*
Obese	Cluster	52.54(23.2)*	-30.68(14.64)	2.41(0.57)	3.31(1.56)
	Traditional	47.25(15.8)	-27.53(9.89)	3.39(1.23)	3.94(2.28)
Pelvic rotation(Z”) (in degrees)					
Normal[1]	Cluster	28.83(7.04)*	-88.50(11.44)	5.02(2.16)	4.88(7.87)
	Traditional	27.60(7.74)	-78.42(10.32)	7.65(2.29)	5.16(7.22)
Over Weight	Cluster	24.78(2.26)*	-59.90(3.56)	1.68(8.53)	5.52(7.87)
	Traditional	28.51(2.70)	-54.90(2.06)	1.25(6.27)	7.76(14.44)
Obese[1]	Cluster	10.90(5.76)*	-74.40(3.02)	1.47(7.35)	4.70(4.16)
	Traditional	0.84(5.66)	-79.51(3.19)	2.51(3.07)	5.09(3.59)

Illustrate the mean values of the ROM, maximum pelvic movement, intra-session and inter-session variability for normal, overweight and obese subjects for all three range of motion during Time-up (*and [1] represent the significant differences between the two methods, p<0.05).

8.2 Repeatability:

BMI	Method	Within-day CMC (SD)	Between-day CMC(SD)	CMD(SD)
Pelvic tilt(X)				
Normal	**Cluster**	0.897(0.088)*	0.923(0.093)*	0.604(0.371)[1,2]
	Traditional	0.784(0.189)	0.788(0.122)	
Over Weight	**Cluster**	0.913(0.060)	0.933(0.069)*	0.603(0.345)[1]
	Traditional	0.896(0.046)	0.841(0.176)	
Obese	**Cluster**	0.910(0.058)*	0.924(0.072)*	0.229(0.314)[2]
	Traditional	0.846(0.072)	0.860(0.074)	
Pelvic obliquity(Y')				
Normal	**Cluster**	0.917(0.094)	0.910(0.103)	0.816(0.278)
	Traditional	0.867(0.184)	0.875(0.155)	
Over Weight	**Cluster**	0.937(0.038)*	0.962(0.031)	0.859(0.120)*
	Traditional	0.898(0.066)	0.943(0.049)	
Obese	**Cluster**	0.918(0.046)	0.937(0.056)	0.657(0.181)*
	Traditional	0.920(0.065)	0.943(0.056)	
Pelvic rotation(Z")				
Normal	**Cluster**	0.950(0.126)	0.883(0.254)	0.894(0.172)
	Traditional	0.946(0.101)	0.883(0.251)	
Over Weight	**Cluster**	0.967(0.082)	0.995(0.009)	0.876(0.198)
	Traditional	0.970(0.042)	0.982(0.034)	
Obese	**Cluster**	0.994(0.013)*	0.998(0.001)	0.858(0.153)
	Traditional	0.957(0.041)	0.976(0.020)	

The within-day CMC, between-day CMC and CMD values of the kinematic waveforms obtained from both the Cluster and traditional methods during Time-up are given for all three range of motion of the pelvis. The inter subject standard deviation is given inside the parentheses (*,[1] and [2] represent the significant difference between the two methods, $p<0.05$).

Appendix F

Principal component analysis (PCA) is a useful statistical technique that has found application in fields such as face recognition and image compression, and is a common technique for finding patterns in data of high dimension. PCA is a way of identification of pattern in a set of data and expressing the data in such a way as to highlight their similarities and differences. PCA is covering standard deviation, covariance, eigenvectors and eigenvalues and variance. If x and y represent the data point obtained from the force plate, the PCA of the data set is calculated as follow:

1. $A_n = \sum_0^n \mathrm{x} - \bar{X}$, $B_n = \sum_0^n \mathrm{y} - \bar{Y}$ Where, $\bar{X}$ and $\bar{Y}$ represent the mean values of data set in x and y directions and n is the number of data points (n=80,000).
2. Calculation of the covariance matrix: as the data are in two dimensions the covariance matrix is a 2×2 matrix, which is:

   CM = $\begin{bmatrix} 2 & 1 \\ 1 & 3 \end{bmatrix}$, where 1= $\frac{\sum_0^{\mathrm{n}}(\mathrm{A_n})(\mathrm{B_n})}{n-1}$, 2= $\frac{\sum_0^{\mathrm{n}}(\mathrm{An})^2}{n-1}$, 3= $\frac{\sum_0^{\mathrm{n}}(\mathrm{Bn})^2}{n-1}$
3. Calculation of the eigenvector and eigenvalues of the CM (covariance matrix):

   Eigenvalues: det(CM-λI)=0 which will result in calculation of λ_1 and λ_2.

