MEASUREMENT OF LUMBAR SPINAL POSTURE AND MOTION USING INERTIAL SENSORS

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Abstract

Back pain is a common and costly disorder affecting 80% of the population, with 80-90% of the symptoms reported to have no pathological cause and it is suggested that this non-specific low back pain can be improved by the adoption of proper posture and body mechanics during normal daily life.

There has been extensive research into the cause and prevention of low back pain, however the results of these studies are mostly contradictory and the method of effective prevention of low back pain is still unclear. It was felt necessary to conduct a study in a normal everyday environment over an extended period of time in order to study the real patterns of spinal posture and motion in a normal population. Two dimensional measurements of the spine do not provide a complete picture of spinal posture and motion; and laboratory based 3 dimensional measurement methods are not suitable for long term measurement due to the size of the instrumentation and complications of use. Inertial measurement systems offer the potential to have addressed these limitations.

The current study aimed to evaluate the use of an inertial measurement system in 3 dimensional spinal posture and motion measurement inside and outside the laboratory setting over an extended period of time; and to monitor and analyse 3 dimensional spinal posture and motion of desk workers in their working environment for a period of 3 hours.

This study showed that an inertial measurement system is a valid tool for use in 3 dimensional spinal posture and motion measurement both inside and outside the laboratory setting over an extended period of time. Pilot studies were carried out to examine possible errors in measurement and it was shown that secure sensor attachment and alignment are important factors in minimising errors in skin surface measurement. The study also showed that by utilising just 2 sensors on the lumbar spine, it was possible to differentiate between 6 different physiological movements, 6 static postures and 2 different functional activities. A feasibility study that monitored spinal posture and motion of desk workers has shown that different sitting behaviours may affect the mobility of the lumbar spine after 3 hours of desk work. The study has shown that an inertial measurement system can provide a useful method for studying posture and motion patterns. This method is suitable for a range of applications which will enable research based on the normal population in everyday life.

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Author's Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Tshui Hung Ha

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Chapter 1. Introduction

1.1 Motivation for the study

The author of this work is an electrical and electronics engineer by training. She worked in a factory as a failure analysis engineer for 6.5 years after her graduation. Over the years, she came across many people who were suffering from acute back pain, including herself, probably due to poor sitting spinal postures and improper movements in the working environment. This initiated the author's interest in the spine and occupational posture and motion which may in the future may bring insights into the causes of low back pain.

Although many risk factors for back pain have been identified, due to the complex properties of the spine, it is still impossible to pinpoint the cause of symptoms of each sufferer. There is still no clear preventive method and the definitions of good spinal posture and motion reported in the literature are contradictory. The causes of low back pain are not fully understood and present a large field of study. Further research is required if a full understanding is to be developed and prevention is to be effectively enabled. This research set out to contribute to the knowledge base relating to the posture and movement of the lumbar spine, thereby providing opportunity for further study of these factors and the impact and influence on the normal population potentially linking in occupational factors increasing the incidence of low back pain.

1.2 Incidence of back pain

Back pain is a very common and costly health disorder. It is estimated that 80% of people will suffer from back pain at some stage in their lives (Maniadakis and Gray 2000). In the UK, 49.1% of the adult population experience back pain for more than a day in any one year (Palmer et al. 2000); and an estimated 493,000 working people suffered from musculoskeletal disorders mainly affecting the back in 2006/2007 (Health and Safety Executive 2008). It was also estimated that 4.7 million working days were lost due to musculoskeletal disorders mainly affecting the back in 2006/2007; on average, 0.2 days per worker were lost in the year due to back pain (Health and Safety Executive 2008). Disability due to back pain has shown an exponential rising rate between 1953 and 1995 (Waddell 2004) and 13% of back pain sufferers were found to be unemployed due to their symptoms (Department of Health 1999). In 1998, the direct and indirect cost of back pain totalled £12.3 billion (Maniadakis and Gray 2000), causing a greater burden on the UK economy when compared to other diseases that have been economically analysed, such as coronary heart disease estimated to cost approximately £10.7 billion, rheumatoid arthritis estimated to cost approximately £1,900 million and lower respiratory tract infections estimated to cost approximately £1,700 million. The direct cost of back pain includes NHS services including GP visits, hospital care, physiotherapy, in and out patient care, radiology and medication, community care; and private services such as private consultations with osteopaths, chiropractors, and other specialists. The indirect costs include working days lost, compensation costs and informal care (Maniadakis and Gray, 2000).

Back pain also seriously affects the quality of life of sufferers (DeFer 2004; Ehrlich 2003; Pain in Europe 2003), it may cause anxiety and depression because of the fear that the pain is harmful or disabling; it may also cause avoidance of activity or movement fearing that they may induce more pain or injury; and back pain sufferers may have a higher tendency of withdrawal from social interaction, which will affect the quality of relationships with family, friends and co-workers.

Back pain can be categorised into acute, sub-acute and chronic conditions. Acute back pain is referred to as pain that lasts less than 6 weeks; sub-acute back pain is defined as pain persisting for between 6 and 12 weeks; and chronic back pain is described as pain that lasts longer than 3 months (Burton et al. 2006; Van Tulder et al. 2002). However in practical terms, such categorisation is not very useful when considering prevention as back pain usually tends to reoccur episodically.

Acute back pain has a high recovery rate at 90% but up to 7% of the patients will develop chronic back pain (Burton et al. 2006), and the possibility of recurrence is high (Byrns et al. 2002; Skovron 1992; Van Tulder et al. 2002). Chronic back pain is often described as a self-sustaining, varying and complicated condition as it's always associated with psychosocial factors, and thus the effectiveness of treatment is usually low due to hypothetical but unidentified and possibly non-existent causes of pain (Waddell 1992; Waddell 2004).

1.3 Causes of back pain

It is reported that 97% of acute low back pain cases are mechanically related (DeFer 2004; Deyo and Weinstein 2001), which includes lumbar strain and sprain, disc herniation, spinal stenosis, osteoporosis, spondylolisthesis, congenital disease, spondylolysis, fracture of the lumbar bony structure, and disc disruption. Only 1% of acute back pain is related to non-mechanical conditions such as neoplasia, infection, inflammatory arthritis, Scheuermann's disease and Paget's disease. The remaining 2% of acute low back pain is caused by referred pain from visceral diseases like gastrointestinal disease, aortic aneurysm, renal disease and genitourinary disease (DeFer 2004; Deyo and Weinstein 2001).

Studies have shown that 85% to 90% of low back pain symptoms have no identifiable pathological causes (DeFer 2004; Deyo and Weinstein 2001; Manek and MacGregor 2005). This type of low back pain is often called non-specific back pain. The cause of non-specific back pain is usually unknown but it is often associated with strains and sprains of spinal structures, such as muscles and ligaments, and mechanical stresses impacting on discs and nerves.

There are 3 main risk factors associated with the occurrence of non-specific back pain, they are individual factors, psychosocial factors and occupational factors (Manek and MacGregor 2005; Van Tulder 2002).

The individual factors that have been reported as a risk for back pain occurrence are age, general health, and back and abdominal muscle strength (Manek and MacGregor 2005; Van Tulder 2002). The prevalence of back pain increases from childhood to adolescence, and the highest proportion of onsets are frequently reported in the older working age group of 35 to 64 years (Burton et al. 2006; Health and Safety Executive 2008; Marras 2000). Smoking is reported as a weak risk factor in a number of studies (Feldman et al. 1999; Goldberg et al. 2000; Leboeuf-Yde 1999). Gender (Leboeuf-Yde and Kyvik 1998; Waddell 2004) and body weight (Leboeuf-Yde 2000; Mayer et al. 2006) are also reported to have a low correlation with the occurrence of low back pain. Some studies have shown that more women report suffering from low back pain than men but the difference overall is not significant (Department of Health 1999; Leboeuf-Yde and Kyvik 1998). There is no clear evidence that height and leg length discrepancy can cause back pain (Adams et al. 2002; Waddell 2004).

Stress, anxiety, mood or emotions, depressive disorders, cognitive functioning and pain behaviour are psychosocial factors that are reported as being associated with back pain (Chany et al. 2006; Manek and MacGregor 2005; Marras 2000; Van Tulder 2002). Psychosocial factors are usually associated in the development of chronic back pain or disability from acute back pain as patients try to avoid physical activities and work due to the fear of inducing more pain or injury, develop psychological distress such as anxiety, depression, and fail to cope and adapt to the pain (Manek and MacGregor 2005; Skovron 1992; Waddell 2004).

Occupational factors include manual materials handling, bending and twisting, pulling and pushing, whole body vibration, static work postures, monotonous tasks, job dissatisfaction, low control over the day to day organisation of work, high perceived stress and job demands, social support and work relations (Manek and MacGregor 2005; Marras 2000; Van Tulder 2002). Studies have shown that occupational factors always provide strong associations with back pain and back injury (Adams et al. 2002; Hoogendoorn et al. 1999; Hoogendoorn et al. 2000; Marras 2000; Palmer et al. 2003; Pope et al. 1999).

Due to the wide range of possible risk factors of non-specific low back pain, it is often difficult and complicated to pinpoint the real cause of the symptoms of a sufferer, particularly given that the symptoms can be due to a single or a combination of a number of risk factors.

1.4 Significance of this study

Back pain is causing a substantial social as well as economic burden to our society (Department of Health 1999; Health and Safety Executive 2008; Maniadakis and Gray, 2000). It would therefore be of significant advantage to increase our understanding of back pain and minimise the risk of symptom development. This will require the application of new technologies to allow us to study the way in which symptoms are associated with factors such as spinal posture and motion within normal daily activity.

It is suggested that many non-specific spinal problems could be prevented if proper posture and body mechanics are adopted (Hobbs and Aurora 1991; Scannell and McGill 2003). Many studies have attempted to define what good postures and body mechanics are (Adams and Hutton 1980; Adams and Hutton 1985; Adams and Hutton 1986; Arjmand and Shirazi 2005; Dolan and Adams 2001; Hobbs and Aurora 1991; Kelsey 1975a; Mannion et al. 2000; Nachemson 1975; O'Sullivan et al. 2006b; Pynt et al. 2001), but such definitions have been rather vague and in many cases contradictory.

Spinal posture is often measured non-continuously, in only 1 or 2 planes of movement, in laboratory settings, or over a short period of time (Bullock-Saxton 1993; Christie et al. 1995; Lord et al. 1997; Ng et al. 2002; Vergara and Page 2000a, Vergara and Page 2002; Vialle et al. 2005). However such studies do not enable the study of an individual’s normal daily postures and how these postures may be associated with low back pain.

Most kinematic studies of the spine have focused on ranges of spinal movement (McGregor et al. 1995; Ng et al. 2001; Peach et al. 1998; Russell et al. 1993; Troke et al. 2005; Van Herp et al. 2000). Others have explored the possibility of detecting or monitoring general body posture and motion in everyday activity (Bussmann et al. 2001; Mathie et al. 2003; Mathie et al. 2004a; Mathie et al. 2004b; Najafi et al. 2003; Veltink et al. 1996), though these studies did not examine the frequency and magnitude of changes in spinal posture and motion specifically. Two dimensional studies (Loebl 1967; Milosavljevic et al. 2005; Reynolds 1975) do not provide a complete picture since the spine possesses movement in 6 degrees of freedom (Lee 2002; Marras 2000; Panjabi et al. 1994; Taylor and Twomey 1980; Van Herp et al. 2000). However, many of the current 3 dimensional techniques are laboratory based, because the equipment is not portable and is often too complicated to be used outside the laboratory. The most popular 3 dimensional techniques are biplanar radiography, opto-electronic systems and electromagnetic tracking systems, which all fall into the laboratory only category and hence do not allow the collection of data related to posture and motion of the spine in normal daily life.

To enable an improved understanding of spinal posture and motion and their relationship with back pain, it is desirable to be able to measure spinal posture and motion continuously over an extended period of time during normal daily activities. Participants may perform differently if movement is monitored by researchers in a laboratory environment; and a short data collection time is unlikely to provide enough information on the normal behaviour of the participants. Such laboratory based studies are unlikely to provide a real picture of how these data could relate to the majority of the population in real life conditions.

Measuring spinal posture and motion during daily activity may be possible utilising advancements in inertial measurement technologies due to its small size, low power consumption and portability. Despite these attractive advantages of inertial measurement systems, there have hitherto been limited studies of spinal posture and motion measurement using these systems. It is therefore necessary to examine the feasibility and validity of inertial measurement systems in spinal posture and motion measurement in order to explore the possibility in continuous long term measurement in normal daily life conditions, where feasibility refers to the capability of being accomplished and validity defined as the extend to which the test measures what it is supposed to measure.

1.5 Aims and objectives of the study

The first aim of the study was to evaluate the feasibility and validity of an inertial measurement system in 3 dimensional assessments of spinal posture and motion. The objectives underpinning this aim were

1. to validate the performance of the inertial sensors against a gold standard;
2. to explore the possible errors and methods to minimise these errors due to skin surface measurement method; and
3. to examine the feasibility and validity of the use of inertial measurement system on human participants in a laboratory environment.

The second aim of the study was to examine the feasibility of an inertial measurement system in 3 dimensional measurements of spinal posture and motion outside the laboratory over an extended period of time and to monitor sitting behaviour of desk workers. The objectives underpinning this aim were

4. to study the 3 dimensional spinal posture and motion patterns of desk workers in their normal daily working environment; and
5. to monitor desk work activities and compare spinal mobility of the desk workers before and after desk working.

1.6 Outline of the thesis

To document the achievement of the aims of the study, the thesis is separated into 7 main parts (Chapters 2-8). In order to study the posture and movement of the lumbar spine, it was essential to first understand its structure and function, therefore Chapter 2 reviews the applied anatomy, biomechanical properties and the role of various lumbar spinal structures; and how different spinal postures and motion could be associated with low back pain.

Once the basic knowledge of the structure and function of the spine was established, it was then necessary to identify suitable measurement methods and equipment to carry out the study. In Chapter 3, the functionality and limitations of various posture and motion measurement methods are discussed. Inertial measurement systems were considered to be the most suitable measurement systems for the current study as they are capable of measuring both 3 dimensional postures and movements, and they are portable, having low power consumption and low cost. The operational theory and applications of inertial measurement systems are also reviewed in Chapter 3.

As the use of inertial measurement systems in spinal posture and motion measurement has not hitherto been researched to any great extent, the validity of inertial measurement systems in posture (inclination) and movement measurement are examined in Chapter 4.

Skin surface measurement is prone to errors due to skin movement and sensor movement during the measurement. In Chapter 5, the possible errors during skin surface measurements and methods for minimising their impact are discussed.

Validating the feasibility of inertial measurement systems in spinal posture and motion measurement was also carried out during the study. The procedure, results and conclusions from this validity study are discussed in Chapter 6.

The application of inertial measurement systems in measuring spinal posture and motion of desk workers over a 3 hour period in their working environment was realised and is discussed in Chapter 7. The duration, frequency and magnitude of sitting postures in the 3 hour period were identified and their relationship with the change of lumbar mobility before and after 3 hours of desk work was analysed.

In Chapter 8, the author has included an overall discussion of the study, the possible applications, the limitations of this work and the methods deployed, and suggestions for future work.

Chapter 2. The spine

2.1 Overview

From Chapter 1, it is clear that low back pain is a universal symptom that can affect anyone at any age; however the majority of cases are non-pathological and classified as non-specific low back pain. The study of spinal posture and motion is desirable to enable an improved understanding of their associations with causes of low back pain. In order to study spinal posture and motion, it is important to first understand the anatomy, kinematics and mechanical properties of the spine.

In this chapter, an overview of the applied anatomy of the spine is presented, spinal kinematics are discussed and the associations between spinal posture and motion with low back pain are deliberated.

2.2 Anatomy of spine

The main functions of the spine or the vertebral column are to provide stability in maintaining upright posture, to allow movement, to provide attachments for muscles, and to protect the spinal cord (Adams et al. 2002; Standring et al. 2005). Each of the spinal structures has different biomechanical properties to allow them to work differently and cooperatively to achieve the functionalities of the spine. The adult vertebral column normally consists of 33 vertebrae and configured 4 curvatures as shown in Figure 2.2.1 (Agur and Lee 1999; Standring et al. 2005). These curves serve as shock absorbers against vertical compressive loads and assist the tendons of the spinal muscles, spinal ligaments and intervertebral discs in absorbing energy due to locomotion movements (Adams et al. 2002; Standring et al. 2005).

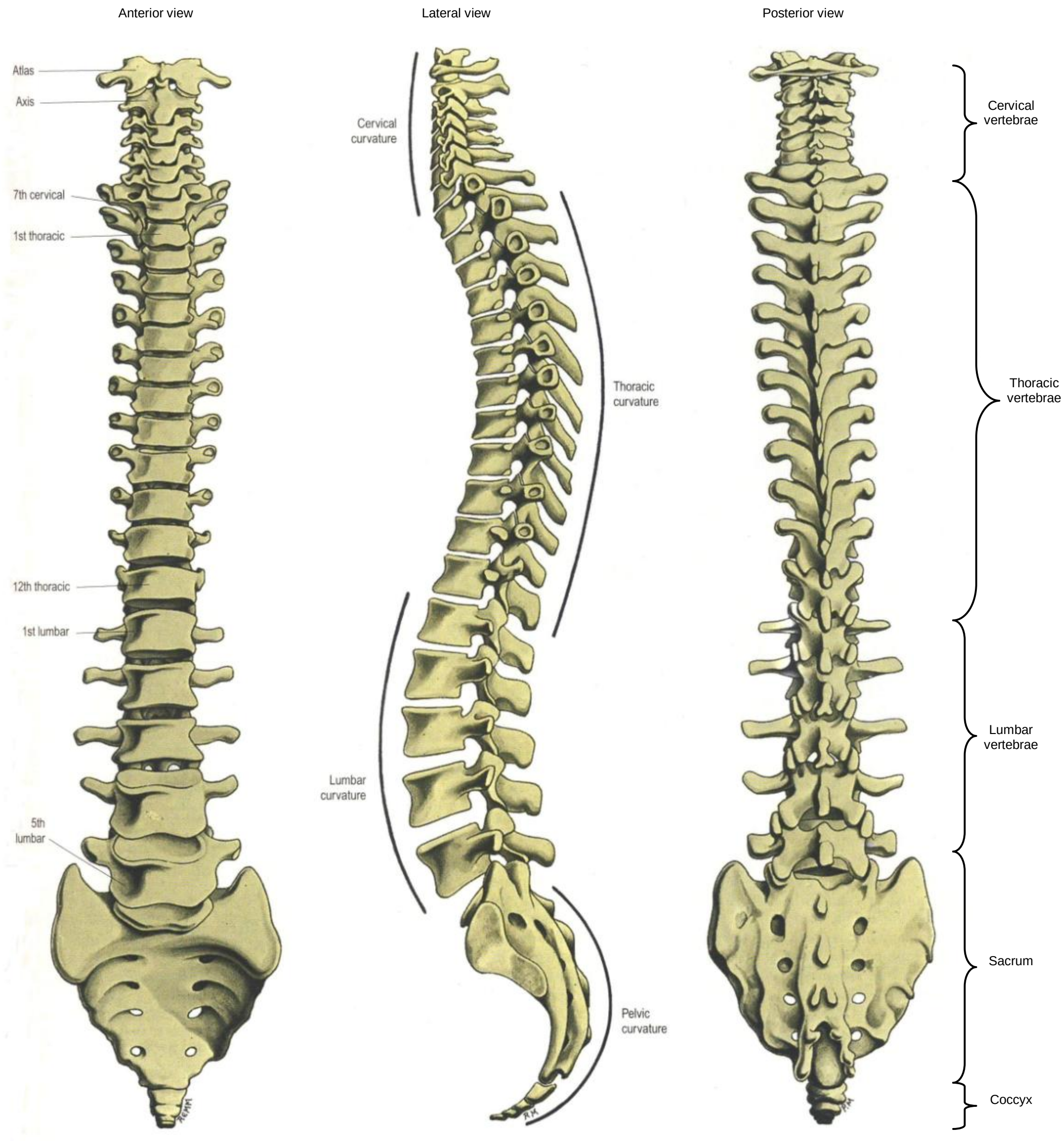


Figure 2.2.1: Illustration of the vertebral column (from Standring et al. 2005 Gray's Anatomy, 39th Edition, with permission of Elsevier, Churchill Livingstone)

The lumbar vertebral column is also built to withstand axial compressive loads that are produced by the weight of the upper body, head and any load carried in the upper limbs (Adams and Dolan 1995; Adams et al. 2002; Bogduk 2005). The lumbar vertebral column consists of 5 vertebrae that provide rigidity and allow mobility, and the posterior elements of the lumbar vertebrae provide stability and control of movements. The intervertebral discs function to transmit loads and to allow movement to occur between the vertebral bodies, while the vertebral endplates enable nutrient diffusion to the nucleus pulposus of the intervertebral discs (Adams et al. 2002; Bogduk 2005). The zygapophyseal joints in the lumbar spine function to limit axial rotation and to resist forward displacement of the vertebrae in order to protect intervertebral discs from excessive torsion and to prevent the vertebrae from dislocating (Adams and Dolan 1995; Adams et al. 2002; Bogduk 2005; Standring et al. 2005). The ligaments and muscles on the other hand work to stabilise, control and restrict excessive movement in order to protect the vertebral column (Adams et al. 2002; Bogduk 2005; Standring et al. 2005).

Please refer to Appendix A5 for more detailed applied anatomy, biomechanical properties and the role of different spinal structures of the lumbar spine.

2.3 Spine kinematics

The spine exhibits 6 degrees of movement (Lee 2002; Marras 2000; Panjabi et al. 1994; Taylor and Twomey 1980; Van Herp et al. 2000). These can be described in 3 dimensional orthogonal axes as shown in Figure 2.3.1. The coordinate system used in this study was a right hand coordinate with the axes standardised to the local axes of the sensors that were used in later chapters, where the X axis refers to the vertical axis that is perpendicular to the ground, and passes through the spine from inferior aspect to superior aspect; Y axis refers to the horizontal axis that passes through the spine from right lateral aspect to the left lateral aspect of spine; and Z axis refers to the horizontal axis passes through the spine from the anterior aspect to the posterior aspect of the spine. The spine is free to move along the axes (translations) or rotate about the axes (rotations) in both directions.