   Eigenvetors: CM.[V_1]= λ_1.[V_1], CM.[V_2]= λ_2.[V_2]

   By calculating the eigenvectors of the covariance matrix we have extract the lines of characteristic for the data. In mathematical terms, PCA defines the direction of principal axis as that of the first eigenvector of the covariance matrix [CM], and the variance along this axis is then corresponding (largest) eigenvalue. The second eigenvector and value define the direction of the minor axis (orthogonal to the first) and its variance, respectively.
4. The final step is to drive a new set of data. Once the eigenvectors are calculated, the transposes of eigenvectors ([eigenV]’) are multiplied on the left of the original data ([Data]’).

   D=[eigenV]’×[Data]’, the final data gives us the original data in terms of eigenvectors.

The expression is the most sufficient as the x and y axes are perpendicular and the eigenvector are perpendicular. Our data from being in the x and y axes are now in terms of our eigenvectors. When the data were in x and y axes, values of each data point didn't really tell us exactly how a single data point relates to the rest of the data. There is a command available in MATLAB that calculates the PCA of a set of data, princomp(zscore(X). In this thesis the PCA was used to measure sway area by expressing the centre of pressure data point as polar coordinates and the furthest point from the centre are found using the ellipse shape to approximate the sway area.

Appendix G

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An alternative technical marker set for the pelvis is more repeatable than the standard pelvic marker set

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Soft tissue artefact

ABSTRACT

Multiple marker sets and models are currently available for assessing pelvic kinematics in gait. Despite the presence of a variety models, there are still debates on their reliability and consistency, and consequently there is no clearly defined standard. Two marker sets were evaluated in this study: the ‘Traditional’ where markers are placed at the anterior and posterior superior iliac spines (ASISs, PSISs); and the ‘Cluster’, where a cluster of three orthogonal markers fixed on a rigid based is attached to the sacrum. The two sets were compared with respect to intra and inter session standard deviations of maximum pelvic tilt, obliquity and rotation angles. The repeatability between and within sessions was measured using coefficient of multiple correlation (CMC). Also the similarity between the two sets was assessed using inter-protocol CMC (ipCMC). Both data sets generated showed high within and between session repeatability in the sagittal plane (CMC > 0.80), although the Cluster method showed higher repeatability than that of the Traditional method in non-sagittal plane motion for both within and between sessions. The authors are not aware of other studies reporting the differences in intra and inter session variability and repeatability values for different body mass index categories such as overweight and obese subjects with relatively large sample size. Hence the Cluster method overcomes a number of theoretical and experimental limitations such as minimising the marker occlusion and is a reliable alternative to the Traditional (the standard) marker set.

1. Introduction

Over the past decade the understanding of pelvic kinematics during gait has increased despite a lack of clearly defined measurement standards. The most commonly used model in gait analysis is the kinematic model described by Kadaba et al. [1] and Davis et al. [2]. In the latter model, calculation of lower limb kinematics is based on the anterior superior iliac spines (ASIS) therefore occlusion of these markers for all or part of the trial will result in loss of some data. Occlusion of the ASIS could be as a result of soft tissue around the anterior abdomen (a common issue in overweight and obese subjects), arm movement, or activities that require high degrees of hip and trunk flexion, such as running, stair climbing or level walking [3]. One known modification to overcome ASIS occlusion is to introduce two technical markers to the pelvis positioned an equal distance laterally and posteriorly to the ASIS marker (often placed on the iliac crest) [4]. In order to use these technical markers, the ASIS marker positions can be expressed in relation to a technical coordinate system created using the technical markers in a static trial where the subject is stationary for couple of seconds with both anatomical and technical markers on the pelvis. However, having these technical markers on the lateral side of the waist does not guarantee reliable results, as again this is a site for fat deposition and substantial amount of fat and skin tissue may be present. There are no reports on how this method could be reliable for overweight and obese subjects. Generally, in the previous studies there has been no reporting on how to minimise the soft tissue artefact for overweight and obese subjects performing range of motion activities. Another previously used method involved a triad of markers directly placed on the posterior aspect of the pelvis. This was used to define directly the pelvic anatomical coordinate frame [5,6]. Pohl et al. [6] similarly used a rigid triad of markers to

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describe pelvic kinematics with the addition of two markers on the iliac crest, noting that this may not be the most reliable method to define the frontal plane of the pelvis [6]. This study proposed a potential solution to this problem which is the use of a cluster of three orthogonal markers attached to a rigid based as technical markers. This cluster is attached to the sacrum (Fig. 1) as this provides more accurate results than the ASIS and has less skin artefact [7]. Using the ‘calibrated anatomical system technique’ (CAST) [8,10] allows the position of ASIS defined relative to the Cluster in a static trial and then during dynamic trial the position of the ASIS is linked to the Cluster and thus affected by the same skin movement artefact that affects the Cluster [11]. The aim of this study is to compare the Cluster method with the Traditional method, which is the use of four surface markers on the right and left anterior superior iliac spine and left and right posterior superior iliac spine, in a population of healthy volunteers with varying body mass index (BMI).

2. Methodology

2.1. Participants

Thirty healthy subjects participated in this study (mean SD age and body mass index of 32.5 12.3 years, and 26.39 4.20 kg/m^2, respectively). They were divided in three equal groups of normal, overweight, and obese according to their body mass index (BMI) (normal 19–24 kg/m^2, overweight 24–28 kg/m^2, and obese 28–35 kg/m^2). None of the subjects had any history of lower back pain, surgery on the hip or lower limbs. They had no musculoskeletal injuries or disorders that affect walking ability. Written informed consent was obtained prior to participation. This study was approved by the Imperial College Research Ethics Committee (ICREC).

2.2. Data collection

An optical motion tracking system (VICON, Oxford, UK) consisting of nine high speed MX-13+ cameras was used at acquisition rate of 150 Hz. The same assessor carried out all data collection and analysis. Spherical reflective markers of 14 mm in diameter were applied concurrently (Fig. 1): (a) RASIS, LASIS, LPSIS, and RPSIS (Traditional); (b) a rigid cluster of three markers on sacrum (Cluster). In addition, three markers were attached to boney landmarks on the right and left foot to

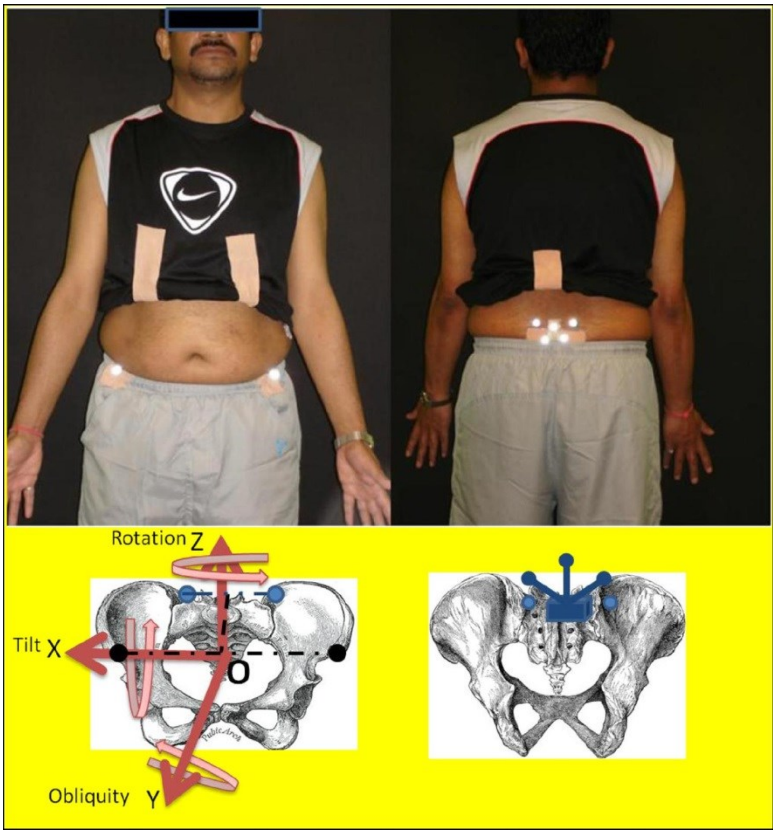

Fig. 1. Shows the markers placed on boney landmarks of the pelvis. Top left picture shows the anterior view of a subject with two markers on the ASIS and top right picture shows the posterior view of two markers placed on the PSIS and the cluster of three markers attached to the sacrum. For the Traditional set four anatomical markers are used to track the motion (two black circles = left/right ASIS and two light blue circles = left/right PSIS are shown on the skeleton) while for the Cluster method, a separate cluster positioned on sacrum is used for tracking the pelvic movement which is shown by blue colour on the bottom left picture. Coordinate frame of the pelvis is in red. Pelvic tilt represents the movement of the pelvis around the X axis (flexion/extension), pelvic obliquity shows the movement of the pelvis around the Y axis (Abduction/adduction), and finally pelvic rotation stands for the movement of the pelvis around the Z axis. The origin of the segment is defined as the midpoint between two ASIS, X axis defined as a line parallel to the ASIS () and the Y axis is defined as a line connecting the midpoints of ASIS and PSIS (- - - - - -). The Z axis is orthogonal to other two axes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1

Definitions of boney landmarks for the Cluster and Traditional sets. These anatomical sets were used to define the segment coordinate frame.