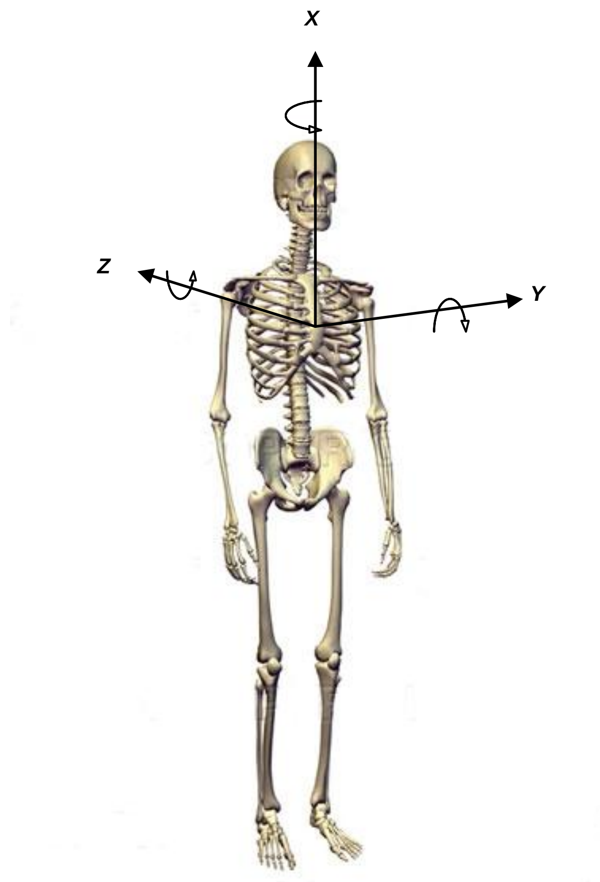


Figure 2.3.1: Three dimensional axes and their represented movements

Spinal movements can be described according to these axes as illustrated in Table 2.3.1. Positive translation of an axis refers to positive movement along the axis, e.g. +Z translation means backward sliding of the spine; while negative translation refers to movement along the axis in the negative or opposite direction, e.g. –Y translation indicates right lateral sliding of the spine. The same principle applies to the directions of rotation. Axial compression refers to movement in the direction of gravitational force, which mostly occur during weight bearing activities when in an upright posture. Axial distraction is the movement in the opposite direction of axial compression, e.g. during upward stretching of the spine.

		X	Y	Z
Translation	Forward			-ve
	Backward			+ve
	Right		-ve	
	Left		+ve	
	Axial distraction	+ve		
	Axial compression	-ve		
Rotation	Flexion		+ve	
	Extension		-ve	
	Right lateral bend			-ve
	Left lateral bend			+ve
	Right axial rotation	-ve		
	Left axial rotation	+ve		

Table 2.3.1: Definition of 3 dimensional movements with respect to their reference axes, -ve = negative and +ve = positive

In reality, movements of the spine do not usually occur solely in one plane of movement and are commonly coupled with other movements in other planes at the same time (Panjabi et al. 1994; Pearcy et al. 1984; Pearcy and Twibrewal 1984; Standring et al. 2005). Every movement may be coupled with different motions of various magnitudes and direction, and these coupled motions and their direction may differ from individual to individual (Lee et al. 2003; Peach et al. 1998; Russell et al. 1993).

Table 2.3.2 shows the ranges of each lumbar vertebra and the typical total ranges of the lumbar spine during different physiological movements. Flexion results in straightening or reversing of the lumbar curve, especially of the upper lumbar vertebrae (Adams and Dolan 1995; Bogduk 2005; Standring et al. 2005) and often coupled with forward translation and 1° of rotation on the X and Z axes (Pearcy et al. 1984). Extension involves posterior rotation of the vertebrae on the Y axis as well as a small (1mm) posterior translation on the Z axis (Bogduk 2005; Panjabi et al. 1994).

	Spine movements	Flexion	Extension	Right lateral flexion	Left lateral flexion	Right axial rotation	Left axial rotation
Rotation at each vertebra (°)	**X**	±1	-	1 to 2	-1 to -2	-1 to -2	1 to 2
	Y	8 to 13	-1 to -5	±1 to ±3	±1 to ±3	1 to 4	-1 to -4
	Z	±1	-	-3 to -5	3 to 5	-	-
Translation at each vertebra (mm)	**X**	-	-	-	-	-	-
	Y	-	-	-	-	-	-
	Z	-1 to -3	1	-	-	-	-
Typical total range (°)		49 to 72	-16 to -28	-16 to -31	16 to 31	-4 to -17	4 to 17

Table 2.3.2: Ranges of each lumbar vertebra (Pearcy et al. 1984; Pearcy and Twibrewal 1984; Pearcy 1985) and typical total ranges of the lumbar spine (Hindle et al. 1990; Lee and Wong 2002; Lee et al. 2003; Peach et al. 1998; Pearcy 1985; Russell et al. 1993; Van Herp et al. 2000) during different physiological movements

As shown in Table 2.3.2, lateral flexion is coupled with a small amount of axial rotation in the opposite direction as well as flexion or extension (Bogduk 2005; Pearcy and Twibrewal 1984; Standring et al. 2005), though flexion appears to be the more pronounced coupled motion (Cholewicki and Crisco 1996; Peach et al. 1998; Russell et al. 1993). As for axial rotation, the rotation is usually accompanied by a small degree of lateral flexion in the contra direction (Bogduk 2005; Pearcy and Twibrewal 1984; Pearcy 1985).

There are many reports on the ranges of physiological movement of the lumbar spine available in the literature. However these ranges vary from study to study possibly due to different measurement methods used; experimental set ups; age group, gender, body mass index, occupation and lifestyle of participants; protocol designs and equipment used in each study.

Ranges of physiological movements were found to decrease with age (Dvorak et al. 1995; Einkauf et al. 1987; Fitzgerald et al. 1983; Hindle et al. 1990; Loebl 1976; McGregor et al. 1995; Russell et al. 1993; Taylor and Twomey 1980; Troke et al. 2005; Van Herp et al. 2000). The decrease in ranges found in older people is believed to be caused by increased stiffness in the dehydrated and fibrous interverterbal discs (Bogduk 2005).

The relationship between gender and ranges of movements is still unclear since the results found in various studies are contradictory. Moll and Wright (1971) found males exhibited greater sagittal movements than females; while females demonstrated greater lateral movements. Russell et al. (1993) reported the same observation as Moll and Wright (1971) in lateral flexion, that females were more mobile than males in these movements. Only males between the ages of 20-29 years old exhibited greater flexion angles than the females in the study carried out by Russell et al. (1993). Hindle et al. (1990) also observed greater flexion in males but reported females exhibited higher ranges in lateral and axial rotation movements. McGregor et al. (1995) on the other hand found that males had better mobility in sagittal and lateral movements; while females had greater ranges of axial rotation. However in the study carried out by Van Herp et al. (2000), it was found that females possessed higher ranges in all 6 physiological movements in all age groups. Dvorak et al. (1995), Loebl (1976) and Troke et al. (2005) however found no significant difference in ranges of movement between the 2 genders. Although the relationship between gender and lumbar range of movement is inconclusive, this factor should be taken into account when comparing range of movement data with other studies.

In terms of equipment, radiography is generally viewed to be the most accurate in-vivo method of measuring spinal ranges of movement as this method is capable of measuring individual intervertebral movement (Bogduk 2005; Pearcy 1985; Schuit et al. 1997; Zuberbier et al. 2001). Except for imaging methods such as radiography and magnetic resonance imaging, other in-vivo measurements are mostly skin surface measurements and consequently true intervertebral movements cannot be reliably quantified and the ranges of movement measured should be considered only as an indicator of spinal movement rather than an absolute measure. The advantages and disadvantages of a range of equipment used in spinal motion measurement are discussed in Chapter 3.

Seven studies from the literature were chosen as the reference for ranges of movement in the current study. These included a measurement study using biplanar radiography (Pearcy 1985) as radiography is considered the most accurate method for spinal motion measurement; studies using electromagnetic tracking systems (Hindle et al. 1990; Lee and Wong 2002; Peach et al. 1998; Russell et al. 1993; Van Herp et al. 2000) as the current study proposed this method of measurement as the reference system; and a study that measured spinal motion using a gyroscopic method by Lee et al. (2003). Table 2.3.3 summarises the ranges of movement recorded in these 7 studies, noting that the mean values of the ranges of movements are compared within a similar age group (20-39 years old) across the studies.

Range of Movement (°)	**Flexion**	**Extension**	**Left lateral bending**	**Right lateral bending**	**Left axial rotation**	**Right axial rotation**	**No. of participant**	**No. of female participants**	**No. of male participants**	**Equipment used**	**Location of measurement**
Pearcy (1985)	51.0	16.0	18.0	17.0	5.0	4.0	31	-	31	Radiographic	L1 and sacrum
Hindle et al. (1990)	69.4	24.6	28.3	28.3	14.7	14.7	80	10/40	10/40	Electromagnetic system	L1 and sacrum
Russell et al. (1993)	70.8	25.0	27.1	27.1	15.3	15.3	253	48/118	31/135	Electromagnetic system	L1 and sacrum
Peach et al. (1998)	71.6	-	29.7	30.8	16.6	15.6	24	7	17	Electromagnetic system	T12 and sacrum
Van Herp et al. (2000)	56.9	28.2	25.5	25.9	15.7	14.0	100	20/50	20/50	Electromagnetic system	T12 and S1
Lee and Wong (2002)	58.1	15.6	21.3	19.9	7.6	9.8	20	-	20	Electromagnetic system	L1 and sacrum
Lee et al. (2003)	48.6	18.7	16.3	16.3	8.9	8.4	19	4	15	Gyroscopic system	L1 and sacrum
Experimental settings	*** The ranges of movements above were the mean values taken from age group of 20-39 year olds for comparison, number of female and male participants in these age range were given against the total number of female and male participants recruited in the particular study**										

Table 2.3.3: Ranges of movement comparison between 7 previous studies

As shown in Table 2.3.3, ranges of movement measured using biplanar radiography by Pearcy (1985) were generally lower than measurements made using skin surface measurement methods such as electromagnetic tracking systems (Hindle et al. 1990; Russell et al. 1993; Peach et al. 1998; Van Herp et al. 2000) and gyroscopic systems (Lee et al. 2003). These differences could be due to the fact that radiographic method measured the movements of the individual intervertebral while skin surface measurement methods measured the movement of the whole lumbar spine, coupled with possible artefacts from skin movements, loose sensor attachment and sensor misalignment. These artefacts are discussed in Chapter 5.

Hindle et al. (1990), Russell et al. (1993) and Peach et al. (1998) all reported similar ranges of movements; while Van Herp et al. (2000) observed a much lower range of flexion (>12.5° difference) although all 4 studies utilised the same equipment (3Space Isotrak) for the measurements. However the range of flexion reported by Van Herp et al. (2000) was closer to those of the radiographic results (Pearcy 1985) than those reported by Hindle et al. (1990), Russell et al. (1993) and Peach et al. (1998). Lee and Wong (2002) although using a similar measurement system to the 4 studies mentioned above, found the results to be within similar ranges to those reported by Pearcy (1985). Ranges of movements measured using gyroscopic systems as reported by Lee et al. (2003) were also found to be similar to those reported by Pearcy (1985).

As discussed previously, there are a range of factors that could contribute to the differences between ranges of movements measured within different studies. The equipment used and protocol designs such as sample size; sensor attachment and alignment; instruction on how to perform the movements; and locations for measurement are all important factors to be taken into consideration when comparing studies.

In Peach et al.'s (1998) study, the participants performed the movements with their feet shoulder width apart and knees slightly bent, while the other studies shown in Table 2.3.3 requested the knees of participants to be extended during the measurement, this difference could contribute to the higher ranges of movements observed by Peach et al. (1998). It is difficult to precisely control the angle of bend of the knees of participants during physiological movements, either as an experimenter or as a participant, and different angles of bend may lead to differences in angle of movement.

Among the skin surface measurement studies shown in Table 2.3.3, only Van Herp et al. (2000) discussed sensor alignment. Hindle et al. (1990), Van Herp et al. (2000), Lee and Wong (2002) and Lee et al. (2003) reported that secure attachment method was used to minimise sensor movements. Russell et al. (1993) reported using similar methodologies as Hindle et al. (1990). However Peach et al. (1998) did not provide any such information and therefore interpretation of the data needs to be mindful of this uncertainty.

The small sample size of Pearcy's (1985) study may weaken the argument of the results being representative of the normal population; while the figures provided in Pearcy's (1985) paper suggested that movements of participants may be constrained as the X-ray tubes were seen to be very close to the participants. However these observations from the figures might not be true and it is noted that the space provided and whether it was sufficient for participants to engage in maximal movement was not discussed in Pearcy's (1985) paper.

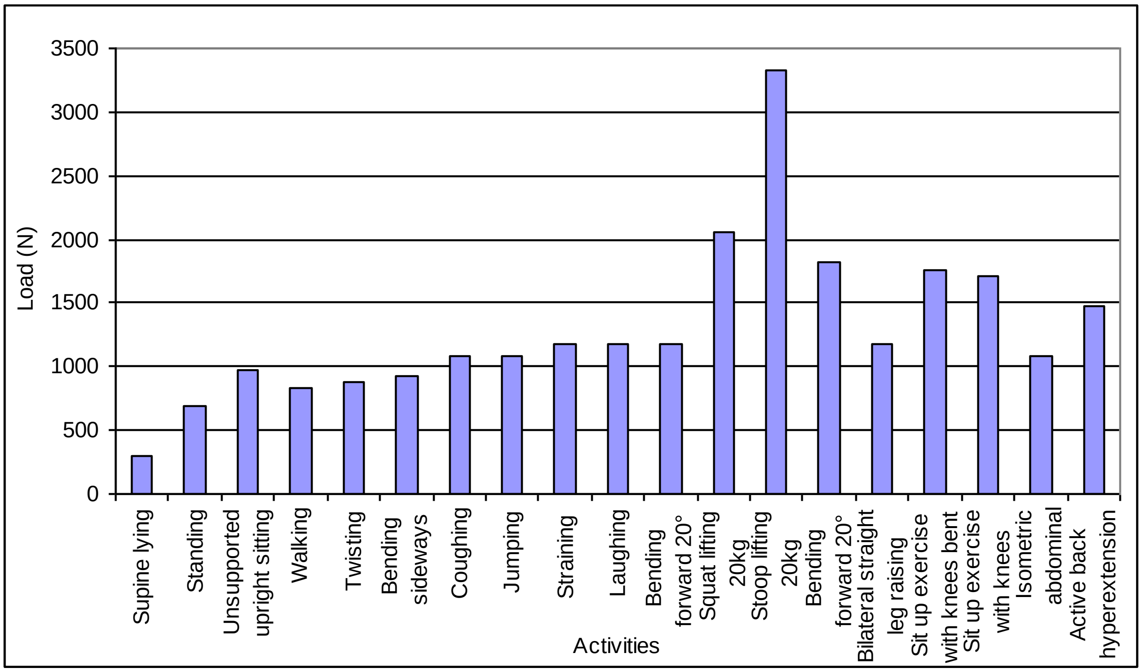
Time of data collection could also cause variation in ranges of movement even within the same participants. The study by Ensink and colleagues (1996) showed an increase of 11.1° in lumbar flexion over the course of a day; Russell et al. (1992) found that ranges of flexion, extension and lateral flexion decreased significantly after sleep and the ranges of flexion, lateral flexion and axial rotation were highest in the afternoon; and Dvorak et al. (1985) observed significant increases in ranges of flexion/extension and axial rotation movement during afternoon and evening when compared to data recorded in the morning. Russell et al. (1992) observed a decrease in ranges of movement after 5:30pm for all movements while Dvorak et al. (1985) found no significant difference between data measured in the afternoon and evening. However none of these 3 studies reported the activities of the participants during the data collection day, and without this information it would be hard to justify whether the changes in spinal movements were due to the time of the day alone or the activities of the participants. Inevitably, intervertebral discs lose their height throughout the day due to compressive loading of the lumbar spine during upright activities (Adams et al. 1990; Adams et al. 2002; Broberg 1993). However the rate of height reduction depends on the compressive load applied to the intervertebral discs, e.g. it depends on the activity levels of the individual. A manual worker who engaged in heavy material handling would be expected to lose more intervertebral disc height at a faster rate compared to sedentary worker (Adams et al. 1990). The amount of fluid lost from the intervertebral discs is also dependent on the age of the individual, as aged intervertebral discs are more fibrous and contain less fluid and thus lose much less disc height compared to young individuals (Adams et al. 1990; Adams et al. 2002). Therefore further information on the activities and age of participants of the study would provide better understanding of the observed results. Nevertheless, these studies provided an insight into possible changes of the spine throughout the day and highlighted this as a factor to consider when comparing ranges of movement data to those available in the literature.

2.4 The relationship between posture and back pain

Every individual will engage in many different postures everyday. Each posture will subject the spinal structures to different levels of mechanical loading. A good posture is a posture that is stable, and produces minimal stress and strain on the spinal structures, such as muscles, ligaments, intervertebral discs and nerves (Scannell and McGill 2003; Pynt et al. 2001). A bad posture is likely to subject the spine to abnormal and high levels of stress and strain (Bullock-Saxton 1988).

Three static postures in everyday life that are commonly employed are standing, sitting and lying. Among the 3 basic static postures, the general conception has been that sitting produces the largest compressive loading on the spine, followed by standing and then lying as reported by Nachemson and Elfstrom (1970) and Nachemson (1975) in the early 70s, as shown in Graph 2.4.1. Callaghan and

McGill (2001a) supported Nachemson and Elfstrom's (1970) finding, that sitting produced a higher compressive load (1698N) on the spine than standing (1076N) by calculating L4/L5 joint forces using data obtained from electromyography.



Graph 2.4.1: Results from Nachemson (1975) on approximate load on L3 intervertebral disc during different activities

Schultz et al. (1982) on the other hand although observing higher intradiscal pressure on the L3 intervertebral disc during relaxed sitting (320kN/m^2) than relaxed standing (270kN/m^2), the mean calculated compressive load was found to be lower during relaxed sitting (380N) than relaxed standing (440N). Similarly, Wilke et al. (1999) found that unsupported relaxed sitting caused a lower intradiscal pressure (460kN/m^2) than relaxed standing (500kN/m^2), opposing the findings reported by Nachemson and Elfstrom (1970). Wilke et al. (1999) also reported higher intradiscal pressures in bending forward tasks during standing (1100kN/m^2) than when fully flexed during sitting (830kN/m^2). By studying the change in stature to estimate the load experienced by the spine during different activities, both Brinckmann et al. (1992) and Leivseth and Drerup (1997) found that shrinkage of the spine was greatest after standing tasks when compared to sitting tasks; while relaxed sitting on the other hand provided the spine with a gain in stature, which suggested that standing or standing tasks loaded the spine much more than sitting, while relaxed sitting loaded the spine the least and therefore encouraged rehydration of the intervertebral discs. These observations contradicted those reported by Nachemson and Elfstrom (1970) and Callaghan and McGill (2001a). Due to different observations within the literature, it is currently inconclusive as to which posture is actually more harmful to the spine in terms of loading.

Sitting causes posterior rotation of the pelvis and this action triggers the lumbar spine to flex compensating for the tilting of the pelvis, thus resulting in a decreased lumbar lordosis (Callaghan and McGill 2001a; Lord et al. 1997; Standring et al. 2005; Wilder and Pope 1996). Research has shown that when the lumbar spine is flexed in sitting, it causes tension in the posterior intervertebral ligaments and hence increases the intradiscal pressure and compressive load on the intervertebral discs (Adams and Hutton 1983b; Adams and Hutton 1985; Adams et al. 1994; Andersson et al. 1975; Hedman and Fernie 1997; Nachemson 1975; Standring et al. 2005). Adams et al. (1994) showed a decrease in intradiscal pressure in intervertebral discs after removal of the posterior ligaments from cadavers that were tested using a computer controlled hydraulic testing machine. The majority of studies have suggested that lumbar lordosis should be maintained during sitting in order to reduce low back pain (Hedman and Fernie 1997; Lord et al. 1997; Nachemson 1975; Pynt et al. 2001). The research carried out by these authors, with either an in-vitro cadaveric study tested using hydraulic testing machine (Adams and Hutton 1983b; Adams and Hutton 1985; Adams et al. 1994; Hedman and Fernie 1997), in-vivo measures using a pressure needle (Andersson et al. 1975; Nachemson and Elfstrom 1970) or an electromyography method (Andersson et al. 1975; Callaghan and McGill 2001a), have indicated that lordotic sitting postures generally produce lower intradiscal pressures and reduce the compression and shear loading on the intervertebral discs due to the load sharing effect of the neural arch. Slump sitting is generally not recommended as it increases spinal flexion leading to increased stress on the spinal structures, induces high intradiscal pressure and causes large fluid outflow from the intervertebral discs (Adams and Hutton 1983b; Adams and Hutton 1986; Callaghan and McGill 2001a; Hedman and Fernie 1997). If such effects are sustained, e.g. through a prolonged flexed sitting posture, it may promote disc degeneration and cause resultant pain (Lotz et al. 1998; Pynt et al. 2001). A prolonged flexed posture may also cause deconditioning of the spinal muscles thus inducing higher risk of injury (O'Sullivan et al. 2006a).

Although many studies have favoured a lordotic sitting posture, some authors have shown that a flexed posture enhances fluid flow and diffusion of nutrients into the posterior annulus fibrosus of the intervertebral discs; while a lordotic posture was found to cause a decrease in the supply of metabolites to the posterior annulus fibrosus (Adams and Hutton 1983b; Adams and Hutton 1986). Adams and Hutton (1986) demonstrated using cadaveric specimens that flexed postures stretched the posterior annulus and reduced its thickness by 37%, which enhanced fluid flow and nutrient diffusion into a deeper region of the posterior annulus. The lack of nutrients to the intervertebral discs is often associated with disc degeneration (Nachemson et al. 1970; Urban et al. 2004). Fahrni and Trueman (1965) reported that there was much less incidence of disc degeneration in a population who adopted a squatting/flexed posture in their daily lives compared to a population who adopted a lower range of lumbar flexion though this study did not investigate the influence of other factors such as individual (diet, culture, physical activities) and occupational factors (prolonged static posture, manual handling, whole body vibration).

In a study carried out by Andersson and colleagues (1975), although flexed lumbar sitting without arm support was reported to produce higher intradiscal pressures (approximately 5.6 times) than erect sitting, once the arms were supported, this flexed lumbar posture showed reduced intradiscal pressure by a fraction of approximately 0.65 times, where the pressure fell to almost the same pressure as erect sitting. Anterior straight sitting (sitting with forward inclined trunk and pelvic) with the lordosis of the lumbar spine preserved showed higher intradiscal pressure (a minimum of approximately 1.31 times) than any of the relaxed flexed sitting postures. Wilke et al. (1999) and Rohlmann et al. (2001) found that erect sitting actually caused higher intradiscal pressures and compressive loads on the intervertebral disc than unsupported relaxed sitting, arms supported flexed sitting, and supported slouched sitting. Although a flexed posture may increase the intradiscal pressure in the intervertebral discs, with proper support the pressure can be reduced; on the other hand, a lordotic posture without support may produce a higher intradiscal pressure than a supported flexed posture.

Studies using cadaveric specimens (Adams and Hutton 1980; Adam et al. 1994; Yang and King 1984) and mathematical simulation (Sharma et al. 1995; Shirazi-Adl and Drouin 1987) have demonstrated that when the lumbar spine is in a lordotic posture, the posterior ligaments are slack thus causing a large increase in loading on the posterior annulus fibrosus and zygapophyseal joints. Although this helps in decreasing the intradiscal pressure in the intervertebral discs, these posterior structures of the lumbar spine are also a reported site of low back pain due to spinal degeneration and injuries (Adams et al. 2002; Dryer et al. 1996; Schwarzer et al. 1994a; Schwarzer et al. 1994b; Schwarzer et al. 1995; Shirazi-Adl and Drouin 1987).