Anatomical sets	Description	Identification
Cluster method		
L/R ASIS	Most prominent point of left and right ASIS	Pointer
L/R PSIS	Most prominent point of left and right PSIS	Marker
Technical set for pelvis		
Marker cluster	Rigid cluster of 3 markers placed sacrum	Marker
Traditional method		
L/R ASIS	Most prominent point of left and right ASIS	Marker
L/R PSIS	Most prominent point of left and right PSIS	Marker
Definition of segment coordinate frame		
Pelvis		
O	Midpoint between ASISs	
X	Parallel to the line connecting ASISs, positive to the right	
Z	Orthogonal to the plane defined by ASISs and PSISs, positive superiorly	
Y	Orthogonal to other two axes, positive anteriorly	

L/R represents left/right.

determine toe-off events. Markers location and segment definitions are described in Table 1.

Each subject was recorded in three sessions, one week apart. The subjects were asked to stand still while LASIS and RASIS were calibrated using the tip of the calibration wand (which is an L-frame used by VICON for the calibration of capturing volume) of known dimensions as proposed by Cappozzo et al. [9]. The wand's technical coordinate frame was then used to define the position of each ASIS with respect to the coordinate frame of the cluster. Following this, a static trial was conducted to allow the cameras to record the marker positions of the Traditional method; this includes the positions of the PSIS markers that are then defined with respect to the cluster for the Cluster method. Vicon Nexus 1.7.1 and Vicon BodyBuilder 3.6.1 were used to capture and process the data.

Each subject was asked to complete five trials in each session for eight different activities of daily living: (1) walking at self selected speed (walking), (2) standing up from standard sitting position, walk a distance of 2 m, turn and back to the chair and sitting down(Time up), (3) picking up a light box from the floor by bending their knees (Box), (4) sitting and standing from a backless chair (Sit-to-Stand), (5) reaching towards the toes without bending the knees (Toe), (6) squatting until they feel the seat (Squat), (7) ascending the stairs (Up-stairs), and (8) descending the stairs (Down-stairs).

2.3. Data analysis

The data for one stride (between two successive left- toe offs) of each trial were time normalised from 0 to 100% of the gait cycle and for activities involved the full range of motion of the pelvis such as Box, Toe and Sit-to-Stand, the data were normalised to 100% of the pelvis movement defined from 20 ms prior to start the task to 20 ms after finishing the task. The data were filtered using a 4th order low-pass Butterworth filter with cut off frequency of 6 Hz. In this study the Left side (left leg) were selected arbitrarily.

The pelvis angles were calculated using XYZ Cardan rotation sequence (tilt, obliquity, and rotation) which is the conventional sequence in many commercial gait analysis software packages (Vicon Clinical Manager: Oxford Metrics, UK) [12]. For each subject, standard deviations of the discrete parameters were calculated using key features that were consistently identifiable in both sets which were maximum pelvic tilt, maximum pelvic obliquity, and maximum pelvic rotation [10,13]. Intra-session variability was assessed for maximum pelvic tilt, pelvic obliquity and pelvic rotation by taking their averaged standard deviations (SD) over three sessions for all ADLs among five trials for each session (intra-session SD-variability). As the marker placement did not change between the trials in each session, the intra-variability is an indicator of repeatability of the subjects'

Table 2

Intra-session and inter-session means of standard deviation of maximum pelvic tilt, obliquity and rotation for activities of daily living that involves the full range of the motion of pelvis and walking.

(n = 30)		Cluster method (SD)			Traditional method (SD)		
		Tilt	Obliquity	Rotation	Tilt	Obliquity	Rotation
Intra-session							
BOX	Normal	5.51 (2.54)	2.65 (0.87)	2.54 (1.83)	5.57 (3.98)	2.71 (1.20)	1.76 (0.79)
	Overweight	2.25 (2.93)*	2.76 (1.52)	1.73 (0.62)	5.88 (3.86)	0.87 (0.54)*	1.23 (0.59)
	Obese	2.60 (1.48)*	2.01 (0.95)	1.99 (1.35)	6.16 (4.22)	1.08 (0.49)	0.83 (0.44)*
Squat	Normal	6.45 (1.78)	2.83 (0.92)	2.42 (1.24)	5.50 (1.59)	2.13 (0.71)	1.89 (1.00)
	Overweight	4.37 (2.85)*	2.60 (1.46)	1.91 (1.26)	7.77 (4.76)	1.25 (0.47)	1.66 (0.93)
	Obese	2.96 (1.54)*	2.25 (1.46)	2.40 (1.52)	4.69 (2.39)	0.80 (0.41)*	1.33 (0.62)
STS	Normal	5.25 (2.84)	2.55 (0.99)	4.06 (1.71)	5.05 (1.92)	2.46 (0.66)	5.45 (7.01)
	Overweight	3.16 (3.16)*	2.56 (1.85)	1.95 (1.18)	5.42 (4.18)	1.39 (1.34)	1.25 (0.58)
	Obese	1.46 (1.08)*	1.62 (1.07)	2.11 (1.21)	3.35 (2.95)	1.08 (1.32)	1.26 (1.05)
Toe	Normal	4.85 (1.95)	2.51 (0.92)	3.87 (2.70)	6.77 (3.72)	3.89 (1.72)	2.96 (1.90)
	Overweight	3.90 (2.75)*	2.80 (2.01)	1.91 (0.75)	5.73 (3.63)	2.49 (2.03)	1.57 (0.85)
	Obese	2.95 (2.32)*	2.19 (1.13)	2.04 (1.19)	5.31 (4.24)	1.35 (0.94)	1.20 (0.33)
Walking	Normal	3.15 (2.10)	2.98 (1.31)	2.22 (0.90)	2.99 (2.09)	2.13 (0.57)	1.69 (0.84)
	Overweight	3.57 (1.49)	2.87 (1.02)	2.36 (1.07)	3.80 (1.69)	2.30 (0.88)	1.54 (0.58)
	Obese	2.20 (1.50)	1.97 (0.57)	2.27 (1.84)	1.47 (0.97)	2.09 (0.64)	1.07 (0.57)
Inter-session							
BOX	Normal	6.91 (3.88)*	3.04 (1.75)	4.32 (1.45)	7.50 (6.32)	3.15 (1.13)	5.08 (2.43)
	Overweight	5.82 (3.44)*	2.94 (0.76)	4.37 (1.41)	8.35 (2.26)	3.38 (1.73)	3.90 (1.91)
	Obese	4.12 (3.43)*	1.89 (0.35)	4.21 (0.94)	8.43 (3.96)	2.93 (1.92)	3.94 (1.93)
Squat	Normal	4.04 (2.81)	2.74 (4.22)	3.81 (0.85)	3.33 (2.07)	2.29 (3.57)	4.21 (1.61)
	Overweight	3.93 (1.37)*	2.84 (1.26)	4.21 (1.82)	5.98 (1.45)	2.52 (1.05)	3.59 (1.19)
	Obese	4.47 (1.99)*	1.85 (0.87)	2.84 (1.00)	6.17 (2.94)	1.94 (0.75)	3.30 (1.42)
STS	Normal	3.68 (1.82)*	4.47 (4.42)	9.66 (2.20)	5.38 (2.77)	4.79 (3.94)	9.71 (2.05)
	Overweight	4.91 (1.24)*	2.72 (1.08)*	3.45 (1.30)	6.05 (2.35)	4.67 (4.95)	3.20 (1.31)
	Obese	5.81 (2.91)*	2.15 (0.72)	3.69 (1.42)	9.11 (9.18)	4.22 (5.53)	4.18 (3.55)
Toe	Normal	4.86 (2.88)	2.76 (2.49)	2.84 (1.56)	5.49 (3.44)	3.61 (3.41)	1.57 (0.93)
	Overweight	4.69 (1.71)*	2.76 (1.02)	3.15 (1.75)	7.40 (3.90)	3.87 (2.51)	2.67 (1.16)
	Obese	4.47 (1.53)*	2.05 (0.64)	2.08 (1.15)	7.70 (3.83)	3.12 (1.82)	2.10 (0.80)
Walking	Normal	4.91 (2.20)	2.63 (1.79)	5.70 (3.16)	4.30 (1.97)	2.81 (0.38)	5.04 (1.36)
	Overweight	2.83 (2.20)	2.41 (1.19)	5.49 (2.85)	2.28 (1.94)	2.96 (0.71)	5.18 (2.02)
	Obese	3.89 (1.07)	1.98 (1.23)	4.66 (1.17)	3.60 (1.00)	0.71 (0.51)	4.63 (0.59)

STS = Sit-to-Stand. * Highlights statistically significant differences between two sets ($p < 0.05$) with bold value higher.

performance within each session. Inter-session variability was quantified by calculating the SD for the average of the five trials between the sessions. This illustrates the consistency of the subjects' performance as well as the system's performance from one day to the other.