It has been argued that moderate flexion should be adopted in static postures (Adams et al. 2002; Dolan and Adams 2001), because a moderately flexed posture reduces loading on the zygapophyseal joints, increases the supply of metabolites and also equalises the compressive load across the intervertebral discs (Adams et al. 2002; Dolan and Adams 2001).

Creep, in spinal anatomical terms, refers to loss in intervertebral disc height due to sustained loading (Adams et al. 2002). The creep of the intervertebral discs is largely due to loss of water (Adams et al. 2002; Broberg 1993; Kraemer et al. 1985; McMillan et al. 1996). After an individual gets out of bed in the morning, the height of the intervertebral discs will decrease due to the loading caused by daily activities, and when the spine is not loaded, as in a lying posture, the intervertebral discs will regain their hydration levels by osmosis (Adams et al. 1990; Adams et al. 2002; Broberg 1993; Kraemer et al. 1985; McMillan et al. 1996). The mechanical properties of the intervertebral discs change to be more elastic with the loss of water (Koeller et al. 1986); they will bulge radially, become stiffer on compression and have less resistance to bending (Adams et al. 1990; Koeller et al. 1984). As the height of the intervertebral discs is reduced, the adjacent vertebrae become closer to each other, hence resulting in increasing compressive loading on the zygapophyseal joints, especially in lordotic postures (Adams et al. 1994; Adams et al. 1996; Adams 2002; Dolan and Adams 2001). The reduction in intervertebral disc height also causes a decline in stability of the motion segment and decreases the shock absorbent properties of the intervertebral discs (Koeller et al. 1984). Due to water loss in the intervertebral discs, the intradiscal pressure in the nucleus pulposus will decrease, this transfers loading to the annulus fibrosus, especially the posterior annulus fibrosus (Adams et al. 1996). Creep may lead to back pain if the intervertebral discs are loaded continuously without sufficient recovery time (Koeller et al. 1984). However a creep loaded intervertebral disc may be harder to prolapse due to the reduced hydration levels in the nucleus pulposus (Adams et al. 1990).

The rate and magnitude of the creep process are affected by age and activity levels of individuals as discussed in Section 2.3, posture is also found to be an affecting factor although the results reported in the literature are non-conclusive. Adams and Hutton (1983b) reported that sustained flexed postures caused more fluid to be expelled from the intervertebral discs than a lordotic posture; however Hedman and Fernie (1997) found that lordotic postures caused greater creep than flexed postures.

Both flexed and lordotic postures present advantages and disadvantages for spinal structures. But a clear definition of what is a good posture is still considered controversial though it is widely accepted that prolonged static postures are high risk factors in the development of low back pain (Andersson 1981; Hedman and Fernie 1997; Kelsey 1975a; Kelsey and White 1980; Macfarlane et al. 1997; Wilder et al. 1988). By using a mouse tail disc and mathematical simulation, Lotz et al. (1998) found that sustained compression loading as experienced in prolonged static postures for a week could cause irreversible cell death in the intervertebral disc. Although it is not possible to directly link the findings of this study with those of humans as the biological properties of the vertebral body and intervertebral disc are different between mice and humans, this study showed the possible effects on intervertebral discs if loaded with a sustained compressive load as during prolonged static postures.

Prolonged static postures will often increase spinal loading on ligaments, intervertebral discs and the zygapophyseal joints (Callaghan and McGill 2001a; Hedman and Fernie 1997; Kelsey and White 1980; Lotz et al. 1998); they increase the stiffness of the lumbar spine (Beach et al. 2005); result in deconditioning and fatigue in spinal muscles (O'Sullivan et al. 2006a; Veiersted et al. 1990); and may also lead to insufficient nutrition being supplied to the intervertebral discs (Kelsey 1975a). In contrast, alternating static and dynamic postures, and flexed and lordotic postures, may help nourish the discs by enhancing metabolite flow, provide muscles with periodic rest and will prevent static loading of the spinal structures (Adams and Hutton 1983b; Adams and Hutton 1985; Adams and Dolan 1995; Callaghan and McGill 2001a; Veiersted et al. 1990).

From the literature, it was difficult to conclude which are the better postures, as some suggested standing and some supported sitting, while some suggested keeping a lumbar lordosis during sitting and some preferred slight lumbar flexion. However prolonged static posture has been agreed as unhealthy to the spine. Although the study of different stresses and strains acting on the spinal structures in different postures is important to provide further understanding of the biomechanical properties of the spine, a measure of the frequency and time spent in engaging different postures is also crucial in providing further understanding of their relation to the changes in biomechanical properties of the spinal structures and possible causes of low back pain. It is questionable whether studies of cadaveric specimens represent the real physiological conditions of a living person; whether studies of animal models really mimic human models; and whether mathematical modelling is sufficiently representative to simulate the actual biomechanical changes in lumbar structures. It is also important to understand how frequently and for what duration a person needs to be in certain postures for certain spinal structures to degrade or fail; and whether studies performed in the laboratory adequately portray activities of normal daily life. It is undeniable that participants tend to perform at their best when a study is executed in a laboratory setting, but this may not reflect the true postures they will engage in on a day-to-day basis. The size and invasiveness of the equipment used are also factors that could affect participants' performance during a study. For instance, Wilke et al. (1999) mentioned that there was increased discomfort reported by the participant who had an implanted pressure transducer within his intervertebral disc. The participant in the study carried out by Wilke et al. (1999) might not have engaged in postures or activities as they did in normal life for the fear of shifting the implanted transducer or causing further discomfort. Similarly, as reported in the study by Nachemson and Elfstrom (1975), the participants tended to restrict their movements due to the fear of fracturing the pressure needle that was inserted into their L3 intervertebral disc. Short measurement time and predefined conditions in the study may further contribute to misconceptions if the results are treated as representing the majority of the population. In order to gain understanding of the relationship between spinal posture and low back pain in normal daily life, the experimental set up for measurement of spinal posture needs to simulate real life conditions as closely as possible.

2.5 How spinal motion affects back pain and vice versa

Flexion, as discussed in Section 2.3 involves anterior translation and rotation of the lumbar spine. The zygapophyseal joints, muscles and ligaments work together to resist both rotation and translation of the lumbar spine during flexion (Bogduk 2005; Standring et al. 2005). Flexion of the lumbar spine compresses the anterior annulus fibrosus and stretches the posterior annulus fibrosus of the intervertebral discs. Flexion also stretches the posterior ligaments and the tension in the posterior annulus fibrosus and posterior ligaments increase the intradiscal pressure of the intervertebral discs (Adams et al. 1994; Adams et al. 2002). When the flexion limit is exceeded, the supraspinous ligaments and the interspinous ligaments will be the first structures to be damaged, followed by the zygapophyseal joint capsular ligaments and then the posterior annulus fibrosus of the intervertebral discs (Adams et al. 1980; Adams and Hutton 1982; Adams 2004). Sustained or repetitive flexion could result in relaxation of the posterior ligaments, thus reducing their protective capability and increasing the risk of posterior ligament and intervertebral disc injury (Adams et al. 2002).

Extension of the lumbar spine involves a small degree of posterior translation and posterior rotation. In extension, movement is limited by the neural arch, intervertebral discs and anterior longitudinal ligaments (Adams et al. 2002; Bogduk 2005). As discussed in Section 2.4, zygapophyseal joints share most of the compressive load during extension and therefore may be the first structures to be damaged during a hyperextension movement. In hyperextension, the interspinous ligaments may be compressed in between the superior and inferior spinous processes and the joint capsule may be damaged when the inferior articular processes deflect posteriorly during impaction with the laminae of the vertebrae below (Adams et al. 2002; Bogduk 2005). During sustained or repetitive hyperextension, intervertebral disc herniation may occur through the anterior annulus (Adams et al. 2002), although this would be unusual in normal life as the anterior annulus fibrosus is much thicker than the posterior annulus.

Lateral flexion is a more complex movement as it is usually coupled with flexion and axial rotation. The zygapophyseal joints, intervertebral discs, muscles and ligaments protect the lumbar spine by limiting the movement during lateral flexion (Adams et al. 2002; Standring et al. 2005). During lateral flexion, the zygapophyseal joints are under compression on the side of lateral flexion, while the lateral annulus fibrosus in the contra direction of lateral flexion is stretched and induces high intradiscal pressure in the nucleus pulposus.

Flexion or extension and lateral flexion always accompany axial rotation movement. In order to protect the lumbar spine in excessive axial rotation, the intervertebral discs, zygapophyseal joint and ligaments of the posterior elements play an important role in resisting the movement (Bogduk 2005). Injury due to axial rotation usually occurs in the zygapophyseal joints before the intervertebral discs (Adams and Hutton 1983a; Adams et al. 2002; Adams 2004). However due to the complex movement of axial rotation, injury in real life is not usually caused by axial rotation itself but also depends on the range and load of other movements.

Flexion, extension, lateral flexion and axial rotation of the lumbar spine often occur either independently or jointly in normal daily life. For instance, working at a desk may involve flexing the lumbar spine forwards to write, extending backwards to lean on a back rest, forward and laterally flex in order to pick up some materials from a low drawer, or rotate the lumbar spine to talk to a person sitting to the side or behind.

Dynamic spinal movement that occurs in multiple planes simultaneously and the velocities of these 3 dimensional movements have been identified as high risk factors for low back pain (Fathallah et al. 1998; Granata and Marras 1999; Lavender et al. 1999; Marras et al. 1993). Flexion in combination with lateral flexion and rotation was considered the greatest risk to the spine (Andersson 1981); while flexion coupled with rotation, lateral flexion coupled with rotation and any asymmetrical 3 dimensional movements were also found to be high risk movements for the spine (Adams 2004; Davis and Marras 2000; Fathallah et al. 1998; Granata and Wilson 2001; Hoogendoorn et al. 2000; Kelsey et al. 1984; Mendez and Gomez-Conesa 2001; Waddell 2004; Wong and Lee 2004). Studies carried out by Adams and Hutton (1982) showed that movements combining flexion, lateral flexion and compression could cause prolapse of the intervertebral discs; and a separate study by Gordon et al. (1991) found that repetitive combined movements of flexion, axial rotation and compression could cause disc herniation. Lu et al. (1996) simulated a rupture of the posterior annulus fibrosus by applying an axial compressive load, lateral flexion and rotation when the intervertebral disc was fully hydrated.

Dynamic movement of the spine potentially reduces spinal strength and this will cause higher muscle recruitment in order to maintain spinal stability. Such action will dramatically increase compressive loading on spinal structures (Davis and Marras 2000; Granata and Wilson 2001). Marras et al. (1993) showed that back pain is related to movement frequency, load magnitude, spinal lateral velocity, spinal rotation velocity and the spinal sagittal angle, by varying these 5 factors appropriately using the predictive algorithm, the risk of back pain may be reduced by a factor of up to 11 in the working environment (Marras et al. 1993). As this was predicted using a mathematical model, the effectiveness of this system has yet to be proven in longitudinal real life situations.

Occupational factors such as whole body vibration and manual handling such as lifting, pulling and pushing, bending and twisting are often associated with low back pain in the workplace (Manek and MacGregor 2005; Marras 2000; Van Tulder 2002).

Lifting requires the carrying of an external weight commonly in a flexed posture, possibly with rotation and/or lateral flexion of the lumbar spine (Hoogendoorn et al. 2000; Kelsey et al. 1984; Lavender et al. 1999; Marras 2000). The weight of the object being lifted, the frequency of lift and the posture during lifting are the main factors in triggering low back pain (Adams and Dolan 1996; Hoogendoorn et al. 2000; Kelsey et al. 1984; Marras 2000).

Hoogendoorn et al. (2000) found that occupations that involve extreme flexion and axial rotation of the spine for more than 5% and 10% of working time respectively will increase the risk of low back pain. The amount of lumbar flexion is believed to be one of the main predictors of injury of spinal structures during lifting (Arjmand and Shirazi-Adl 2005; Dolan and Adams 1998; Hoogendoorn et al. 2000; Morl et al. 2005). Repetitive compressive loading and bending of the spine will decrease muscle reflexes as well as induce creep and muscle fatigue; these will reduce muscle protection, alter spinal loading and increase the risk of failure of the spinal structures (Adams and Dolan 1995; Adams and Dolan 1996; Adams 2004; Callaghan and McGill 2001b; Dolan and Adams 1998; Gordon et al. 1991; Hansson et al. 1987; Parkinson et al. 2004; Sbriccoli et al. 2004; Solomonow et al. 1999).

Whole body vibration, which includes industrial and non-industrial vibration, is also considered a high risk factor in the development of low back pain (Bovenzi 1996; Bovenzi and Hulshof 1998; Marras 2000; Palmer et al. 2003; Pope et al. 1999). Vibration can also cause higher muscle tension in order to maintain spinal stability (Seroussi et al. 1989; Pope et al. 1999). With the increase of muscle tension, higher compressive loads will be induced onto the spine and this could cause damage or failure of the spinal structures due to fatigue (Adams and Dolan 1995; Pope et al. 1999; Wilder and Pope 1996). Research has shown that a herniated nucleus pulposus was more common in people who were exposed to frequent vibration in their daily lives, for example truck drivers (Kelsey 1975b; Kelsey and Hardy 1975). Jobs that involved sitting and whole body vibration, such as truck, tractor and bus drivers were not only subject to muscle fatigue but also creep and increased spinal loading due to prolonged sitting (Bovenzi 1996; Bovenzi and Hulshof 1998; Kelsey and Hardy 1975; Pope et al. 1998; Wilder and Pope 1996). Jobs that require drivers to perform lifting, bending and twisting, and pulling and pushing after being exposed to whole body vibration will further increase the risk of low back pain (Bovenzi 1996; Bovenzi and Hulshof 1998; Pope et al. 1998; Wilder and Pope 1996; Wilder et al. 1988). The risk of whole body vibration could be reduced if vibration dampening could be applied (Pope et al. 1999), however further studies are needed to determine the best dampening methods in vibration environments.

Although many studies have been carried out on these risk factors, there are no conclusive findings as to what are good spinal mechanics. Variables such as weight of load, velocity of movement, loading frequency, magnitude and direction of simultaneous movements were identified as risk factors for low back pain. However the safe levels of these variables in order to reduce the risk of developing low back pain have not been discussed in the literature and as yet remain to be identified.

Cadaveric specimens and mathematical models for predicting occupational injury may not be as representative of real life conditions. Identifying risk factors and their magnitude in developing low back pain in occupational settings is complex due to many underlying factors. Different occupations in different industries provide different parameters within the working environment and tasks performed vary considerably. Aggravating factors could also be involved, e.g. the workers' experience, individual factors and psychosocial factors; and thus it is a complicated situation for investigation.

Instrumentation for measurement is also an issue in occupational settings; the equipment used has to be portable, possible to attach under participants' clothing and not affect the participants' normal working pattern. More research into both kinematics and kinetics of the spine is needed to aid understanding of the nature of spinal mechanics in order to provide better understanding and more effective prevention of occupational low back pain.

2.6 Summary and conclusions

Each lumbar spinal structure has its unique biomechanical characteristics and works in different ways to provide the spinal column with mobility and stability.

The lumbar spine is a complex structure that exhibits 6 degrees of movement which involve translation and rotation about 3 orthogonal axes. The main physiological movements of the lumbar spine are flexion, extension, lateral flexion and axial rotation. The measured ranges of these movements varied from study to study within the literature. During comparison of the ranges of physiological movements between studies, factors such as age, gender, body mass index, occupation, lifestyles, time of day when measurement was taken, equipment and methodology should be taken into consideration.

Different spinal postures and movements subject spinal structures to different levels of compressive loads and strains. Even with the significant amount of literature available, defining the optimal posture and body mechanics is not possible due to contradictory evidence. The studies discussed have mainly investigated failure properties and stress and strains on different spinal structures under predefined conditions.

Spinal posture and movements are important measures as they may be used to predict mechanical forces and loads acting on spinal structures. An alternative way of measuring spinal posture and motion of individuals during normal daily activity is needed to provide a more relevant perspective on the relationship between spinal posture and motion and low back pain. Most of the in-vivo spinal posture and motion measurements have hitherto been performed in a laboratory setting over a short period of time due to the constraints of the measurement systems; with a risk that participants may not be performing tasks as they would in normal daily life. Therefore measurements may not be adequate to quantify the intended measure in order to represent the general population in normal life outside the laboratory. It is proposed that assessment of spinal posture and motion over an extended period of time outside the laboratory is essential in gaining insight and understanding of how individuals use their spine in normal daily life and the significance of this information in relation to low back pain.

Chapter 3. Posture and motion measurement methods

3.1 Overview

As proposed in Chapter 2, it is essential to further the study of spinal posture and motion outside laboratory settings over an extended period of time in order to gain a deeper understanding of real life postures and motions. In order to implement this study and achieve reliable measurement of spinal posture and motion, it was necessary to identify the most appropriate measurement tool.

There are many methods and a range of equipment available for spinal posture and motion measurement. These different measurement methods vary in size, cost, accuracy, dimensions of measurements, ease of use and invasiveness, and each has its advantages and disadvantages. In this chapter, the functionality, operation, advantages and limitations of a range of different methods of spinal posture and motion measurements are discussed.

3.2 Current methods of posture and motion measurement

There has been a considerable amount of research into spinal posture and motion measurement. Direct observation, graphical checklists and questionnaire assessment have often been used to assess spinal posture and motion in the workplace (Baty et al. 1986; Burt and Punnett 1999; Heinsalmi 1986; Juul-Kristensen and Jensen 2005). However these methods are subject to reliability and repeatability issues as they depend solely on observers' or participants' judgement. The limitations of these methods include subjectivity and bias, interobserver unreliability, observers' level of training, lack of accuracy, and the requirement for long hours of analysis (Baty et al. 1986; Burt and Punnett 1999; Vieira and Kumar 2004).

Quantitative measures on the other hand provide an accurate and direct measurement of the posture and motion of participants. Different methods and equipment present different levels of accuracy and each have advantages and disadvantages, therefore it was important to assess the application and limitations of available systems in order to source a method that was best suited for the intended study. Tables 3.2.1 and 3.2.2 summarise the use of different equipment in various spinal posture studies.

The majority of spinal posture studies have focused on non-continuous measurement of spinal angles in 1 or 2 planes, in a laboratory environment, and/or over a short period of measurement time. These measures are unlikely to provide information directly representing the true postures of individuals in a normal daily life.

2 dimensional studies		
Equipment/Measurement methods	**Authors**	**Study design**
Radiography	Lord et al. (1997)	Measurement of segmental and total lumbar curvature angles in standing and sitting
	Harrison et al. (2001)	Reliability study of different methods for analysis of lumbar curvature
	Vaz et al. (2002)	Measurement of sagittal morphology and balance of pelvis and spine
	Vialle et al. (2005)	Measurement of sagittal alignment and balance of spine of asymptomatic individuals
	Damasceno et al. (2006)	Measurement of vertebral bodies and intervertbral discs role in lumbar curvature
	Been et al. (2007)	Predicting of lumbar curvature angle with orientation of inferior articular processes
	Dunk et al. (2009)	Measurement to determine if intervertebral disc joints of the lumbar spine approaching end range of motion in sitting
Flexicurve	Burton (1986)	Measurement of lumbar sagittal mobility and posture
	Youdas et al. (1996)	Measurement of lumbar curvature of asymptomatic adults
	Youdas et al. (2000)	Measurement of lumbar curvature of adults with chronic low back pain
Inclinometers	Bendix et al. (1996)	Measurement of sitting spinal curvature changes with different backrest of chair
	Youdas et al. (1996)	Measurement of pelvic inclination of asymptomatic adults
	Ng et al. (2001)	Reliability study to validate inclinometers in lumbar curvature measurement
	Ng et al. (2002)	Measurement of lumbar curvature in comparison between back pain patients and matched controls
	Mork and Westgaard (2009)	Field measurement of back posture in female computer workers
Electrogoniometer	Bullock-Saxton (1993)	Measurement of spinal curvature and pelvic inclination
	Boocock et al. (1994)	Field measurement of lumbar posture in 4 garage mechanics
Rachimeter/Flex sensor	Vergara and Page (2000a)	Measurement of use of backrest in sitting posture when performing office tasks
	Vergara and Page (2000b)	Reliability study of rachimeter in lumbar curvature measurement
	Vergara and Page (2002)	Measurement to compare relationship between comfort and back posture in sitting
	Carcone and Keir (2007)	Measurement of sagittal lumbar and cervical angles during use of different backrest
Photographic/Videotaping	Colombini et al. (1986)	Study to analyse lumbar and pelvis position in different sitting postures
	Mandal (1986)	Study to evaluate effect of furniture height in seated spinal flexion
	Wick and Drury (1986)	Study to analyse spine, neck/head and extremities posture during sewing work
	Christie et al. (1995)	Measurement of spinal curvature in comparison between chronic and acute low back pain patients in standing and sitting

Table 3.2.1: Summary of different 2 dimensional methods in spinal posture measurement

3 dimensional studies		
Equipment/Measurement methods	**Authors**	**Study design**
Electromagnetic tracking systems	Beach et al. (2005)	Measurement of spinal flexion during prolonged sitting (2 hours)
	Dankaerts et al. (2006)	Measurement of upper and lower lumbar angle and sacral tilt between asymptomatic individuals and chronic low back pain patients
	Claus et al. (2008)	Study to compare spinal curvature in different sitting postures
	Mitchell et al. (2008)	Study to measure and compare upper and lower lumbar angle of individuals with and without history of low back pain during static and dynamic tasks
Opto-electronic systems	Dumas et al. (2009)	Study to compare seated spinal posture between women in late pregnancy and non pregnant controls, with different desk board attachments
	Howarth et al. (2009)	Study to compare changes in spinal posture and motion in lifting after prolonged sitting
	Kingma and Van Dieen (2009)	Study to compare working posture and movement in females between sitting on an office chair and on an exercise ball
Inertial measurement systems	Wong and Wong (2008a)	Study to detect sitting spinal posture change in sagittal and coronal planes, using opto-electronic systems as reference
	Wong and Wong (2008b)	Study to monitor spinal posture in sagittal and coronal plane using smart garment that integrated with inertial sensors, using opto-electronic systems as a reference
	Wong and Wong (2008c)	Study to monitor spinal posture in sagittal and coronal plane, using opto-electronic systems as a reference

Table 3.2.2: Summary of different 3 dimensional methods in spinal posture measurement

A number of spinal motion studies have focused on ranges of movement of the spine, both in-vivo (Frymoyer et al. 1979; McGregor et al. 1995; Ng et al. 2001; Peach et al. 1998; Pearcy et al. 1984; Pearcy 1985; Russell et al. 1993; Taylor and Twomey 1980; Troke et al. 2005; Van Herp et al. 2000) and in-vitro (Cholewicki et al. 1996; Panjabi et al. 1994; Taylor and Twomey 1980).