For each subject, coefficient of multiple correlation (CMC), was used to describe the repeatability of kinematic data using the waveform of each ADL for within (wCMC) and between (bCMC) sessions, with greater than 0.8 indicating high repeatability. Inter-protocol coefficient of multiple correlation (ipCMD) was used to evaluate the overall similarities between the waveforms of the two methods [14,15].

ANOVA for repeated measures was selected to obtain the kinematic differences between the two methods, activities of daily living, and body mass index.

3. Results

Intra-session and inter-session of mean standard deviation of maximum pelvic tilt for walking and some of the daily living activities that required full range of movement of the pelvis are summarised in Table 2 (results for the rest of the activities are available online).

For intra-session SD of normal subjects, there was no significant difference between the two methods for non-rotational planes (tilt $p = 0.31$ and obliquity $p = 0.14$) while for inter-session SD there was no significant difference between the two methods in all planes (tilt $p = 0.23$, obliquity $p = 0.16$, rotation $p = 0.50$). On average for overweight and obese subjects, the standard deviation of mean pelvic tilt using the Traditional was significantly higher than that of the Cluster method for both intra and inter-session ($p < 0.05$). The performance of each method during activities of daily living is also compared individually. Table 2 summarised the result obtained for normal, overweight and obese subjects during activities such as Box, Sit-to-Stand, Toe, Squat and walking (extra online material is provided for other activities). The results for overweight and obese subjects shows that the intra-session variability of the kinematic data using the Traditional method is significantly higher than that of the Cluster method in sagittal plane for activities that involves the full range of pelvic motion ($p < 0.05$).

Table 3 summarises the within-day, between day CMC results. The w and bCMC values obtained by two methods for each activity of daily living were compared between the three groups (detailed data are available online). The result shows that on average there are no significant differences between the repeatability of the kinematic waveforms between the two methods for normal subjects across all activities (tilt $p = 0.21$, obliquity $p = 0.09$, rotation $p = 0.11$). For activities that involve the full range of motion of pelvis in the sagittal plane, the b and wCMC values are significantly higher than those of the activities that involve a small movement of pelvis in sagittal plane ($p < 0.05$).

The inter-protocol CMC values are also summarised in Table 4. Higher values of ipCMC represent the similarity between the waveforms. As shown in Table 4, normal subjects have higher ipCMC values in comparison to the overweight and obese subjects in all planes.

4. Discussion

Establishing the repeatability of measuring three-dimensional angular kinematics of the pelvis during different daily living activities is critical if one wishes to distinguish the pathological changes from technical or experimental artefacts [16].

This study demonstrated that the pelvic kinematics in the sagittal plane during gait shows a high level of repeatability for both the Cluster and Traditional methods (Table 3). Comparing the

Table 3

Coefficient of multiple correlation averages (CMC) and its standard deviation for within, between day (w, b).

(n = 30)		Cluster method (SD)			Traditional method (SD)		
		Tilt	Obliquity	Rotation	Tilt	Obliquity	Rotation
Within-day CMC							
BOX	Normal	0.92 (0.05)	0.70 (0.18)	0.87 (0.11)	0.93 (0.06)	0.88 (0.11)	0.84 (0.12)
	Overweight	0.98 (0.02)	0.96 (0.03)	0.95 (0.02)	0.97 (0.02)	0.92 (0.07)	0.93 (0.04)
	Obese	0.98 (0.02)	0.96 (0.04)	0.96 (0.02)	0.98 (0.02)	0.92 (0.06)	0.94 (0.04)
Squat	Normal	0.98 (0.01)	0.97 (0.03)	0.97 (0.01)	0.97 (0.02)	0.94 (0.05)	0.95 (0.02)
	Overweight	0.99 (0.01)	0.97 (0.03)	0.96 (0.03)	0.97 (0.04)*	0.91 (0.15)	0.93 (0.05)
	Obese	0.99 (0.01)	0.98 (0.03)	0.98 (0.01)	0.97 (0.04)*	0.94 (0.03)	0.92 (0.08)
STS	Normal	0.99 (0.01)	0.99 (0.01)	0.96 (0.03)	0.99 (0.01)	0.96 (0.04)	0.93 (0.12)
	Overweight	0.99 (0.01)	0.98 (0.01)	0.96 (0.03)	0.98 (0.02)	0.91 (0.09)	0.90 (0.14)
	Obese	0.99 (0.01)	0.98 (0.01)	0.97 (0.02)	0.97 (0.03)*	0.91 (0.12)	0.92 (0.06)
Toe	Normal	0.99 (0.01)	0.97 (0.03)	0.96 (0.03)	0.99 (0.01)	0.94 (0.03)	0.95 (0.04)
	Overweight	1.00 (0.00)	0.97 (0.02)	0.96 (0.02)	0.99 (0.01)	0.96 (0.03)	0.96 (0.03)
	Obese	0.99 (0.01)	0.97 (0.03)	0.98 (0.02)	0.98 (0.03)*	0.93 (0.08)	0.96 (0.03)
Walking	Normal	0.93 (0.04)	0.98 (0.01)	0.96 (0.02)	0.89 (0.06)*	0.98 (0.01)	0.96 (0.02)
	Overweight	0.92 (0.04)	0.99 (0.01)	0.97 (0.02)	0.86 (0.06)*	0.99 (0.01)	0.96 (0.02)
	Obese	0.96 (0.02)	0.99 (0.01)	0.97 (0.01)	0.91 (0.05)*	0.98 (0.02)	0.96 (0.02)
Between-day CMC							
BOX	Normal	0.92 (0.05)	0.86 (0.10)	0.87 (0.11)	0.93 (0.06)	0.88 (0.11)	0.84 (0.12)
	Overweight	0.93 (0.10)	0.91 (0.06)	0.87 (0.12)	0.90 (0.11)*	0.72 (0.24*	0.90 (0.07)
	Obese	0.99 (0.01)	0.91 (0.07)	0.94 (0.05)	0.94 (0.04)*	0.64 (0.25*	0.83 (0.14)
Squat	Normal	0.93 (0.10)	0.78 (0.28)	0.82 (0.15)	0.95 (0.04)	0.65 (0.29)	0.79 (0.15)
	Overweight	0.95 (0.09)	0.85 (0.12)	0.81 (0.11)	0.92 (0.11)*	0.68 (0.22*	0.80 (0.15)
	Obese	0.98 (0.02)	0.90(0.08)	0.79(0.18)	0.93(0.06)*	0.65(0.28*	0.85(0.09)
STS	Normal	0.97(0.02)	0.73(0.16)	0.77(0.25)	0.98(0.01)	0.80(0.19)	0.77(0.26)
	Overweight	0.97(0.02)	0.91(0.07)	0.87(0.14)	0.96 (0.03)	0.78 (0.16*	0.86 (0.12)
	Obese	0.97 (0.02)	0.94 (0.08)	0.90 (0.12)	0.98 (0.02)	0.86 (0.13*	0.89 (0.08)
Toe	Normal	0.98 (0.02)	0.79 (0.09)	0.81 (0.09)	0.97 (0.03)	0.67 (0.28)	0.82 (0.11)
	Overweight	0.98 (0.04)	0.82 (0.11)	0.77 (0.21)	0.98 (0.02)	0.65 (0.23*	0.79 (0.15)
	Obese	0.99 (0.02)	0.87 (0.11)	0.84 (0.10)	0.96 (0.04)*	0.67 (0.22*	0.75 (0.24)
Walking	Normal	0.81 (0.12)	0.98 (0.02)	0.97 (0.04)	0.74 (0.23)	0.89 (0.12)	0.97 (0.02)
	Overweight	0.75 (0.19)	0.98 (0.03)	0.96 (0.03)	0.76 (0.15)	0.89 (0.11*	0.94 (0.04)
	Obese	0.85 (0.12)	0.90 (0.05)	0.95 (0.02)	0.87 (0.12)	0.99 (0.01)	0.97 (0.03)

* Highlights statistically significant differences between two sets ($p < 0.05$) with bold value higher.

Table 4
Inter-protocol coefficient of multiple correlations for walking and activities of daily living involving full range of motion.

		Inter-protocol CMC				
(n = 30)		Box	Squat	STS	Toe	Walking
Pelvic tilt	Normal	0.68 (0.26)	0.70 (0.28)	0.86 (0.11)	0.86 (0.21)	0.55 (0.44)
	Overweight	0.56 (0.41)	0.65 (0.36)	0.65 (0.29)	0.79 (0.27)	0.04 (0.36)
	Obese	0.54 (0.32)	0.49 (0.33)	0.46 (0.25)	0.63 (0.31)	0.08 (0.34)
Pelvic obliquity	Normal	0.19 (0.51)	0.19 (0.53)	0.19 (0.48)	0.02 (0.48)	0.59 (0.33)
	Overweight	0.05 (0.45)	0.01 (0.47)	0.03 (0.35)	0.00 (0.38)	0.46 (0.30)
	Obese	0.04 (0.34)	0.10 (0.31)	0.18 (0.30)	0.11 (0.39)	0.37 (0.37)
Pelvic rotation	Normal	0.46 (0.34)	0.36 (0.36)	0.26 (0.45)	0.24 (0.44)	0.78 (0.13)
	Overweight	0.35 (0.38)	0.31 (0.43)	0.31 (0.38)	0.16 (0.47)	0.69 (0.26)
	Obese	0.20 (0.45)	0.06 (0.47)	0.10 (0.43)	0.10 (0.48)	0.55 (0.26)