2 dimensional studies	
Equipment/Measurement methods	**Authors**
Finger-tip-to-floor	Moran et al. (1979)
	Ensink et al. (1996)
Skin distraction	Macrae and Wright (1969)
	Moll and Wright (1971)
	Moran et al. (1979)
	Fizgerald et al. (1983)
	Einkauf et al. (1987)
	Ensink et al. (1996)
Photographic	Davis et al. (1965)
Inclinometers	Loebl (1976)
	Ensink et al. (1996)
	Nattrass et al. (1999)
	Ng et al. (1999)
	Nitscheke et al. (1999)
Spondylometers	Sturrock et al. (1971)
	Hart et al. (1974)
	Taylor and Twomey (1980)
Goniometers	Einkauf et al. (1987)
	Fizgerald et al. (1983)
	Nattrass et al. (1999)
	Nitscheke et al. (1999)

3 dimensional studies	
Equipment/Measurement methods	**Authors**
Biplanar radiography	Frymoyer et al. (1979)
	Portek et al. (1983)
	Pearcy et al. (1984)
	Pearcy and Tibrewal (1984)
	Pearcy (1985)
Magnetic resonance imaging	Harvey et al. (1998)
	Vitzthum et al. (2000)
Opto-electronic systems	Gracovetsky et al. (1995)
Electromagnetic tracking systems	Hindle et al. (1990)
	Russell et al. (1993)
	Peach et al. (1998)
	Van Herp et al. (2000)
	Lee and Wong (2002)
Triaxial electrogoniometers	Dvorak et al. (1995)
	McGregor et al. (1995)
	Lee et al. (2002)
	Troke et al. (2005)
Gyroscopic systems	Lee et al. (2003)

Table 3.2.3: Summary of different methods in spinal ranges of movement measurement

There are many different ways of measuring spinal ranges of movement. Table 3.2.3 shows a range of 2 and 3 dimensional methods used for spinal ranges of movement measurement. Although 2 dimensional methods are easy and quick to use, they can only provide information about the end movement of the measured plane and record no information on the quality of movement and velocity of the spine from the neutral position to the maximum range of movement. Some of the 2 dimensional methods can only be used to measure certain movements, mostly flexion or/and lateral flexion. The accuracy and reliability of these methods is also questionable (Mayer et al. 1997; Portek et al. 1983; Reynolds 1975; Saur et al.

1996). In clinical settings, inclinometers and goniometers are popular choices for assessing spinal ranges of movement as these instruments are inexpensive, easy to use and with careful measurement, the results are reproducible (Lee 2002; Portek et al. 1983; Taylor and Twomey 1980). However the limitations of goniometers or electrogoniometers are that the tight attachment across the joint may limit natural movement due to mechanical constraint, the inherent nonlinear effects in the mechanical linkage system may also affect the measurement outcomes, and the system can be heavy and the attachment across the joint is often cumbersome (Ladin 1995). The CA-6000 Spine Motion Analyzer (Orthopedic Systems Inc) is a popular triaxial electrogoniometer system used for spinal range of movement measurements (Coates et al. 2001; Dvorak et al. 1995; Lee et al. 2002; McGregor et al. 1995; Troke et al. 2005). There have been contradictory reports on the accuracy of this system. While Christensen (1999) found no agreement in 27 sets of angles measured between the CA-6000 system and 2 different precision protractors, with a maximum mean difference of 11.5%; Schuit et al. (1997) found that CA-6000 system provided good agreement with radiographic results during sagittal and frontal movements, with the mean differences falling within 95% confidence interval. In the studies carried out by Dvorak et al. (1995) and McGregor et al. (1995), the range of axial rotation movements were reported to be between 32° to 48° and between 23° to 31° respectively, these values are large when compared to those reported by studies using radiography (4° to 5°), an electromagnetic tracking system (8° to 17°) and a gyroscopic system (8° to 9°) as tabulated in Table 2.3.3 in Section 2.3. Dvorak et al. (1995) commented that the fixation of the device was the largest source of error and suggested that the low validity of axial rotation movement measurements was due to fixation difficulties. Troke et al. (2005) reported a much lower range of axial rotation (7°) in their study that measured ranges of movement using the CA-6000 Spine Motion Analyzer system. In Troke et al.'s (2005) study, the system was modified using a skin pad fixation system to improve the fixation problem of this device. However, this system is not suitable for measurement of spinal motion in normal daily life due to the size of the mechanical linkages of the system.

Studies of spinal ranges of movement alone do not provide a critical insight into low back pain because many back pain patients possess normal ranges of movement (Burton et al. 1989; Esola et al. 1996; Ng et al. 2002; Okawa et al. 1998; Park et al. 2003; Pearcy et al. 1985) and some healthy individuals have stiffer structures and produce smaller ranges of movements than patients with low back pain (Burton et al. 1989). Ranges of movements of the spine are governed by many other factors such as age, gender, spinal structure properties, physical build and lifestyles, or even the individual's motivation. Therefore these measurements can only serve as a reference in assessing patients with low back pain. However measurement of ranges of movement can be useful in monitoring progress or changes in spinal movement characteristics of individuals over time, for instance measures to examine the effectiveness of a particular treatment protocol.

Methods that measure spinal posture or ranges of movement in just 1 or 2 dimensions do not provide the complete picture of spinal posture and motion because as discussed in Section 2.3, the spine exhibits 6 degrees of freedom of movement and none of the spinal movements occur isolated to a single plane. For range of movement measurements, another limitation is that these can only provide the end results of the motion and the patterns and velocity of movements cannot be assessed. This limitation also applies to biplanar radiography and magnetic resonance imaging. The 3 dimensional kinematics information of the spine during these physiological movements may be significant in the analysis of spinal mechanics as the end range of movement alone may not be sufficient for the identification of spinal disorders as discussed in the above paragraph.

Except for radiography and magnetic resonance imaging, which can measure intervertebral movements through the captured images, other in-vivo or skin surface measurements as discussed previously are prone to errors due to skin movement, intra and inter observer reliability, the security of sensors or markers attachment and alignment, and the reliability and validity of the equipment and methods of measurement (Bogduk 2005; Cappozzo et al. 1996; Chiari et al. 2005; Leardini et al. 2005; Portek et al. 1983; Pope et al. 1986; Taylor and Twomey 1980; Taylor et al. 2005; Zhou and Hu 2004). Therefore a carefully planned protocol needs to be developed before measurement of spinal posture and motion take place in order to minimise errors and produce reliable, repeatable and valid results.

From the range of equipment available, biplanar radiography, opto-electronic systems, electromagnetic tracking systems, and inertial measurement systems are all capable of both 3 dimensional spinal posture and motion measurements. Biplanar radiography, opto-electronic systems and electromagnetic tracking systems are the more established and common methods employed. Inertial measurement systems have not yet been widely used for spinal posture and motion measurement as this method of measurement is relatively new and further validation is required for this field of study.

Radiography or X-ray is one of the popular methods used in posture and motion measurement, especially in spinal mobility measurement (Pearcy et al. 1984; Pearcy and Twibrewal 1984; Pearcy 1985; Portek et al. 1983; Wong et al. 2004); intersegmental vertebra kinematic analysis (Frymoyer et al. 1979; Thomas et al. 1997); and postural tracking (Harrison et al. 2005). Biplanar radiography is used to provide a 3 dimensional illustration of the posture or motion measured. Radiography is not suitable for multiple exposure or long term measurement as repeated doses of radiation have harmful long term effects (Pearcy 1985; Stokes 1995). Another disadvantage of radiography is that the participant needs to keep still during the process while the image is captured (Stokes 1995; Lee 2002; Lee et al. 2003; Thomas et al. 1997) and consequently it is not possible to measure continuous dynamic movements. Digital radiography is an advancement of conventional radiography that produces lower radiation and a more convenient analysis of the images, but the risk and overall disadvantages still exist (Stokes 1995).

Opto-electronic systems are another common option in human motion tracking. Arjmand and Shirazi-Adl (2005), Morl et al. (2005) and Kingma et al. (2004) have used this system to monitor lifting techniques; while Esola et al. (1996) employed this method in examining participants' spine and hip motion during flexion; and, Crosbie et al. (1997), Fowler et al. (2006), Lamoth et al. (2004) and Taylor et al. (2001) used such a technique to measure spinal movement during walking. Opto-electronic systems are also a popular method for use in gait analysis (Fuller et al. 1997; Konz et al. 2006; Levinger and Gilleard 2006; Manal et al. 2003; McIntosh et al. 2006). These systems track motion by detecting markers on the participants using high speed video cameras with the detected images being reconstructed into 3 dimensional coordinates for subsequent analysis (Ladin 1995; Pedotti and Ferrigno 1995; Zhou and Hu 2004). There are 2 different types of marker systems, active markers that emit light and passive markers that reflect light. Active marker systems usually utilise light emitting diodes (LED) that emit infrared light into detecting cameras (Ladin 1995; Pedotti and Ferrigno 1995; Chiari et al. 2005; Welch and Foxlin 2002; Zhou and Hu 2004). The system's markers are easily identified due to their active nature (Ladin 1995; Pedotti and Ferrigno 1995). Because the active markers require an external power source to supply the LED, wires are usually attached to the sensors and this could limit or affect the freedom of movement of the subject being studied (Ladin 1995; Pedotti and Ferrigno 1995; Chiari et al. 2005). The active marker systems are prone to errors during movements that incur rotation of the markers due to the restricted light emission angle of the LEDs (<50°) and this problem is amplified if 3 dimensional analysis is required (Pedotti and Ferrigno 1995). In order to facilitate 3 dimensional analysis, a minimum of 2 cameras have to be used and with the restricted light emission angle, it is difficult for both cameras to detect the LED simultaneously (Pedotti and Ferrigno 1995).

Passive marker systems work by reflecting light emitted from the cameras (Ladin 1995; Pedotti and Ferrigno 1995; Chiari et al. 2005; Welch and Foxlin 2002; Zhou and Hu 2004). The advantages of using a passive marker system are the wider visibility angles of the markers and the provision of greater flexibility as there are no wires attached to the markers (Ladin 1995; Pedotti and Ferrigno 1995). The shortcoming of the passive systems however is the extreme difficulty in identifying the markers (Ladin 1995; Pedotti and Ferrigno 1995). Whether using an active marker system or a passive marker system; opto-electronic measurement must be performed in an area that is within the sight of the cameras, if a marker is not detected by at least 2 cameras, a 3 dimensional reconstruction will not be possible (Pedotti and Ferrigno 1995; Chiari et al. 2005; Welch and Foxlin 2002). The lighting in the study environment may also affect the detection of markers as cameras depend on the reflectivity of markers to determine their locations in space (Rohmert and Mainzer 1986).

Some researchers have explored the option of using a visual tracking system without the use of markers. They have tracked human motion with camera/s and reconstructed 3 dimensional models by using a series of complex image matching computational algorithms (Aggarwal and Cai 1999; Bowden et al. 1998; Cai and Aggarwal 1996; Kakadiaris and Metaxas 2000; Krosshaug and Bahr 2005; Sminchisescu and Triggs 2001; Song et al. 2000). This method is less restrictive than marker based systems; however it lacks detailed segmental information as it is mainly constructing boundaries or features of the human body (Zhou and Hu 2004). This tracking system may be useful in monitoring human behaviour but it is insufficient to provide valuable and reliable information on regional changes of spinal posture and motion angles and patterns. Obstructions like loose clothing, the back rest of a chair during sitting or any other object in the study environment are also likely to further impair the feasibility of monitoring spinal changes. As with the marker based systems, the subject being studied must be within the sight of cameras and therefore the measurement is restricted to a constrained area which is usually laboratory based.

Electromagnetic tracking systems have gained popularity in human motion measurement due to their accuracy, no line of sight problems and the capability of real time 3 dimensional tracking (Lee 2002; Lee et al. 2003; Zhou and Hu 2004; Welch and Foxlin). Some studies have utilised electromagnetic tracking systems for measuring range of movement (Park et al. 2003; Peach et al. 1998; Russell et al. 1993; Thomas et al. 1997; Van Herp et al. 2000); others have used them to monitor lifting motion (Dolan and Adams 1998; Kollmitzer et al. 2002; Parkinson et al. 2004); and some have used it to monitor spinal postures (Beach et al. 2005; Dankaerts et al. 2006; O'Sullivan et al. 2006a) and motion (Lee 2001; Tsung et al. 2005). Gatton and Pearcy (1999) in addition analysed the sequence of movement of the lumbar spine during flexion with an electromagnetic tracking system. Electromagnetic tracking systems consist of 2 main components, the source and the sensors, both contain 3 sets of orthogonal coils that represent the 3 dimensional axes (Ladin 1995; Welch and Foxlin 2002). When the orthogonal coils in the source are excited with low frequency magnetic field vectors, a pattern of 3 excitation states is generated in the source as a reference state; the sensors are used to detect the field vectors in order to produce information on the relative position and orientation of the sensors with respect to the source (Ladin 1995; Jordan et al. 2001; Welch and Foxlin 2002). This system has been found to be accurate (total RMS error of less than 0.2° reported by Pearcy and Hindle 1989) in monitoring rigid body motion but its limitations include interference from nearby metallic objects, a relatively low sampling rate depending on the number of sensors used, and only a limited number of sensors can be used (Ladin et al. 1995; Milne et al. 1996; Welch and Foxlin 2002).

These 3 dimensional techniques described above are mostly expensive, are laboratory based, and to date have not been developed to be portable, therefore they are currently impractical to be used outside the laboratory. Consequently, in their current state of development, they are not suitable for the study of posture and motion of the spine in normal daily life or in the clinical setting. In order to study the posture and motion of the spine external to the laboratory environment, an alternative portable measurement method is required.

Inertial measurement systems address these problems as the advanced inertial measurement systems are small, portable, and of low cost. Inertial measurement systems present a potential instrument for measurement outside the laboratory environment. The theory and applications of inertial measurement systems are discussed in the sections that follow.

3.3 Inertial sensing technology

Conventional inertial measurement systems have been mostly used in aerospace and nautical navigation (Welch and Foxlin 2002), and are often referred to as Inertial Navigation Systems (INS). Conventional inertial navigation systems are very expensive due to the high precision and performance needed in such navigation; and therefore the use of INS in other applications has been limited. As technology has advanced, MEMS (micro-electromechanical systems) inertial measurement technologies have been successfully developed to produce inertial sensors that are small in size (typically 4.0x4.0x1.45mm for a triaxial accelerometer and 7.0x7.0x3.0mm for a gyroscope), light weight, having low power consumption (1.8-3.6V, 350uA for a triaxial accelerometer and 4.75-5.25V, 3.5mA for a gyroscope) and are of relatively low cost (approximately £1.46 for a triaxial accelerometer and £12.30 for a gyroscope). This makes inertial measurement outside the laboratory setting over an extended period of time in normal daily life potentially achievable if the measurement systems can provide appropriate accuracy and resolution for the application. Inertial measurement systems have gained popularity in various research areas, such as automobile (Dissanayake et al. 2001), robotics (Borenstein et al. 1997; Lobo et al. 2003; Madni et al. 1998; Roumeliotis et al. 1999; Vaganay et al. 1993), gaming technology (Crampton et al. 2007; Kim et al. 2005), medical equipment (Ang et al. 2000; Rebello 2004), biomechanics measurement (Bouten et al. 1997; Najafi et al. 2003), in telecommunication, military applications, commercial appliances and many more

(Avizzano et al. 2004; Park and Horowitz 2004; Tan and Park 2002). The 2 inertial sensors that are often integrated into an inertial measurement system are accelerometers and gyroscopes.

3.3.1 Gyroscope applications

Gyroscopes measure the rate of rotation, or the angular velocity about its sensitive axis. Compared to conventional mechanical gyroscopes, MEMS (micro-electromechanical systems) gyroscopes have the advantage of not having any moving parts that will wear over time; they are much smaller in size, require lower power and are low maintenance (see Appendix A6.1 for detailed gyroscope theory).

Gyroscopes often suffer from drift over time and integrating the results complete with the drift component will result in large errors in orientation (Dejnabadi et al. 2006; Luinge and Veltink 2005). To overcome the drift problem, some studies have suggested the use of a high pass filter (Tong and Granat 1999); resetting the system (Tong and Granat 1999); time-frequency (wavelet) transformation (Aminian et al. 2002; Najafi et al. 2002; Najafi et al. 2003); or using Kalman filters to fuse the gyroscope data, with tilt information measured by accelerometers and/or magnetic sensor data to produce an estimation error for correction (Lee et al. 2002; Luinge et al. 1999; Luinge and Veltink 2005). Most of the modern MEMS gyroscopes are also provided with a temperature drift compensation option that can be used to minimise the drift error computationally.

In recent years, MEMS gyroscopes have been widely used in human movement studies. Najafi et al. (2002) utilised gyroscopes in measuring sit to stand and stand to sit transitions to identify the risk of falling in 11 elderly participants, and reported that high fall and low fall risk groups were discriminated successfully. Although a larger sample size might be necessary to further confirm the validity of the results, this work does imply that gyroscopes may offer an alternative method for human movement measurement.

Due to their size and portable features, MEMS gyroscopes have started to gain popularity in gait measurement. Coley and co-workers (2005) used gyroscopes to identify and monitor stair climbing during daily physical activity and showed that one gyroscope was sufficient to differentiate stair climbing from other kinds of walking with high accuracy (less than 8% error). However during the study (Coley et al. 2005), it was not possible to differentiate walking on a level surface from stair descent due to similar angular velocity patterns of the lower legs during these 2 movements. A more extensive study will be needed in order to explore the extended use of gyroscopes in gait measurement, possibly exploring attachment of gyroscope to other parts of leg (e.g. ankle) and the use triaxial gyroscopes to analyse rotational movement in other planes.

Tong and Granat (1999) also used gyroscopes to analyse gait movement and it was suggested that one sensor on the lower leg would be sufficient to provide gait information. However this study was only performed on 2 participants and further studies utilising more participants are required in order to validate the findings. The authors (Tong and Granat 1999) also noted there was a problem with the signals if the participant changed direction of locomotion due to the limited information from the uniaxial gyroscope. A better resolution of gait patterns may be able to be achieved if a 3 dimensional study using triaxial gyroscopes is employed.

Another study of gait movement carried out by Aminian and colleagues (2002) showed that gyroscopes are capable of detecting gait events when compared to a foot pressure sensor. It was observed by the authors that a few of the participants had slight asymmetric gait patterns but no significant variation was observed, the authors suggested the use of another sensor on the left thigh for measuring asymmetric gait, however it was not discussed in the paper whether the authors had used this method to verify their observations on the insignificant variation of asymmetric gait patterns.

In addition to gait analysis, gyroscopes have also been used in assessing spinal motion. Lee et al. (2003) showed that gyroscopes are capable of measuring spinal motion and the results were in close agreement with other studies that measured ranges of motion with an electromagnetic tracking system (Lee and Wong 2002) and radiography (Pearcy 1985), as shown in Table 2.3.3 in Section 2.3.

3.3.2 Accelerometer applications

Accelerometers measure acceleration along the sensing axes of the sensors. If an accelerometer is mounted securely on a body segment, the accelerometer can measure the acceleration of that segment along the direction where the sensitive axis is attached. Accelerometers also measure acceleration due to gravity. This characteristic enables accelerometers to be used as inclinometers to measure tilt angles with respect to the vertical axis or to the ground when there is no acceleration due to body movement or the acceleration due to body movement is relatively small when compared to the gravitational component (Mathie et al. 2004b; Veltink et al. 1996; Zheng et al. 2005). One example of this application is spinal tilt angle measurement using accelerometers during static (see Appendix A6.2 for detailed accelerometer theory).

However, when the acceleration due to body movement is large, for example during measurement of spinal movement, the acceleration measured will include components due to body movement and gravitational acceleration. This then presents a challenge to subtract the gravitational component from the accelerometer signals without knowing the direction of the sensor. In this case, inclination information may need to be obtained from other sensors such as gyroscopes.

There have been many studies of posture and motion classification using accelerometers. Different algorithms, placements of sensors and numbers of sensors needed have been explored. Veltink et al. (1996) demonstrated the use of accelerometers in static and dynamic activities detection by applying a threshold on the time variation component of the accelerometer signal.

Foerster and Fahrenberg (2000) employed a reference pattern based classification to identify different postures and motions. The method of classification used by these authors (Foerster and Fahrenberg 2000) proved to be very accurate; however the reliability of the method over time was not discussed. If the initial reference patterns were recorded just before the data collection, the high accuracy might have been due to participants remembering the posture of the previous recording thus producing similar patterns during the actual data collection. A longitudinal study comprising repeated measurements over an extended period of time would verify the repeatability of this classification system.

Culhane and co-workers (2004) on the other hand discriminated static and dynamic activities using a fixed threshold classification. It was found that the accelerometer method was able to detect different static activities with a 92% success rate. This study however was carried out with only 5 participants. This area of study was further investigated by the same authors and published as Lyons et al. (2005), a similar method was used but only 1 participant was measured in this study, a successful identification rate of 90% was obtained in identifying static postures with their approach. The small sample size of both studies may subject the findings to doubt, and a larger population should be studied to ensure the configurations of these studies are truly viable for discriminating different static postures. The authors of these 2 studies aimed to evaluate the accuracy of accelerometer based mobility measurements over an extended period in an uncontrolled setting, and to establish a threshold for the identification of standing, sitting and lying postures. However with only a sensor attached to 1 thigh, this set up may not have been sufficient for posture discrimination especially in an uncontrolled setting, where misdetection could easily occur, for instance if the participant lifted the leg with the sensor attached and rested it on a higher surface during standing, the angle of the thigh sensor may fall into the sitting threshold designed by the study; this scenario may also be true for the 2 other studies discussed above. However there was no report on this type of misdetection being reported by the authors (Culhane et al. 2004; Lyons et al. 2005). Identifying different static and dynamic activities can only be used to monitor activity levels and postural behaviour of individuals; in order to gain further information on the adopted spinal angles and orientations, the angles of the measured segment can be obtained by further computation.

Some other physical activity monitoring studies that have utilised accelerometers included a study carried out by Steele et al. (2000) in which the authors aimed to validate the use of triaxial accelerometer for measurement of walking and daily activity in chronic obstructive pulmonary disease patients. Steele et al. (2000) claimed that accelerometers are reliable, valid and stable in walking and daily physical activity measures. Uiterwaal et al. (1998) also reported that accelerometer systems are reliable in monitoring physical activity in working situations; Haeuber et al. (2004) observed high accuracy and reliability of an accelerometer monitoring system in quantifying ambulatory activity levels in stroke patients; and Mathie et al. (2003) found high sensitivity (0.98) and specificity (>0.88) in detecting daily physical activities using accelerometers. In a study carried by Janssen and colleagues (2005), it was found that accelerometer data was closely correlated with data from opto-electronic systems during sit to stand movements and the authors concluded that accelerometer data was significant to detect kinematic events.

MEMS accelerometers are a popular device in gait studies (Kavanagh et al. 2006; Moe-Nilssen and Helbostad 2004). Bussmann et al. (2000) performed a study to verify the feasibility of accelerometers in gait analysis and it was suggested a proper filtering algorithm that remove gravitational component may further improve the feasibility. Sekine et al. (2000) were able to classify and distinguish level walking, stair climbing and stair descent by using a triaxial accelerometer with wavelet transformation analysis. Other studies that used accelerometers in gait analysis included those by Moe-Nilssen and Helbostad (2004) who concluded that accelerometers can be used to provide cadence, step length and measures of gait regularity and symmetry during locomotion. Moe-Nilssen and Helbostad (2005) further reported that fit and frail older adults could be differentiated by studying the accelerometer signals during gait; Mansfield and Lyons (2003) found accelerometer based systems are valid in detecting heel contact events during walking and Kavanagh et al. (2006) suggested accelerometers were reliable in 3D acceleration of head, neck, trunk and lower leg during walking over a range of speeds.

Accelerometers are also used in ambulatory monitoring and are often used to estimate energy expenditure (Bouten et al. 1997; Chen and Sun 1997; Karantonis et al. 2006). Bouten et al. (1997) found that the accelerometer data underestimated energy expenditure during intensive activities and overestimated energy expenditure during sedentary activities, however the results showed that a significant relationship (correlation coefficient of 0.89) between accelerometer output and energy expenditure. Chen and Sun (1997) also used triaxial accelerometers to estimate energy expenditure in daily activities and observed similar results to those reported by Bouten et al. (1997). The authors (Chen and Sun 1997) suggested the accuracy of the estimation depended on the mathematical models used in the study, they proposed that a generalised model that incorporates participants' body mass index, height, age and gender yielded a higher accuracy in energy expenditure estimation.

Wong and Wong (2008a) used accelerometers to detect changes in sagittal and coronal spinal postures of 3 healthy participants during sitting by means of inclination calculation. Wong and Wong (2008a) found that triaxial accelerometer systems are feasible for detecting change in static calibrations with an RMS error of less than 1° however when using an opto-electronic system as a reference, error in detecting spinal change was relatively large during dynamic conditions (RMS error of about 10°) when compared to static conditions (RMS error of <5°). As the accelerometers measure acceleration due to movement and due to gravity, it is not possible to use the same inclination calculation as used during static conditions to estimate inclination during dynamic conditions. In order to obtain the true inclination of the spinal segments during dynamic condition, the inclination of sensors has to be known in order to deduct the gravity component from the resultant acceleration. However this has to be achieved with the use of other sensors, such as gyroscopes. This may explain the errors experienced by Wong and Wong (2008a), though their work does demonstrated that accelerometers can be used in spinal posture measurement during static conditions.

Accelerometers have been the favoured choice in physical activity and ambulatory monitoring, gait analysis and spinal posture measurement. However with the use of accelerometers alone lacks inclination information during movement, this limits the application of the system to a smaller context. Though, integrating the accelerometer system with a system that is capable in providing rotational orientation during movement, such as gyroscopic system, could greatly improve the usability in a various applications. An integrated inertial measurement system is introduced and its current applications are discussed in the next section.

3.3.3 The integrated system – Inertial Measurement Systems

As discussed in Sections 3.3.1 and 3.3.2, gyroscopes measure angular velocity while accelerometers measure acceleration of the object or body segment where the sensors are attached. Integrating these 2 sensors into a system will yield a powerful inertial measurement system that can provide 6 essential kinematic parameters: angular velocity, attitude, linear acceleration, velocity, displacement and inclination. An inertial measurement system typically consists of 3 dimensional sensors in order to provide kinematic information in 6 degrees of freedom. The inertial measurement system is often referred to as the strapdown inertial measurement system due to the fact that the coordinates of this system are not fixed in space but are constantly moving with the object or the body segment where the inertial measurement system is attached. Some inertial measurement systems also include magnetic sensors to form a more robust and accurate system by using the magnetic data to correct any axial drift of gyroscopes.

Inertial measurement systems have been used in various areas of kinematic measurement, for instance in detecting human knee angles and angular velocity (Williamson and Andrews 1999); in measuring lower limb movements (Dejnabadi et al. 2006; Mayagoitia et al. 2002; O'Donovan et al. 2007; Picerno et al. 2008; Veltink et al. 2003; Williamson and Andrews 2001); upper limb motion measurement (Luinge et al. 2007; Zhou and Hu 2007; Zhou et al. 2008); and monitoring daily physical activity (Najafi et al. 2003).

In the study that monitored daily physical activity of the elderly by Najafi et al. (2003), the authors claimed that the results of the study showed high success rate (sensitivity of 99%) in detecting postural transitions. Boonstra and co-workers (2006) studied the spinal kinematics of rising from a chair with accelerometers and gyroscopes, where the authors concluded that the inertial measurement systems were capable in providing an accurate measure of kinematic movement during rising from a chair. Plamondon et al. (2007) utilised inertial measurement systems with a potentiometer in spinal posture measurements during lifting movements and concluded that inertial measurement systems could be useful in quantifying 3 dimensional spinal postures and motion.

Studies by Wong and Wong (2008b; 2008c) showed that inertial measurement systems are viable for monitoring spinal postures during daily activities. The authors defined the participants' natural spinal curvature as the good posture for the feedback system to prompt the participants to resume a posture that was in the tolerable range. The authors reported that the sagittal spinal postures of the 5 participants differed significantly between trials, with the trial days without the feedback system resulting in higher mean sagittal lumbar flexion in the participants than trial days when the feedback system was turned on. The authors concluded that a feedback system could be used in training and to improve posture. However this study was only performed over a period of 4 days and consequently it is difficult to anticipate the long term effect of training by the feedback system, a further longitudinal study with larger sample size may further validate the reliability of this application. Another plausibility factor in the study was that the authors assumed the neutral standing posture as the "good posture" and used this as a reference; however this posture may not be feasible to adopt during other activities, such as relaxed sitting. As discussed in Section 2.4, it is necessary to alternate flex and lordose posture in order to provide periodic rest from static loading, however if the feedback system restricts posture to within a small range of movement, it may not necessary correct posture but induce a static load to the spinal structures for prolonged periods. Therefore a carefully defined feedback mechanism that takes into consideration the biomechanical properties of different spinal structures in different postures is needed for such applications.

Goodvin et al. (2006) examined the accuracy of an inertial measurement system (MT9 Xsens) in spinal motion measurement using an opto-electronic system as a reference. The authors found that the inertial measurement system was an accurate movement measurement method when compared to an opto-electronic system, with results within 3.1° of the orientation recorded by the opto-electronic system.

Although an integrated inertial measurement system provides better accuracy in kinematic measurement, a drift correction algorithm is necessary to rectify the drift error incurred by gyroscopes unless this can be eliminated at source. Due to this limitation, many researchers have suggested the design of an inertial measurement system without the use of gyroscopes (Giansanti et al. 2003; Padgaonkar et al. 1975). Gyroscope free inertial measurement systems have been used to measure the angular acceleration with the use of 6 (Giansanti et al. 2003; Hung and Lee 2006; Hung et al. 2006), 9 (Padgaonkar et al. 1975; Wang et al. 2003; Yoganandan et al. 2006) and 12 linear accelerometers (Zappa et al. 2000). However these multiaxial accelerometer systems are prone to errors due to inaccurate sensor positioning and misalignment of the axes within the assembly, and the response (offset and sensitivity) of each accelerometer (Hung et al. 2006; Giansanti et al. 2003). The position and orientation estimation by these systems were found to be inaccurate even for a short duration of analysis (4s as reported by Giansanti et al. 2003 and 0.1s as reported by Padgaonkar et al. 1975). Giansanti et al. (2003) suggested that multiaxial accelerometer systems are not suitable for position and orientation measurement of body segments. Most of these studies were based on theoretical mathematical models and simulations (Giansanti et al. 2003; Hung and Lee 2006; Hung et al. 2006; Wang et al. 2003; Zappa et al. 2000), without any experimental validation, or were only tested on mechanical jigs (Padgaonkar et al. 175; Yoganandan et al. 2006). More studies are needed in this area in order to determine whether these systems are appropriate for human movement measurement.

Inertial measurement systems have been proved to be feasible for use in various aspects of human posture and movement monitoring and measurement. However there have not been many studies measuring 3 dimensional lumbar spinal posture and motion. More studies are needed in order to provide better knowledge in these areas.

3.4 Summary and conclusions

There are many different methods of spinal posture and motion measurement available; however these methods differ from each other in size, cost, accuracy, ease of use, invasiveness, and planes of measurement. Each measurement method has its advantages and disadvantages depending on the study design. Studies of spinal posture have mainly been performed in 1 or 2 planes over a short period of time in a laboratory and this may not provide information directly relevant to true/natural postural measurements of the normal population. Spinal motion studies have been focused mainly on ranges of movement measurements; however this is not adequate to quantify normal motion of the spine in normal daily life. Two dimensional measurements of the spine do not provide a complete picture of spinal posture and motion; while the laboratory based 3 dimensional measurement methods such as radiography, opto-electronic tracking systems and electromagnetic tracking systems, are not suitable for long term, out of laboratory measurement due to their invasiveness (radiography), size and constraints caused by long cables and constrained observation space. MEMS Inertial measurement systems address these limitations due to their small size, low power consumption and portable capability. Gyroscopes are capable of measuring angular velocity while accelerometers can be used to measure acceleration and inclination during static conditions. By integrating these 2 sensors into a measurement system it is possible to provide both position and orientation information of the object being studied. Despite the large number of studies on human posture and motion assessment using inertial measurement systems, not many studies have been undertaken which have measured lumbar spinal posture and motion in particular. This area of knowledge needs to be further established.

Inertial measurement systems enable the possibility of 3 dimensional spinal posture and motion measurements outside the laboratory. However, the feasibility of these systems for use in spinal posture and motion measurements first needs to be validated.

Chapter 4. Study to determine the validity of inertial measurement systems in posture and movement measurements

4.1 Overview

Chapter 3 has shown that inertial measurement systems have gained popularity in the measurement of human posture and movement and that they may be a useful measurement system for monitoring postural position and movement. However as inertial measurement systems are still a relatively new technique in human measurement, it is essential to examine the suitability, validity and reliability of these systems in posture (inclination) and movement measurement. This chapter presents the findings of a study to validate inertial measurement systems in movement and inclination measurements.

In this study, the validity of the movement measured using inertial measurement systems was examined through calibration with a rotating device and comparison with data measured using an electromagnetic tracking system as the reference system. Electromagnetic tracking systems have been widely used in human motion tracking and found to be a very accurate method of spinal movement measurement (Burnett et al. 1998; Mannion and Troke 1999; Pearcy and Hindle 1989). As electromagnetic measurement systems are also skin surface measurement techniques similar to the inertial measurement systems, comparison between these 2 measurement methods was more directly relevant.

The validity of inertial measurement systems in posture or inclination measurement was also calibrated and examined using the true gravitational and ground axes as the references. The sections below discuss the methods, results and conclusions from these experiments.

4.2 Calibration of the inertial measurement system

This experiment was designed to calibrate inertial measurement systems in rotational movement.

The inertial measurement system used in this study was the Xsens MTx system (Xsens Technology), each inertial sensor comprising of triaxial gyroscopes, accelerometers and magnetometers. The dimensions of each individual sensor were 38x53x21mm and each weighed 30g. The Xsens system provided communication using Bluetooth technology to transfer information to a personal computer or handheld device. The manufacturer's data claims that the Xsens MTx system has a static accuracy of 0.5° for roll and pitch, 1° for yaw and 2° RMS dynamic accuracy.

A calibrated turntable was used to provide the rotational movement in this experiment. The turntable was capable of producing different rotational speeds in both clockwise and anticlockwise directions using a stepper motor and its control circuits.

4.2.1 Methods

The 250mm diameter turntable used in this experiment had been previously designed and built for the use in digital image capture applications and had a claimed accuracy of better than 1°/s in rotational speed. This accuracy was verified at rotational speed of up to 96°/s (16rpm) by manually counting complete revolutions using a marker on the turntable against an adjacent fixed point, estimated to give a maximum error of 1mm at the circumference equating to 1.44°. This was completed at 4, 8, 12 and 16rpm, counting revolutions for 1 minute in each case. None of these calibration exercises resulted in more than 2mm deviation from precise alignment of the turntable marker at the end of the minute, leading to a worse case error of 2.88° in the minute, which was equivalent to 0.05°/s, this being considerably better than the claimed 1°/s accuracy.

Consequently the turntable was considered to be a calibrated reference for rotational speeds over this range.

A wooden block was used on the turntable as the base of attachment for 2 Xsens sensors. The wooden block was secured on the turntable by double sided tapes. The Xsens sensors were oriented in 3 configurations with each of the 3 sensitive axes of the triaxial gyroscopes aligning with the axis of rotational of the turntable, as shown in Figures 4.2.1 to 4.2.3. The sensors were securely attached to the wooden block using double sided tapes and the alignments of the sensors to the rotational axis of the turntable were ensured using spirit levels with an estimated accuracy of ±1°.

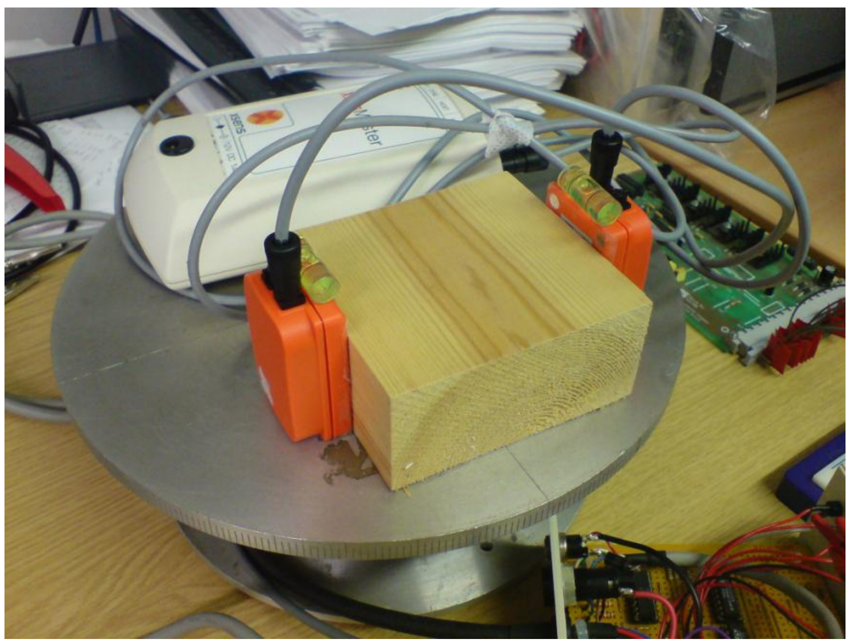


Figure 4.2.1: Experimental configuration for rotational measurement of X axes of the Xsens sensors

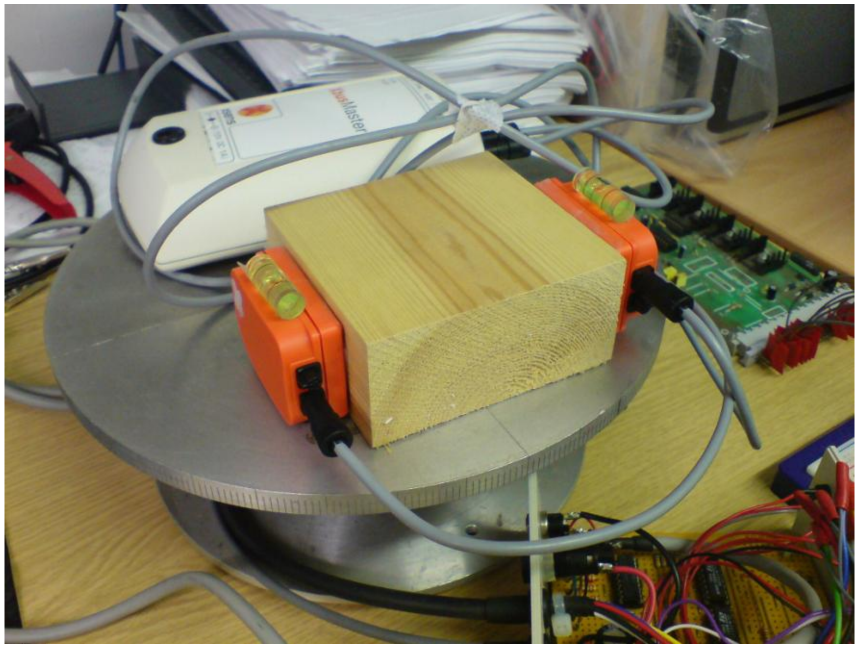


Figure 4.2.2: Experimental configuration for rotational measurement of Y axes of the Xsens sensors

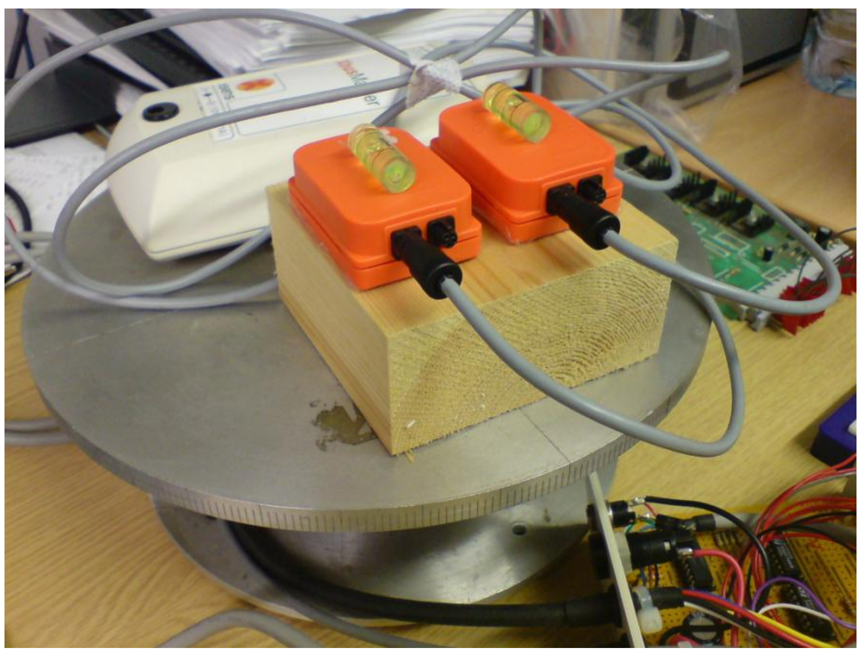


Figure 4.2.3: Experimental configuration for rotational measurement of Z axes of the Xsens sensors

Four different rotational rates were tested: 24°/s (4rpm), 48°/s (8rpm), 72°/s (12rpm) and 96°/s (16rpm) in both positive and negative directions. The speed of the turntable was controlled by an electronic control unit, calibrated as described above. Five sets of 1 minute data were collected at each rotational rate and direction on each axis, i.e. a total of 120 sets of data were collected in this experiment. The data were collected with a sampling rate of 100 samples/second. The collected gyroscopic data were compared against the tested rotational rates to study the correlation and validity of the system in rotational movement measurement.

4.2.2 Results

Table 4.2.1 shows the data collected by the Xsens system with respect to the preset rotational rates of the turntable. Table 4.2.1 shows that the Xsens system produced matching rotational rates with the tested rotational rates produced by the turntable, with maximum error of 1°/s.

	Sensor 1 (°/s)			Sensor 2 (°/s)		
Turntable rate (°/s)	**X**	**Y**	**Z**	**X**	**Y**	**Z**
-96	-95.7	-96.0	-95.9	-95.5	-95.9	-95.9
-72	-71.8	-72.0	-71.9	-71.5	-72.0	-71.9
-48	-47.6	-47.8	-47.8	-47.3	-47.7	-47.8
-24	-24.1	-24.3	-24.3	-23.7	-24.0	-24.1
0	0.1	-0.1	-0.3	0.1	0.4	0.1
24	23.6	23.3	23.5	24.1	24.0	23.7
48	47.5	47.0	47.2	47.8	47.4	47.3
72	71.6	71.2	71.6	71.9	71.7	71.7
96	95.6	95.1	95.3	96.0	95.7	95.6

Table 4.2.1: Comparison of the rotational data collected by each axis of the triaxial gyroscopes of the Xsens system with the tested known rotational rates of the turntable

The calibrated data showed that the Xsens system was valid in rotational movement measurement by showing highly correlated results ($R^2 = 1$) when compared to known rotational rates, as shown in Table 4.2.2.

	Sensor 1 (°/s)			Sensor 2 (°/s)		
	X	Y	Z	X	Y	Z
Sensivity	0.995	0.994	0.996	0.996	0.997	0.997
Offset	-0.089	-0.397	-0.298	0.228	-0.041	-0.148
Regression R^2	1.000	1.000	1.000	1.000	1.000	1.000

Table 4.2.2: Regression and calibration data of the gyroscopes of the Xsens system when tested against known rotational rates of the turntable

4.2.3 Discussion

The gyroscopes of the Xsens sensors were calibrated against a set of rotational rates of a turntable and the data were within the specifications claimed by the manufacturer. The results showed that the Xsens system was a valid system for use in rotational movement measurement with a maximum error of less than 1°/s and regression R^2 of 1 when compared to preset rotational rates of the turntable.

The data was computed using the gyroscope data and hence any possible effect of the surroundings on the magnetometers did not affect the results of this experiment.

4.3 Validation of inertial measurement systems in movement measurement

This experiment aimed to validate inertial measurement systems for 2 dimensional and 3 dimensional movement measurements using an electromagnetic tracking system as a reference.

The Xsens MTx system as discussed in Section 4.2 was used in this experiment. The electromagnetic tracking system used in the current study was the 3Space Fastrak system (Polhemus). The Fastrak system is recognised as a highly accurate measurement system in motion tracking (Burnett et al. 1998; Jasiewicz et al. 2007; Mannion and Troke 1999; Pearcy and Hindle 1989; Saber-Sheikh et al. 2009) and, as discussed in Section 3.2, such electromagnetic tracking systems consist of 2 main components, which are the source that generates reference field vectors and the sensors that detect positions and orientations in space (Ladin 1995; Jordan et al. 2001; Welch and Foxlin 2002). The Fastrak system can be used with up to 4 sensors at a maximum sampling rate of 120 samples/second across all the sensors deployed. Each electromagnetic sensor used was 28x23x15mm in dimension and weighed 17g. The manufacturer's data claims that the Fastrak system has a static accuracy of 0.8mm RMS for sensor position and 1.5° for sensor orientation.

4.3.1 Methods

Two Xsens sensors and 2 Fastrak sensors were used in this experiment.

The experiment was separated into 3 parts, part 1 where the Xsens sensors and Fastrak sensors were used to measure 2 dimensional cyclic movements, part 2 where 3 dimensional random movements were made with only 1 pair of sensors moving, and part 3 where both pairs of sensors were moved in 3 dimensional random movements.