bCMC from previous studies [15,17], both set of markers results were higher in all non-rotational values. As CMC is based on the ratio of error variance to true variance, therefore the low bCMC value of pelvic tilt in previous studies [13,15,17] may be related to a smaller range of motion of the pelvis during walking. In this study, activities of daily living such as Squat, Sit-to-Stand, Box, or Toe involved the full range of motion of the pelvis in the sagittal plane with little or no movement in the transverse and frontal planes. Therefore the CMC values obtained from kinematic waveform for such activities were higher due to the larger range of motion of the pelvis.

This study also compared the influence of BMI on repeatability of pelvic kinematics. The wCMC and bCMC values for overweight and obese subjects showed a significantly higher repeatability for the Cluster method than that of the Traditional method in all planes (Table 3 and online table). The moderate [18] results of bCMC for the Traditional method may indicate difficulty with occlusion of ASIS markers and soft tissue artefact during data collection for overweight and obese subjects.

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Standard deviation was also selected to quantify variability between marker sets for normal, overweight and obese subjects (Table 2). Inter-session variability was higher than the intra-session variability. This is due to the fact that intra-session variability is not impacted by marker placement differences while inter-session variability includes changes in the subject's walking pattern from day to day that are part of the natural variability of the subject as well as marker placement differences. The intra and inter session variability of the Cluster method is lower than that of the Traditional method especially for overweight and obese subjects. Higher variability in the Traditional method may arise from soft tissue artefact, marker occlusion during the data collection due to excess of soft tissue (for obese subjects); while introducing the technical frame and the concept of anatomical landmark calibration [9] in the Cluster method minimised the effect of soft tissue artefact. This fact can be explained further by comparing the performance of the two methods across activities that involves higher range of pelvic motion therefore more prone to soft tissue artefact. This showed that for activities such as Squat, Box, Sit-to-Stand and Toe the intra and inter session variability was significantly ($p < 0.05$) higher for the Traditional method than the Cluster method for overweight and obese subjects in the sagittal plane and there were no significant differences between the two methods for such activities in normal subjects ($p = 0.28$). As the soft tissue artefact is not consistent from one trial to the next, the high variability of the Traditional method in such activities may be as a result of such errors as well as movement of the markers independently relative to each other. For activities that require less movement of the pelvis such as walking, Up-stairs and Down-stairs there were no significant differences between the two methods for intra and inter variability for different BMI groups ($p = 0.48$, $p = 0.09$). For activities that involved speed (Time up), significant differences ($p < 0.05$) were found between the two methods in the sagittal plane for obese and overweight subjects (intra and inter-session). Details of these results are available on line.

In addition to standard deviation, the similarity between the two marker sets was reported using ipCMC (Table 4). The low ipCMC values for overweight and obese groups indicate the poor similarity between the two methods while for normal subjects there is a good similarity. To determine whether the cluster mounted on the sacrum does minimise the effect of the soft tissue artefact, we can compare the result of this study with Bull and McGregor [7] in which they demonstrated that it is possible to accurately measure the motion of the lumbo-sacral spine using a sensor attached to the sacrum and provide useful and important information on the motion of the body segments during rowing with average error of 1.08.

5. Conclusion

Both marker sets generally showed high repeatability for all three subject groups, while for overweight and obese subjects the Cluster method showed significantly better repeatability than that of the Traditional method. Both methods were comparable in the measurement of gait with the Traditional method demonstrating high level of repeatability. This is not surprising as this is what the Traditional method was originally intended to measure. The Cluster method overcomes a number of theoretical and experi-mental limitations such as minimising the effect of movement of markers relative to each other as well as to the underlying bone, fewer cameras are required to track the cluster with implication for cost and laboratory set up procedures. Also less time is needed for post processing the data as there is no marker occlusion in the dynamic trials therefore no further programming is needed to fill the gaps in dynamic trials.

This study provides evidence that a new technical marker set is superior for three-dimensional data collection of overweight and obese subjects, and when the ASIS markers are occluded for all or part of the trial particularly during a range of activity of daily living. The accuracy of both marker sets to follow the underlying bone movement was not determined in this study and warrants further investigation. Notwithstanding these limitations, a repeatable measure of pelvic motion has been tested in this study.

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Conflict of interest statement

The authors had no conflict of interest when performing the study or when preparing the manuscript.

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