Two dimensional cyclic movements. A wooden hinged joint that had a fixed movement in 2 dimensions was used in this experiment. The base of the wooden hinged joint was clamped to a table with plastic clamps to prevent any undesired movement. An Xsens sensor and a Fastrak sensor were mounted approximately 100mm apart from each other on the base of the wooden hinged joint as the reference sensors (non-moving). The other sensors of both systems were mounted the same distance apart on the moving section of the wooden hinged joint as the moving sensors, as shown in Figure 4.3.1. Five sets of data were collected by moving the wooden hinged joint at random speed and amplitude for 30 seconds per set. Thirty seconds was found to be sufficient to produce a minimum of 10 cycles of movements for comparison.

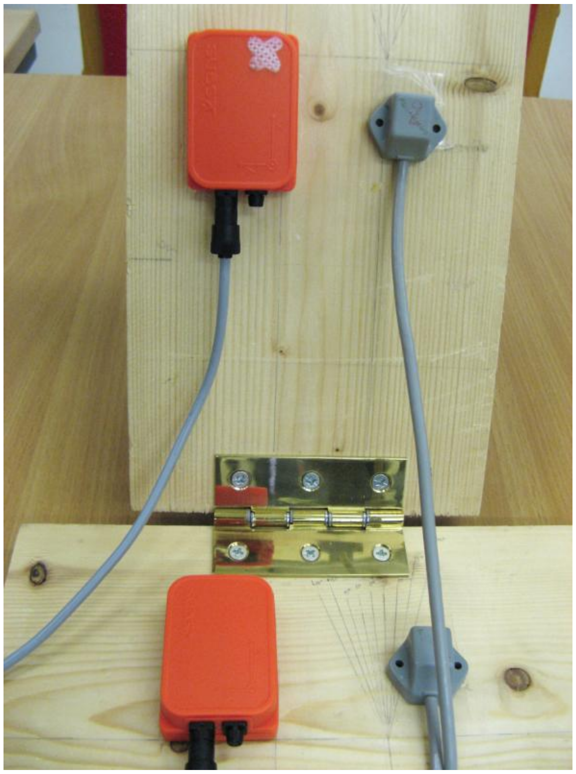


Figure 4.3.1: Experimental configuration for 2 dimensional cyclic movements

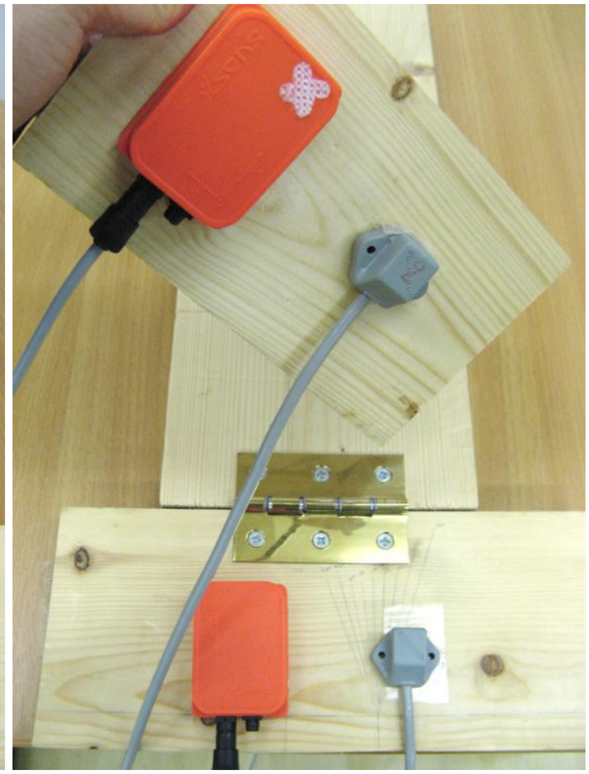


Figure 4.3.2: Experimental configuration for 3 dimensional random movements – 1 pair of moving sensors

Three dimensional random movements – 1 pair of moving sensors. An Xsens sensor and a Fastrak sensor were mounted approximately 100mm apart on the base of the wooden hinged joint as the reference sensors (non-moving) and a sensor of both the Xsens and the Fastrak were mounted the same distance from each other on a free moving wooden block, as shown in Figure 4.3.2. The free moving wooden block was moved randomly in space for a duration of 40 seconds to allow sufficient random movements in all directions being recorded, and this was repeated to acquire 5 sets of data. This part of experiment was designed to test the validity of 3 dimensional movement measurements in a fixed reference frame.

Three dimensional random movements – all sensors moving. One Xsens sensor and 1 Fastrak sensor were mounted approximately 100mm apart from each other on 2 separate free moving wooden blocks as shown in Figure 4.3.3. Both the wooden blocks were moved randomly in space, 5 sets of data were collected and each set of data was collected for 40 seconds to enable sufficient random movements of both moving and reference sensors in all directions being recorded. This part of the experiment was to determine the validity of inertial measurement systems in motion measurement that involved a moving reference frame.

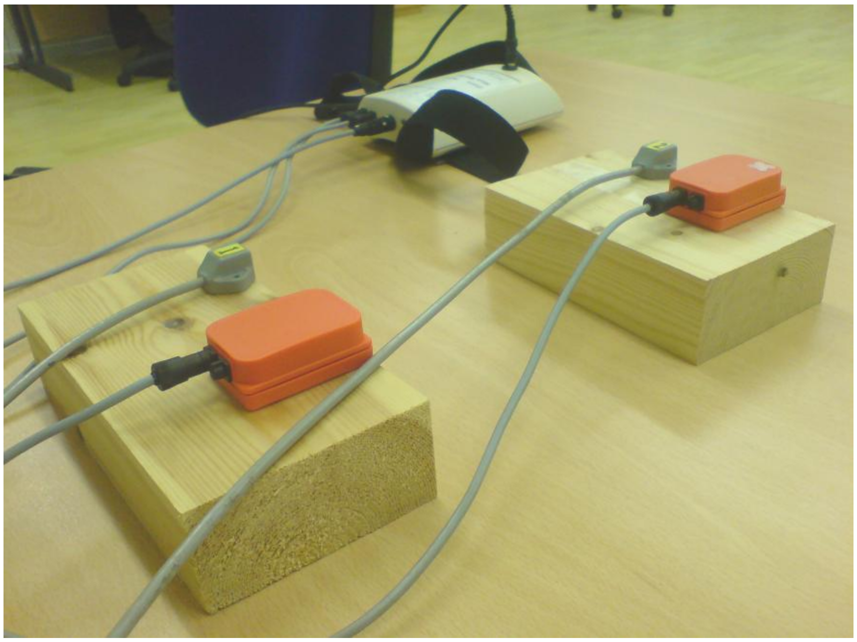


Figure 4.3.3: Experimental configuration for 3 dimensional random movements – all sensors moving

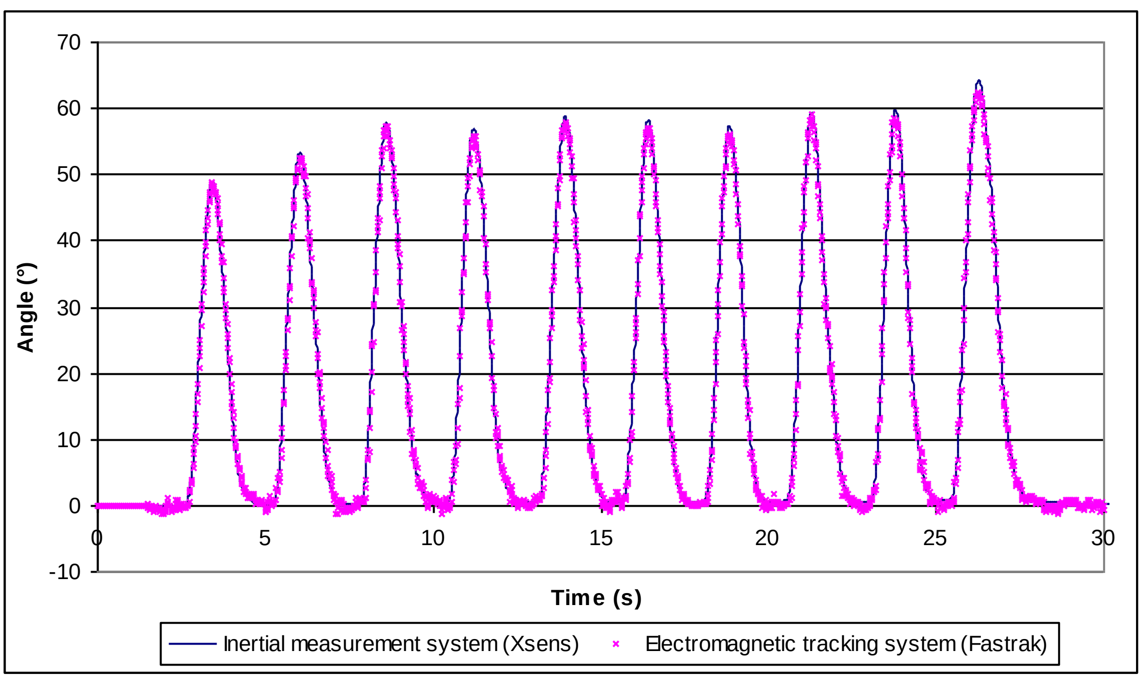
The sensors were securely mounted onto the wooden hinged joint and wooden blocks with double sided tape. Before each set of data collection, neutral position data (no rotation in the plane of movement) of 5 seconds was taken as the initial reference condition for the sensors. The sampling rate for the Xsens sensors was 100 samples/second and 60 samples/second for the Fastrak sensors in both 2 dimensional and 3 dimensional movements, as the Fastrak system had a non-selectable sampling rate whilst the Xsens system did not provide an option of 60 samples/second. The relative angles between the 2 Xsens sensors and the Fastrak sensors were computed using direction cosine matrices and were expressed in 3 anatomical angles by using Euler equations, as described in

Appendix A6.1. The relative angles from the Xsens sensors were then mathematically resampled to 60 samples/second using MATLAB (Matrix Laboratory R2006a, MathWork) software in order to compare them with the relative angles obtained from the Fastrak sensors.

4.3.2 Results

The results showed that both inertial measurement systems (Xsens) and electromagnetic tracking systems (Fastrak) were strongly correlated with high regression R^2 when compared to each other, which ranged from 0.914 to 0.998.

Two dimensional cyclic movements. Graph 4.3.1 shows a typical plotted result of 2 dimensional cyclic movements. The plotted results of all other data sets were similar to Graph 4.3.1, with data computed from both Xsens and Fastrak sensors overlapping each other. These results showed that both inertial measurement by Xsens sensors and electromagnetic sensors by Fastrak sensors produced very similar data.



Graph 4.3.1: Typical plotted result for 2 dimensional cyclic movements, Xsens Vs Fastrak

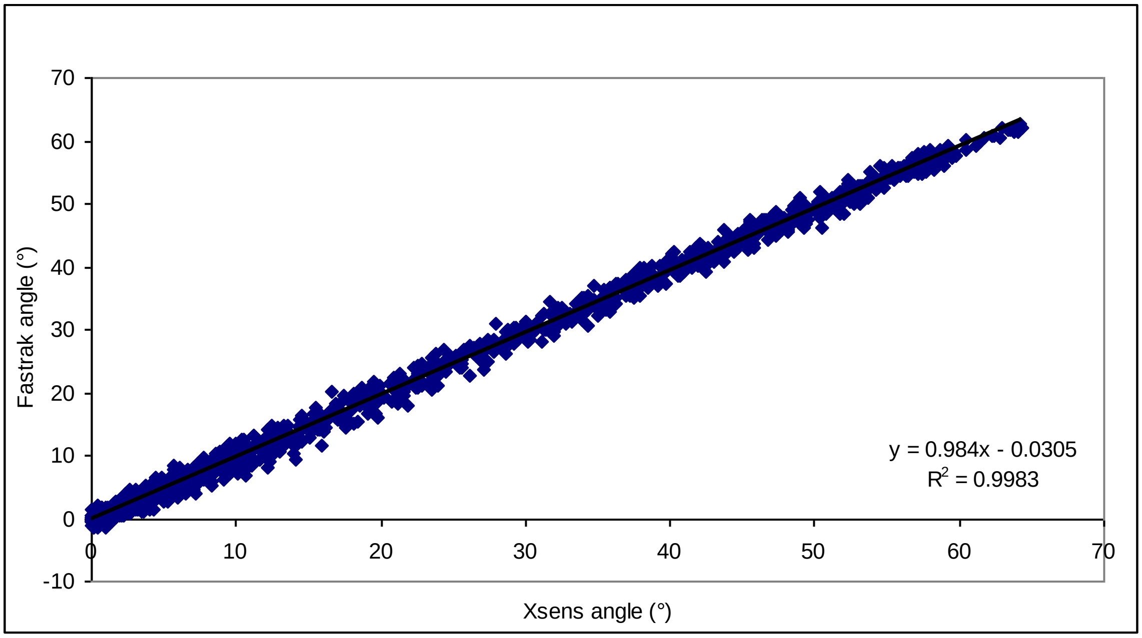
From the results as shown in Table 4.3.1, the data correlated well between the 2 measurement systems, with a maximum offset of 0.388°. When compared to the each other, the regression R^2 was 0.998. The maximum deviation of gradient, m of the regression equation from the value of 1 was calculated to be 0.009. This implied that for 2 dimensional cyclic movement,

Fastrak data = (1.007 x Xsens data) - 0.067°

	Regression R^2	**Gradient, m**	**Intercept, c**
Set 1	0.9976	1.0089	0.2676
Set 2	0.9977	1.0075	0.1364
Set 3	0.9975	1.0033	-0.1911
Set 4	0.9980	1.0063	-0.1597
Set 5	0.9976	1.0084	-0.3883
Minimum	0.9975	1.0033	-0.3883
Maximum	0.9980	1.0089	0.2676
Mean	0.9977	1.0069	-0.0670
Standard Deviation	0.0002	0.0022	0.2648

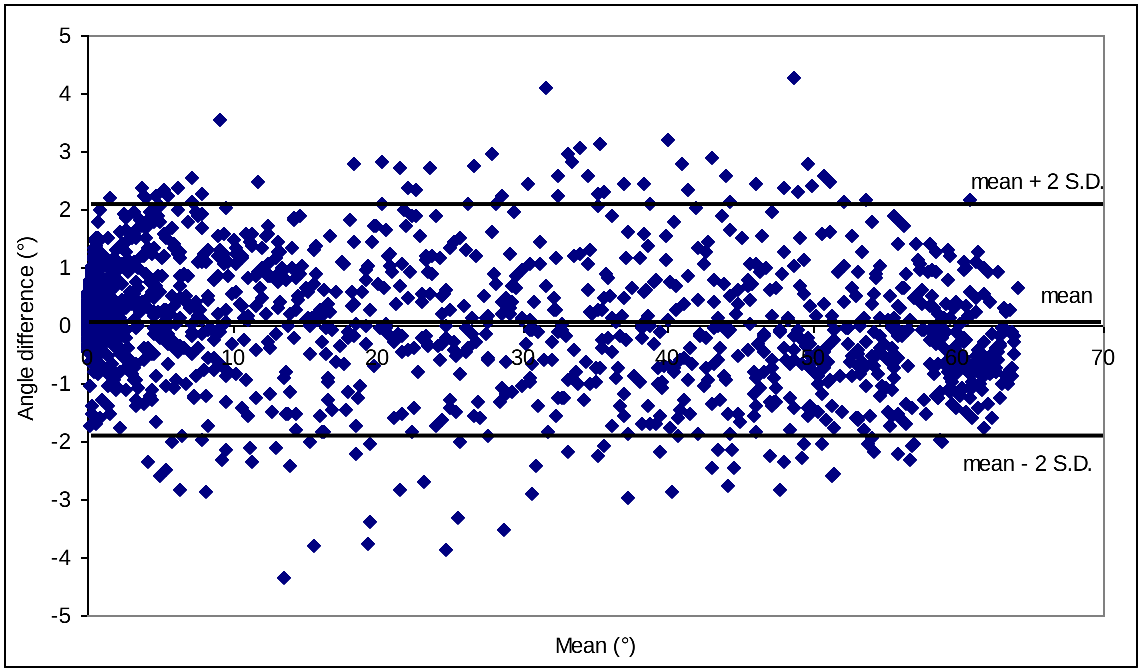
Table 4.3.1: Regression R^2, gradient and intercept of the regression equation between inertial measurement system (Xsens) and electromagnetic tracking system (Fastrak) for 2 dimensional cyclic movements

Graph 4.3.2 shows the total regression plot of all 5 sets of data.



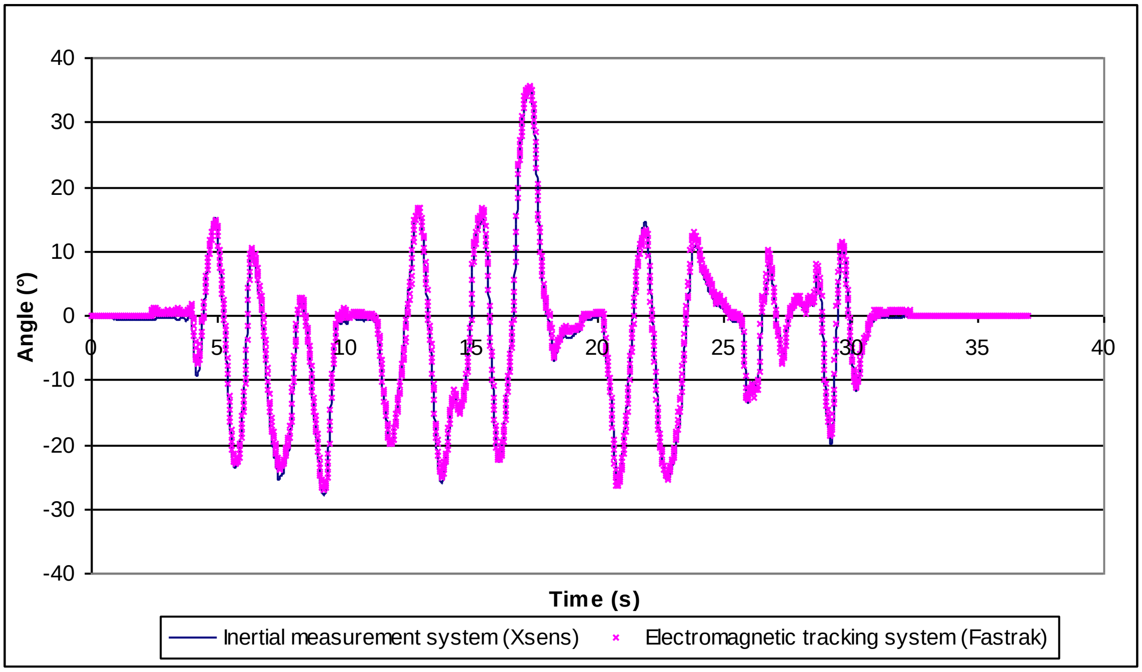
Graph 4.3.2: Total regression plot for 2 dimensional cyclic movements, where the R^2 was 0.998

Graph 4.3.3 shows the distribution of means and angle differences between the 2 measurement systems in 2 dimensional cyclic movement using the Bland and Altman method (Bland and Altman 1986). The x-axis on the graph shows the mean values between the 2 measurement systems while the y-axis shows the angle differences between the 2 measurement systems. Graph 4.3.3 shows that the 2 measurement systems were in good agreement with each other with a mean difference of 0.04° and standard deviation of 0.99°.



Graph 4.3.3: Distribution of means and angle differences on the moving axes for 2 dimensional cyclic movements, where the mean difference was 0.04° and standard deviation was 0.99°

Three dimensional random movements – 1 pair of moving sensors. From Graph 4.3.4, it can be observed that both data from Xsens and Fastrak systems produced plots that overlapped each other. This verified that both systems agreed with each other during 3 dimensional movement measurements with a static reference frame. The plotted results of all other data sets were similar to Graph 4.3.4.



Graph 4.3.4: Typical plotted result for 3 dimensional random movements – moving sensors with respect to non-moving sensors, Xsens Vs Fastrak

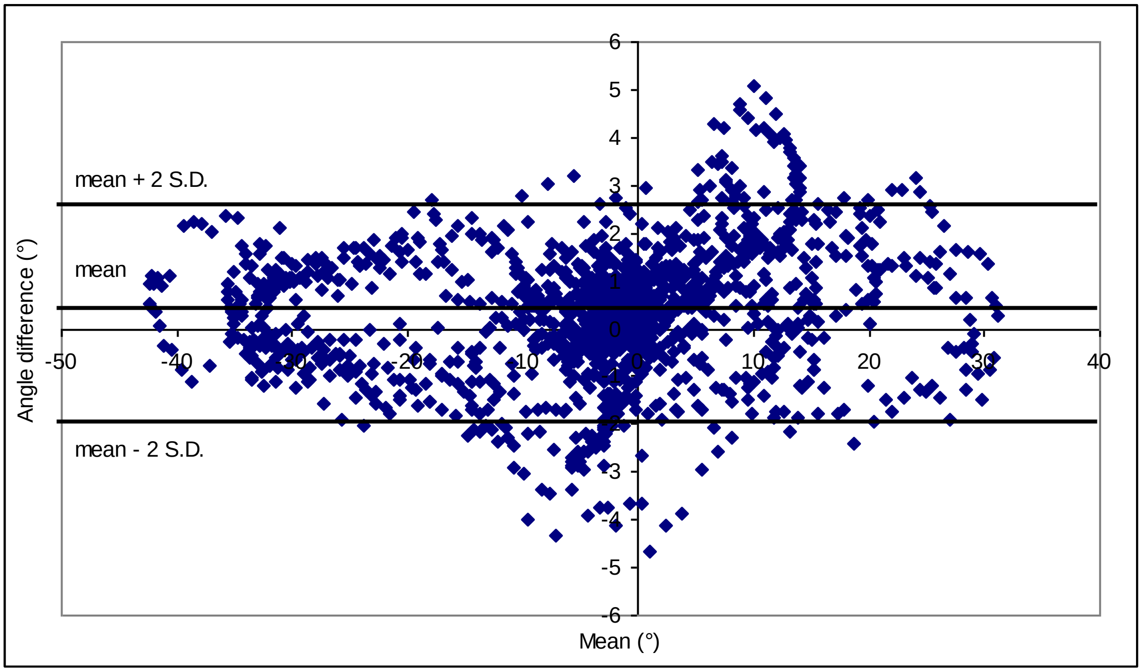
Table 4.3.2 tabulates the regression analysis between data obtained from Xsens and Fastrak systems during 3 dimensional random movements, when only 1 pair of sensors was moved. When the 2 measurement systems were compared, the minimum regression R^2 was 0.984 and the maximum R^2 was 0.991. The maximum deviation of gradient, m of the regression equation from the value of 1 was calculated as 0.02 and the maximum offset was 0.282°. From Table 4.3.2, the relationship between Fastrak and Xsens data during 3 dimensional random movements with only 1 pair of moving sensors can be written as

Fastrak data = (0.993 x Xsens data) + 0.123°

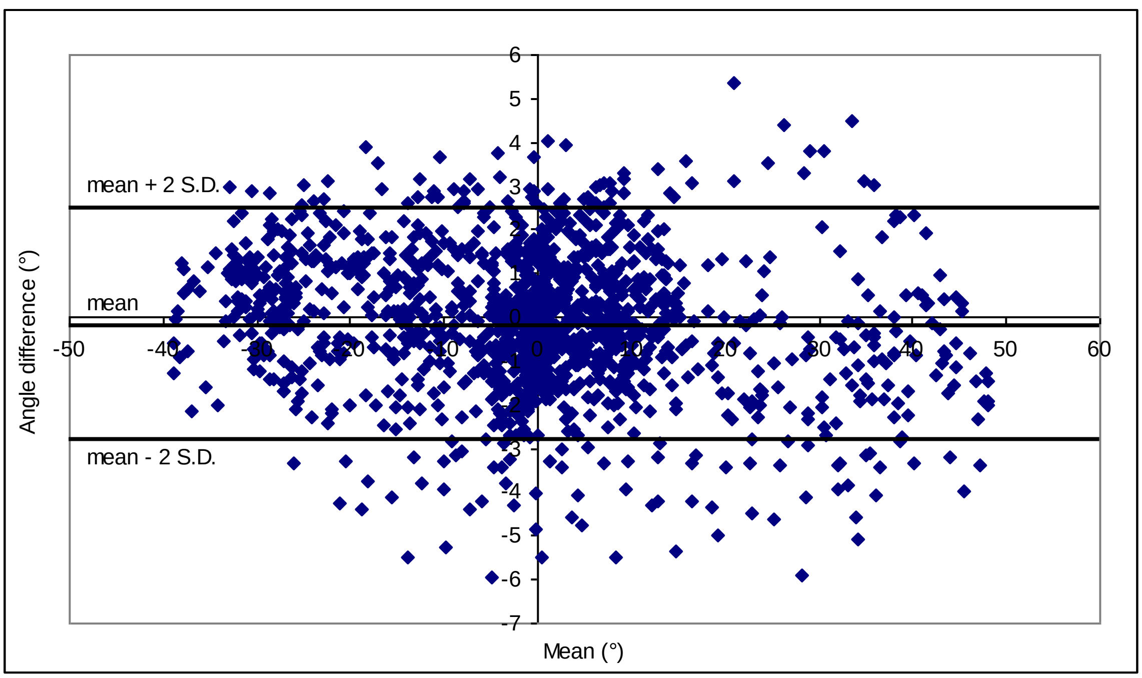
	Regression R^2	Gradient, m	Intercept, c
Set 1	0.9908	1.0106	0.0830
Set 2	0.9839	0.9806	-0.0917
Set 3	0.9907	0.9946	0.2770
Set 4	0.9891	0.9876	0.0658
Set 5	0.9887	0.9902	0.2824
Minimum	0.9839	0.9806	-0.0917
Maximum	0.9908	1.0106	0.2824
Mean	0.9887	0.9927	0.1233
Standard Deviation	0.0028	0.0112	0.1582

Table 4.3.2: Regression R^2, gradient and intercept of the regression equation between inertial measurement system (Xsens) and electromagnetic tracking system (Fastrak) for 3 dimensional random movements – moving sensors with respect to non-moving sensors

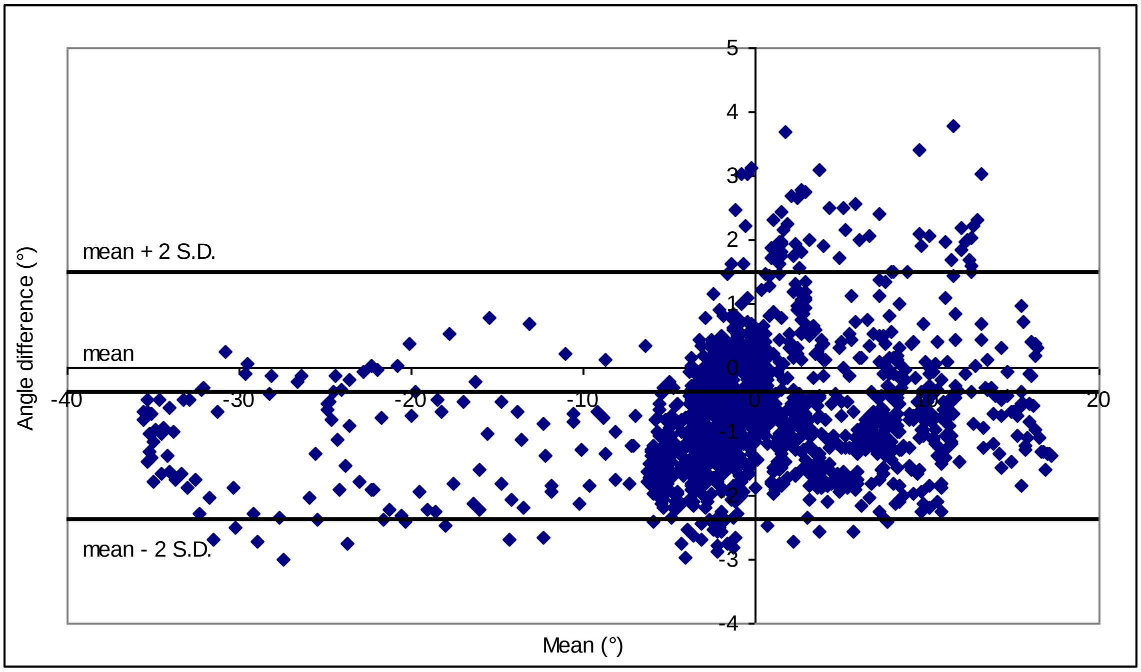
Graphs 4.3.5 to 4.3.7 show the distribution of the means and angle differences on all 3 X, Y and Z axes between the 2 measurement systems during 3 dimensional random movements with the static reference frame plotted using the Bland and Altman (1986) method. Similar to Graph 4.3.3 shown earlier, the x-axis of all 3 Graphs 4.3.5 to 4.3.7 show the mean angle between the Fastrak and Xsens systems while the y-axis of the graphs show the angle difference between these 2 measurement systems. From Graphs 4.3.5 to 4.3.7, both systems showed to be in good agreement with each other, the mean difference was 0.32° (standard deviation was 1.14°) on the X axis, -0.15° (standard deviation was 1.35°) on the Y axis and -0.43° (standard deviation was 0.94°) on the Z axis.



Graph 4.3.5: Distribution of means and angle differences for 3 dimensional random movements – 1 pair of moving sensors, where the mean difference was 0.32° and standard deviation was 1.14° for X axis

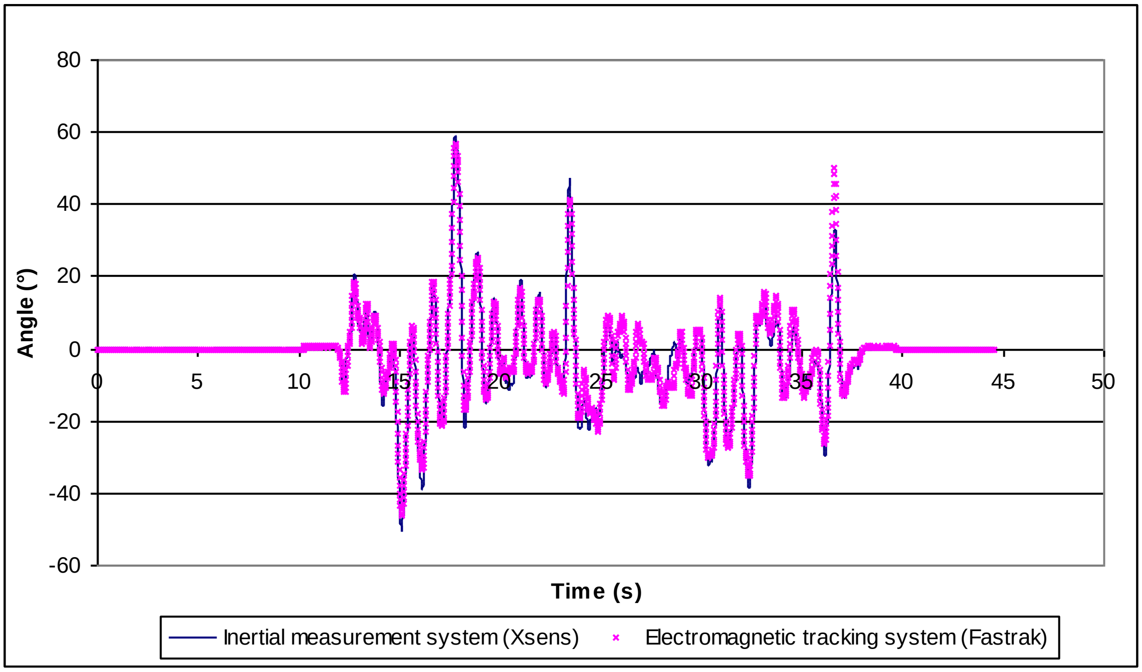


Graph 4.3.6: Distribution of means and angle differences for 3 dimensional random movements – 1 pair of moving sensors, where the mean difference was -0.15° and standard deviation was 1.35° for Y axis



Graph 4.3.7: Distribution of means and angle differences for 3 dimensional random movements – 1 pair of moving sensors, where the mean difference was -0.43° and standard deviation was 0.94° for Z axis

Three dimensional random movements – all sensors moving. By moving both pairs of sensors randomly, a typical plotted result as shown in Graph 4.3.8 was obtained. The plotted results of all other data sets were similar to Graph 4.3.8, with data computed from both Xsens and Fastrak sensors in agreement with each other.



Graph 4.3.8: Typical plotted result for 3 dimensional random movements – all sensors moving, Xsens Vs Fastrak

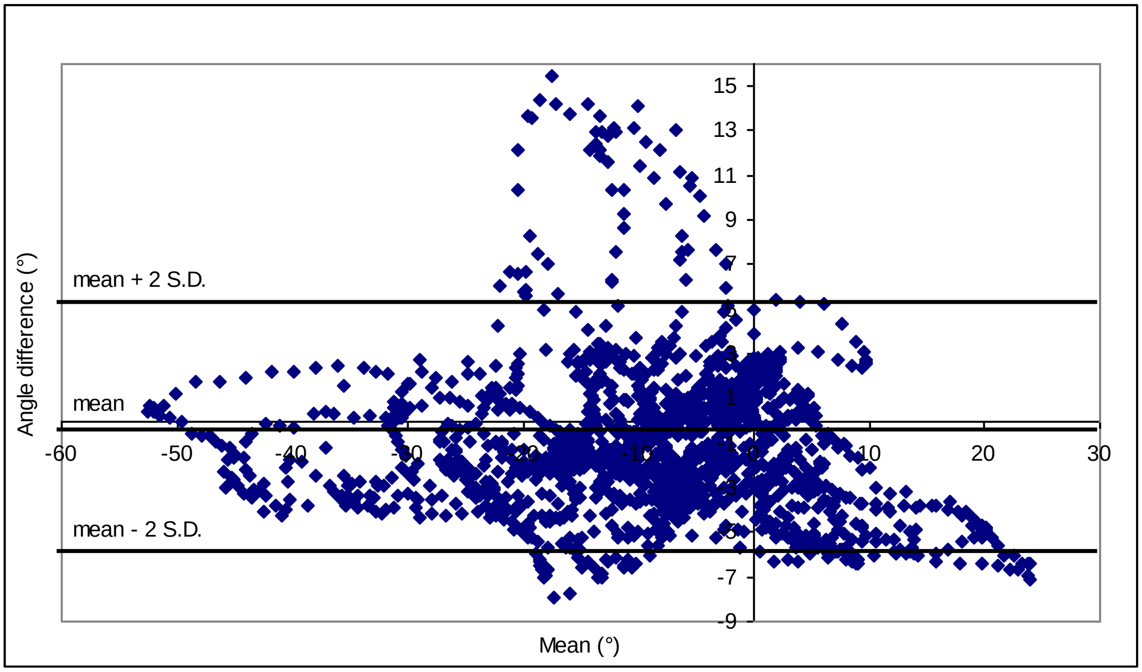
Table 4.3.3 shows the regression analysis obtained from Xsens and Fastrak systems during 3 dimensional random movements, when both pairs of sensors were moving randomly during data collection. From the results, most data showed good agreement between the 2 measurement systems but was less closely correlated when compared to the results of the 2 dimensional cyclic movements and the 3 dimensional random movements with a static reference sensor. When the 2 measurement systems were compared to each other, the minimum regression R^2 was 0.914 and the maximum R^2 was 0.961. The maximum deviation of gradient, m of the regression equation from the value of 1 was calculated as 0.08, and the maximum offset was 0.798°. Based on Table 4.3.3, the association between Fastrak and Xsens systems in 3 dimensional random movement with moving reference frame can be written as

Fastrak data = (0.970 x Xsens data) - 0.410°

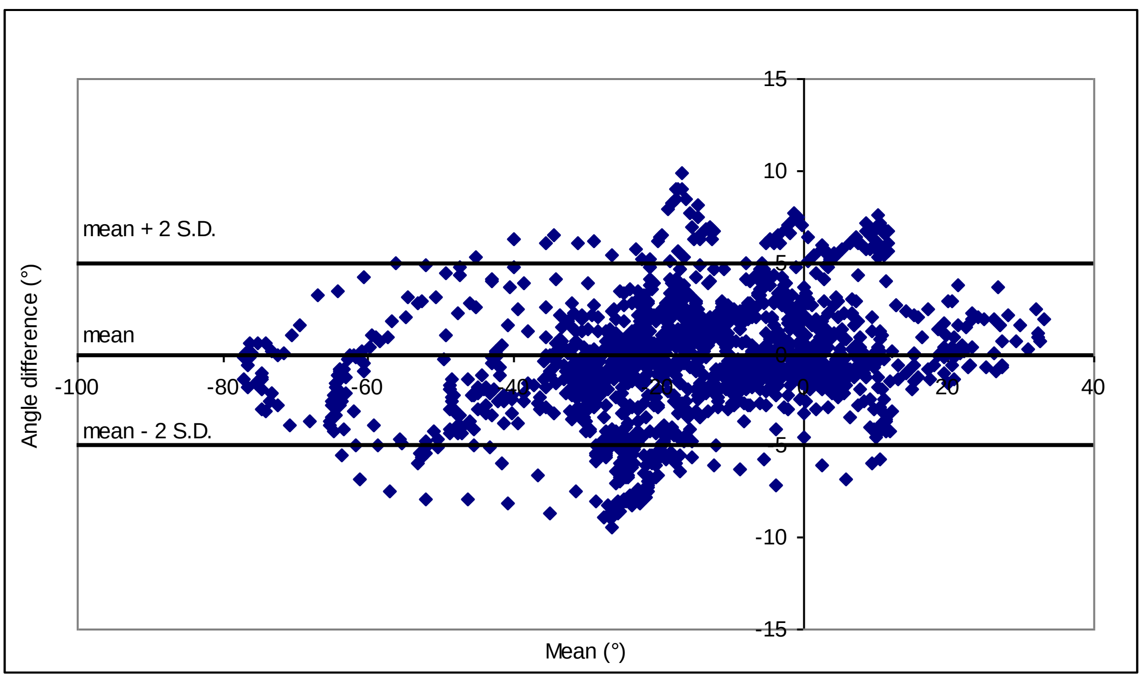
	Regression R^2	Gradient, m	Intercept, c
Set 1	0.9465	0.9660	-0.7398
Set 2	0.9612	0.9749	0.2284
Set 3	0.9142	0.9228	-0.0266
Set 4	0.9269	0.9985	-0.7981
Set 5	0.9392	0.9864	-0.7120
Minimum	0.9142	0.9228	-0.7981
Maximum	0.9612	0.9985	0.2284
Mean	0.9376	0.9697	-0.4096
Standard Deviation	0.0181	0.0289	0.4757

Table 4.3.3: Regression R^2, gradient and intercept of the regression equation between inertial measurement system (Xsens) and electromagnetic tracking system (Fastrak) for 3 dimensional random movements – all sensors moving

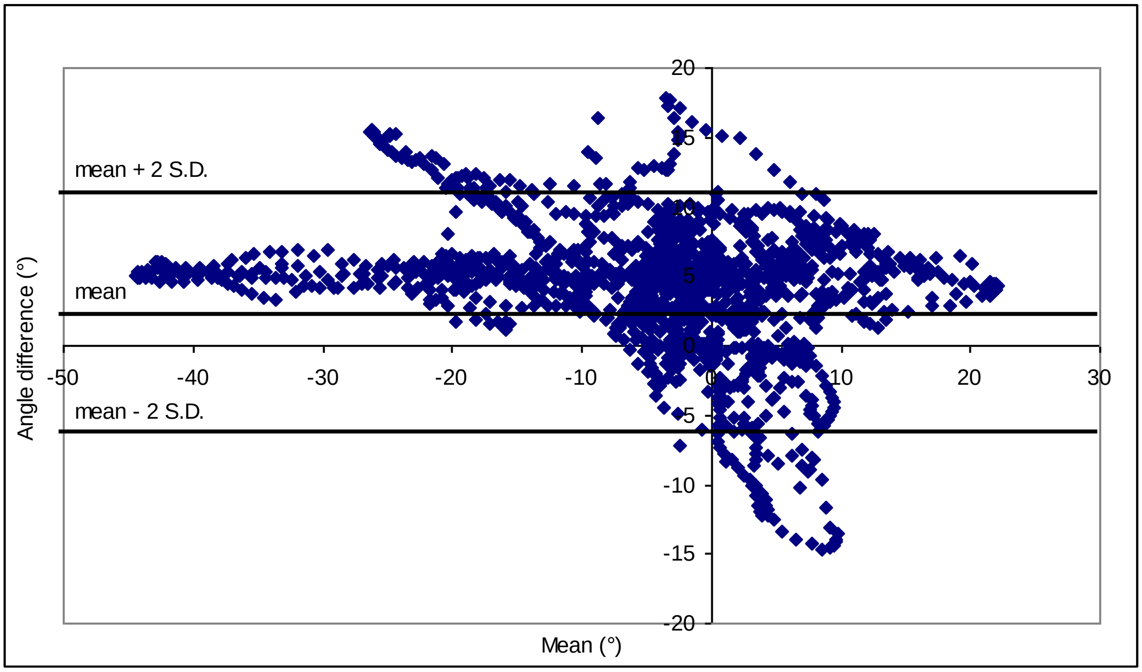
Graphs 4.3.9 to 4.3.11 show the plotted distribution of means and angle differences between the 2 measurement systems during 3 dimensional random movements when both sensors were moved in space using the Bland and Altman method (1986), where the x-axis shows the mean angles and y-axis shows the angle difference between the 2 measurement systems. From the graphs (Graphs 4.3.9 to 4.3.11), it can be seen that both measurement systems showed good agreement with each other. However the agreement was not as high as for 2 dimensional cyclic movement and 3 dimensional static reference frame sensor, especially on the Z axis. The mean difference on the X axis was reported to be -0.39° (standard deviation was 2.78°), -0.11° (standard deviation was 2.46°) on the Y axis and 2.33° (standard deviation was 4.26°) on the Z axis.



Graph 4.3.9: Distribution of means and angle differences for 3 dimensional random movements – all sensors moving, where the mean difference was -0.39° and standard deviation was 2.78° for the X axis



Graph 4.3.10: Distribution of means and angle differences for 3 dimensional random movements – all sensors moving, where the mean difference was -0.11° and standard deviation was 2.46° for the Y axis



Graph 4.3.11: Distribution of means and angle differences for 3 dimensional random movements – all sensors moving, where the mean difference was 2.33° and standard deviation was 4.26° for the Z axis

4.3.3 Discussion

Inertial measurement systems (Xsens) comprising 3 orthogonal axes of gyroscopes, accelerometers and magnetometers have been shown to be a valid system for measuring angular movements when compared to the results obtained from the electromagnetic tracking system (Fastrak).

During the experiment, the magnetometers of the Xsens system were found to interfere with the Fastrak system as both systems are sensitive to magnetic disturbance; this effect was especially obvious with the Fastrak sensors as the Kalman filter used by the Xsens system could correct magnetic distortion experienced by the magnetometers. The closer that both sensors were placed together, the worse the interference was due to the stronger interaction between the magnetic fields. In this experiment, it was found that no interference effects were evident if the sensors were placed more than 100mm apart. Also during the experiments, the Fastrak sensors needed to be as close as possible to the source of the electromagnetic systems in order to minimise the interference with the Fastrak data, with distances beyond 50mm leading to erroneous results. The hinged joint used in the data collection for 2 dimensional cyclic movements was made of metal, though no magnetic interference was observed in the Fastrak or Xsens data.

A factor that could have contributed to the measurement difference between the Xsens and Fastrak systems in this experiment was the alignment of the sensors of both systems relative to each other. Although special care was taken to align the axes of the sensors of both systems to the same coordinate frame, it was not possible to align these axes perfectly on the hinged joint and wooden blocks due to parallax effects.

From the results, the agreement between the data obtained from both systems was lowest when both pairs of sensors were moved randomly in a 3 dimensional frame, and were best in agreement during 2 dimensional cyclic movements. For spinal movement measurements, the condition would be closer to the configuration where both body and reference sensors moved in a 3 dimensional manner. Although with a less correlated comparison when compared to static reference sensor configurations, the results of 3 dimensional movements involving the moving reference frame of the Xsens system showed the association was still strong between the 2 measurement systems with a mean regression R^2 of 0.938. Although both the Fastrak sensors were moved in space during this configuration, the position and orientation of these movements were calculated based on the reference states provided by the source of the system, which was static during the whole experiment, the relative angle between the 2 sensors was then calculated from the orientation data of the 2 sensors using a direction cosine matrix and expressed in 3 Euler angles using Euler equations as described in Appendix A6.1. On the other hand, the Xsens system computed the orientation based on the moving local frame of the sensors, from which the relative angle between the sensors was calculated using a similar approach as the Fastrak sensors. During a situation when the direction of angular velocity vectors does not remain fixed in space but is constantly rotating, as in the configuration of 3 dimensional random movements with both Xsens sensors moving, the non-inertially measurable component of the angular motion becomes significant in the computation of orientation (Titterton and Weston 2004). However the computation algorithms used in this study did not take into account this component. Bortz (1970) presented an alternative method in computing rotation angles by deriving a differential equation that takes account of the non-inertially measurable component of the motion. An earlier pilot study (Ha et al. 2009) that compared 4 different orientation computational algorithms for measurement of movements using an inertial measurement system (Onavi Gyrocube 3A) found that the comparison between the orientations computed by Bortz's method and Euler method yielded a mean correlation coefficient of 0.995 and regression R^2 of 0.990 during 3 dimensional random movements. The orientations computation using Bortz's method would require more computational efficiency compared to the method used in this current experiment, as while the difference between the 2 algorithms was found to be small, with a mean angle difference of 5.9°, this difference could also be due to drift correction algorithm used in the study (Ha et al. 2009). In the current experiment, the Xsens system used was integrated with a Kalman filter which is a more effective method for correcting drift errors due to the integration of the accelerometers and magnetometers data and that from the gyroscopes. The computation algorithm used in this current experiment was used throughout this study in order to standardise the algorithm used for both Fastrak and Xsens systems.

The current results were in close agreement with a similar study reported by Saber-Sheikh et al. (2009), in which the Xsens system was compared to the Fastrak system using a 2 dimensional wooden jig and 3 dimensional movements. Saber-Sheikh et al. (2009) reported that the mean difference between the 2 measurement systems during 2 dimensional movements was -0.05°, which compares favourably with the current study which shows a small mean difference of 0.04°. During 3 dimensional movements, Saber-Sheikh et al. (2009) found that the mean differences were -0.69°, -0.4° and -0.28° for the X, Y and Z axes respectively, though there was limited discussion of the conditions under which the 3 dimension movement study was conducted, however through communication with the authors (Saber-Sheikh et al. 2009), the condition for the 3 dimensional movement study was found to be similar to the configuration of the current study when only 1 pair of moving sensors were used. Comparing their results with the similar configuration of the current study, i.e. the configuration of 3 dimensional movements with 1 pair of moving sensors, resulted in comparable small mean differences (0.32°, -0.15° and -0.43° in X, Y and Z axes respectively) as those reported by Saber-Sheikh et al. (2009). However, Saber-Sheikh et al. (2009) did not compare the Xsens system with the Fastrak system in the condition when both of the moving and reference sensors rotated in 3 dimensions, and therefore a full comparison with the current study could not be established.

Jasiewicz et al. (2007) carried out a study to verify the performance of an inertial measurement system (InertiaCube3, Intersense) in cervical range of movement measurement by comparing the results to an electromagnetic tracking system (Fastrak). In the study, 10 healthy participants were recruited to have their cervical head movement measured with a pair of sensors on their forehead and another pair of sensors on their C7 spinous process. The 3 movements tested by Jasiewicz et al. (2007) were flexion, left lateral flexion and left rotation. The authors found that the inertial measurement system was an accurate (0.97 to 0.99 cross correlations and RMS errors of 0.7° to 2.5°) device for head and neck motion measurement when compared to the Fastrak system. Jasiewicz et al. (2007) did not find any strong interference between the 2 systems used in their study, they suggested that was due to the sensors were placed some distance away from the source of the electromagnetic tracking system. However in the current experiment, even with the source of the Fastrak system was placed far from the sensors, the interference was strong between the 2 systems as long as they were placed within

100mm next to each other, this could be due to different inertial measurement systems used in the 2 studies.

In this experiment, the relationship between the Xsens and Fastrak systems in 2 and 3 dimensional conditions were examined using regression analysis. It was found that the 2 measurement systems highly correlated with each other with a minimum regression R^2 of 0.998 in 2 dimensional conditions and a minimum R^2 of 0.914 in 3 dimensional conditions. The agreement between the 2 measurement systems was also evaluated with the Bland and Altman (1986) method, which showed that the 2 measurement systems strongly agreed with each other, with only small mean differences in both 2 dimensional and 3 dimensional conditions. Therefore, it was concluded that inertial measurement system consisting of 3 orthogonal gyroscopes, accelerometers and magnetometers (Xsens) were valid in measuring movements when data were compared to an electromagnetic tracking system (Fastrak) in 2 and 3 dimensional conditions.

4.4 Validation of inertial measurement systems in inclination measurement

As discussed in Section 3.3.3, accelerometers are capable of measuring acceleration during dynamic conditions and inclination during static conditions. The objective of this experiment was to examine the validity of inclination measurement during static conditions using the accelerometers in the Xsens sensors. Two Xsens sensors were used in this experiment.

4.4.1 Methods

Both the Xsens sensors comprised 3 orthogonal accelerometers. During static conditions, the acceleration measured by an accelerometer includes only gravitational component. Therefore when the sensitive axis of an accelerometer is vertical in the gravitational axis, the acceleration would be expected to read 1g when the sensitive axis is pointing upwards and -1g when the sensitive axis is pointing towards the ground. When the sensitive axis of the accelerometer is horizontal, which is perpendicular to the gravitational axis, measured acceleration would be expected to read 0g. A positive tilt angle would be reported if the axis tilts above the horizontal axis and a negative reading would be showed when the axis tilts below the horizontal axis.

By utilising the inclination properties of accelerometers, the current experiment was designed to calibrate and measure the inclination using Xsens sensors by arranging the sensitive axes of the accelerometers in the gravitational (90°) and horizontal axes (0°), with the inclination angles calculated with respect to the horizontal axis using the tilt angle measurement method (see Appendix A6.2). The 2 Xsens sensors were oriented in 6 configurations as shown in Figures 4.4.1 to 4.4.6. Spirit levels were used to ensure the sensors were aligned to the axis of measurement. Five sets of data were collected in each configuration for a duration of 30 seconds in each data set.

Figure 4.4.1: the Z axis points up on a vertical axis, while X and Y axes are horizontal, spirit levels were used to ensure the alignment to the horizontal axis

Figure 4.4.2: the Z axis points down on a vertical axis, while X and Y axes are horizontal, spirit levels were used to ensure the alignment to the horizontal axis

Figure 4.4.3: the X axis points up on a vertical axis, while Y and Z axes are horizontal, spirit levels were used to ensure the alignment to the horizontal axis

Figure 4.4.4: X axis points down on a vertical axis, while Y and Z axes are horizontal, spirit levels were used to ensure the alignment to the horizontal axis

Figure 4.4.5: the Y axis points up on a vertical axis, while X and Z axes are horizontal, spirit levels were used to ensure the alignment to the horizontal axis

Figure 4.4.6: the Y axis points down on a vertical axis, while X and Z axes are horizontal, spirit levels were used to ensure the alignment to the horizontal axis

4.4.2 Results

Table 4.4.1 summarises the mean angles of the 5 sets of data for all 6 configurations, with the data collected with the sensitive axis of the accelerometer in the vertical and horizontal axes segregated. Table 4.4.1 also shows the angle difference between the measured inclination angles with respect to 90° on the vertical configurations and with respect to 0° on the horizontal configurations. During vertical configurations, when the sensitive axes of the accelerometers were on the gravitational axis, the ideal acceleration would be 1g and an angle of 90° with respect to the horizontal axis, in the current results, the accelerometers produced a mean angle of almost 90° (89.57° to 89.86°) in all axes of both sensors, with a mean maximum error of 0.43° as seen in the Z axis of Sensor 2. When the sensitive axes of the accelerometers were horizontal and perpendicular to the gravitational axis, an acceleration of 0g should be read and an angle of 0° with respect to the horizontal axis, however with the current sensors, the maximum difference was found to be 0.9° on the Z axis of Sensor 1.

	Sensor 1 (°)			Sensor 2 (°)		
	X	Y	Z	X	Y	Z
Vertical configuration	89.77	89.86	89.84	89.86	89.70	89.57
Angle difference	0.23	0.14	0.16	0.14	0.31	0.43
Horizontal configuration	0.44	-0.43	-0.90	0.17	-0.29	-0.76

Table 4.4.1: mean angle and angle difference with respect to 90° in vertical axis and angle difference with respect to 0° in horizontal axis

4.4.3 Discussion

From the results, it can be seen that accelerometers are capable of measuring inclination angles during static conditions, with a maximum mean angle difference of less than 0.9° between the inclination angles measured by the accelerometers and the true vertical (90°) and horizontal (0°) axes. There are a number of potential experimental errors in this piece of work, the most predominant being sensor alignment. While every effort was made to align the sensors using spirit levels, the accuracy of these and the parallax effects of setting up by eye might have led to non-alignment with the relevant axis, however any error was likely to be very small and was estimated at being less than 1°.

This experiment only tested the inclination angles of 0° and 90°, a more sophisticated system that could test the accelerometers at different angles would further validate the results.

From the current results of the experiment, the accelerometers within the Xsens systems proved to be valid tools for measuring posture/inclination angle during static conditions.

4.5 Summary and conclusions

In this chapter, 3 different validation studies were performed on an inertial measurement system, Xsens. The validity of the measurement of rotational movement and both 2 dimensional and 3 dimensional angular movements were established using a calibrated rotating device (a turntable) and an electromagnetic tracking system (Fastrak) respectively, while the inclination measurements of the accelerometers were validated by utilising the true gravitational and ground axes as references.

Calibrating the gyroscopes of the Xsens system using a turntable showed the system was valid for rotational measurement.

In the angular movement validation experiments, if both systems are needed to be used simultaneously on the same measurable segments, the sensors have to be as far apart as possible from each other due to the magnetic interference between the Fastrak system and the magnetometers of the Xsens system, and the Fastrak sensors have to be as close as possible to the electromagnetic source of the system. This placement of both systems may not be feasible if the area of the measurement segment is small, such as the spinous process and therefore in such situation an alternative approach would be necessary.

When both sensing and reference sensors move randomly in a 3 dimensional space, the orientation algorithm may result in slight underestimation (maximum difference of 5.9°) due to the non-inertially measurable component caused by the moving coordinate frame of the inertial measurement system. During these conditions, the agreement between Fastrak and Xsens systems were lower when compared to conditions with a static reference sensor, however a strong correlation existed between the 2 systems.

Posture/inclination measurements using accelerometers were found to produce excellent agreement with respect to the vertical (90°) and horizontal (0°) axes, however a more comprehensive study would be required to further validate the results.

Although the Xsens system was found to be a valid measurement system, the main limitation was that the magnetometers in the system may compromise the accuracy in orientation computation in a heavily distorted magnetic environment, such as a room with significant metal flooring, wall or ceiling beams, and/or metallic equipment. For short durations of data collection, the Kalman filter used by the Xsens system could correct magnetic distortion that is experienced by the magnetometers (Roetenberg et al. 2005), however if the data collection times are longer, the orientation of the magnetometers will be distorted and settle in the local magnetic field producing inaccurate orientation data (De Vries et al. 2009). The length of time before this effect is perceived depends on the strength of the local magnetic disturbance: in a heavily distorted magnetic field, the Kalman filter can only correct the distortion for up to 20 to 30 seconds (De Vries et al. 2009). However, during such situations, it is still feasible to use the Xsens system in orientation measurement by computing the results using only gyroscopic data (Ha et al. 2009). As discussed in Section 3.3.1, gyroscopes drift with time, therefore an effective drift correction algorithm (e.g. resetting technique, filtering, wavelet transformation) needs to be in place for such computation.

Another disadvantage of the Xsens system in spinal measurement was the fact that the system was a skin surface measurement system, and it was prone to errors due to skin movement and misalignment issue. However these issues had been explored and are further discussed in Chapter 5.

From these 3 sets of experiments, it was concluded that the Xsens system is a valid system for potential use in movement and posture measurement.

Chapter 5. Determination of possible errors in three dimensional spinal motion measurements with skin surface motion sensors

5.1 Overview

As the inertial measurement systems appeared to be valid for movement and inclination measurement as discussed in Chapter 4, such systems might be a valid tool for human spinal posture and motion measurement. However, as skin surface measurement devices such systems are potentially prone to errors due to non-alignment of the sensors, skin movement, lack of intra and inter observer reliability, and issues with anatomical landmark identification (Bogduk 2005; Portek et al. 1983; Pope et al. 1986; Taylor and Twomey 1980). The alignment of sensors with the plane of movement is important in minimising measurement errors (Van Herp et al. 2000). Sensor attachment is also a common source of error in skin surface measurement (Hindle et al. 1990; Lee et al. 2003; Pearcy and Hindle 1989; Portek et al. 1983; Russell et al. 1993), and for this study it was essential to identify a secure attachment method in order to minimise errors due to loose sensor attachment and artefacts caused by skin movement and muscle contraction.

In this study, the 2 most significant potential errors in 3 dimensional spinal motion measurement using skin surface motion sensors were evaluated, sensor alignment and sensor attachment. The Fastrak system was used for both experiments as the system is a ‘gold standard’ in skin surface spinal motion measurement and furthermore it was the only instrument readily available throughout the period of the early stages of the study when these experiments were performed. As the inertial measurement system and the electromagnetic tracking system were both skin surface measurement systems and used the same computation algorithm, the findings and indications of this study into possible errors due to skin surface measurement method were equally applicable to both measurement systems. The effect of sensor misalignment in spinal motion measurement was assessed and a potential method of attaching sensors to the lumbar spine for the current study was determined.

The methods and results of these studies are discussed in the following sections.

5.2 Importance of sensor alignment in spinal posture and motion measurement

The objective of this part of the experiment was to study the effect of sensor misalignment with the plane of movement during movement measurement. Two electromagnetic tracking sensors (Fastrak) were used in this experiment.

5.2.1 Methods

The Fastrak sensors were placed on a 2 dimensional wooden hinged joint marked with angles of 0˚, 5˚, 10˚ and 15˚ with the 0˚ aligned to the plane of movement of the wooden hinged joint. The angles were marked on both moving and non-moving segments of the wooden hinged joint by using a conventional goniometer, with an error of less than 1°. The wooden hinged joint was clamped to a table with plastic clamps to prevent undesired movement. The sensors were attached to the wooden hinged joint securely with double sided tape. One sensor was placed at the base as the reference sensor (non-moving) and the other was fixed to the moving part of the wooden hinged joint as the moving sensor. The wooden hinged joint was moved at a random speed and amplitude (between 50° to 60°). Five sets of data were collected with the moving sensor at 0˚, 5˚, 10˚ and 15˚ misalignment with the wooden hinged joint movement plane for 2 different configurations as shown in Figures 5.2.2 where the moving sensor was misaligned with the moving plane (Configuration 1) and 5.2.3 where the reference sensor was misaligned with the moving plane (Configuration 2). Before each set of data collection, a neutral position (no rotation on the plane of movement) was held for 5 seconds as an initial reference condition of the sensors.

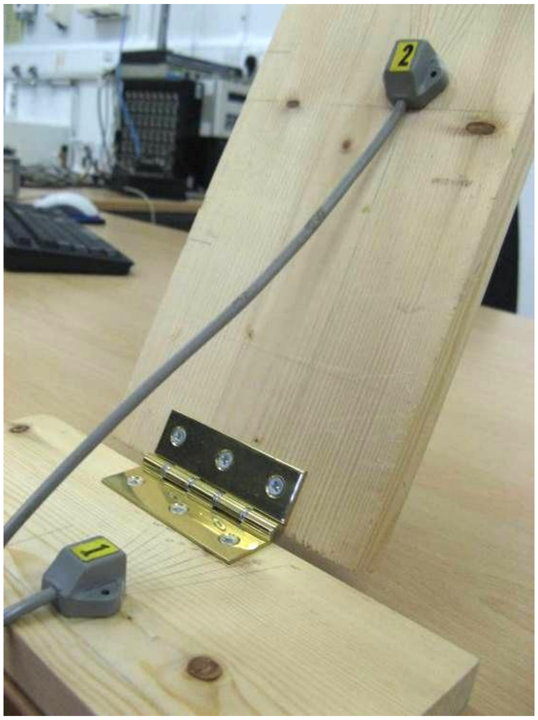


Figure 5.2.1: Both sensors aligned with the wooden hinged joint movement plane

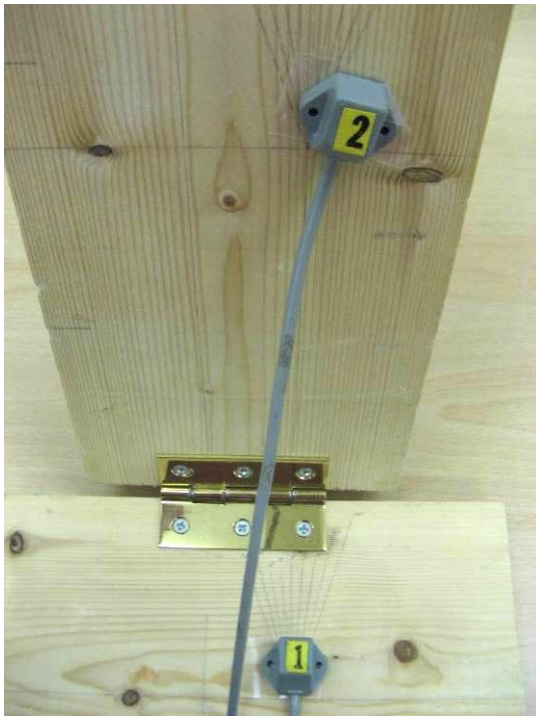


Figure 5.2.2: Configuration 1, the moving sensor was 15°misaligned with the wooden hinged joint movement plane

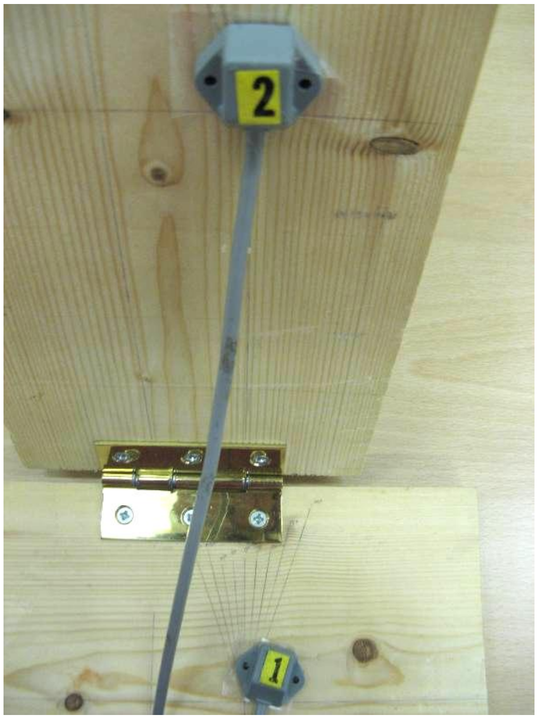


Figure 5.2.3: Configuration 2, the reference sensor was 15°misaligned with the wooden hinged joint movement plane

The sampling rate (non-selectable) of the data was 60 samples/second. The relative angles between the 2 sensors were calculated based on the direction cosine matrix and expressed as 3 dimensional Euler angles using Euler equations as described in Appendix A6.1 and the results were compared to the data collected when the sensors were aligned with the wooden hinged joint movement plane as shown in Figure 5.2.1.

5.2.2 Results

Table 5.2.1 below shows the results with the moving sensor misaligned with the movement plane of the wooden hinged joint at 5°, 10° and 15°. The Y axis of the Fastrak sensors was aligned with the moving plane of the wooden hinged joint, and the X and Z axes were the coupled axes in this configuration, as shown in Figure 5.2.4 below.

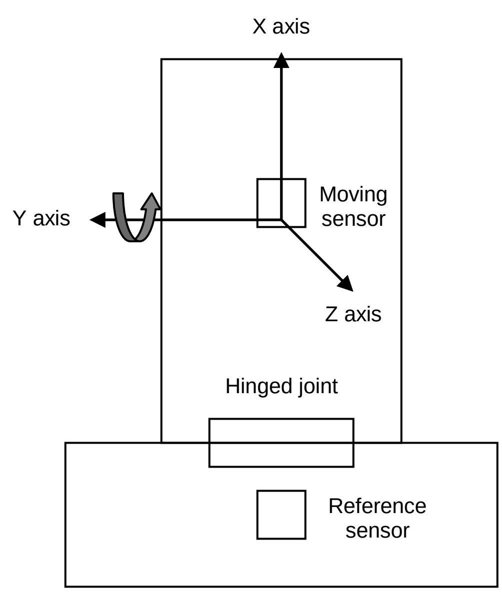


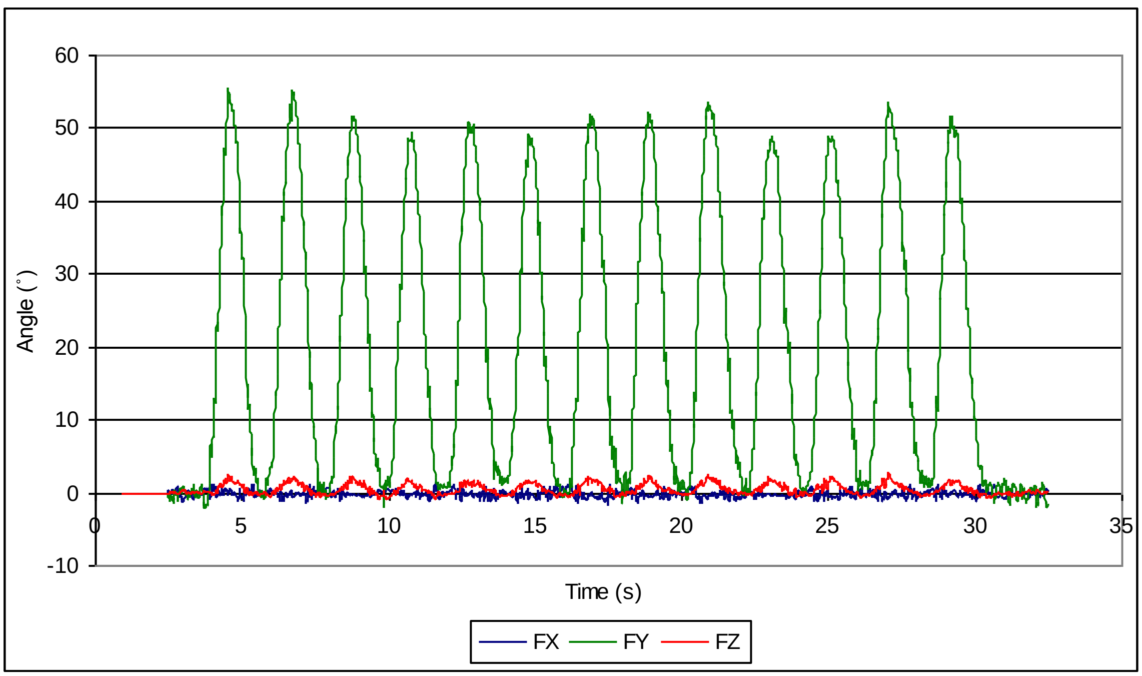
Figure 5.2.4: The coordinate frame of the Fastrak sensors on the 2 dimensional wooden hinged joint, the X axis points from bottom to top, the Y axis points from right to left, and the Z axis points from beneath to the surface of the wooden hinged joint

In ideal conditions, the movement of the hinged joint would induce a change in rotational velocity in the Y axis, but no rotational change in both X and Z axes, e.g. both X and Z axes should produce an output of 0 rad/s. However in real world conditions, even if the sensor is placed stationary on a table and not moving, the axes would never record 0 rad/s due to the sensitivity of the sensor and electrical or electronic disturbance such as noise, though these disturbances could be mathematically removed during data analysis. In the current study, the angles recorded in the non-moving axes could also be due to accuracy of the alignment drawn on the wooden hinged joint (error estimated to be less than 1°). In Table 5.2.1, the readings recorded in the X and Z axes are shown to demonstrate the effect of misalignment on the non-moving axes.

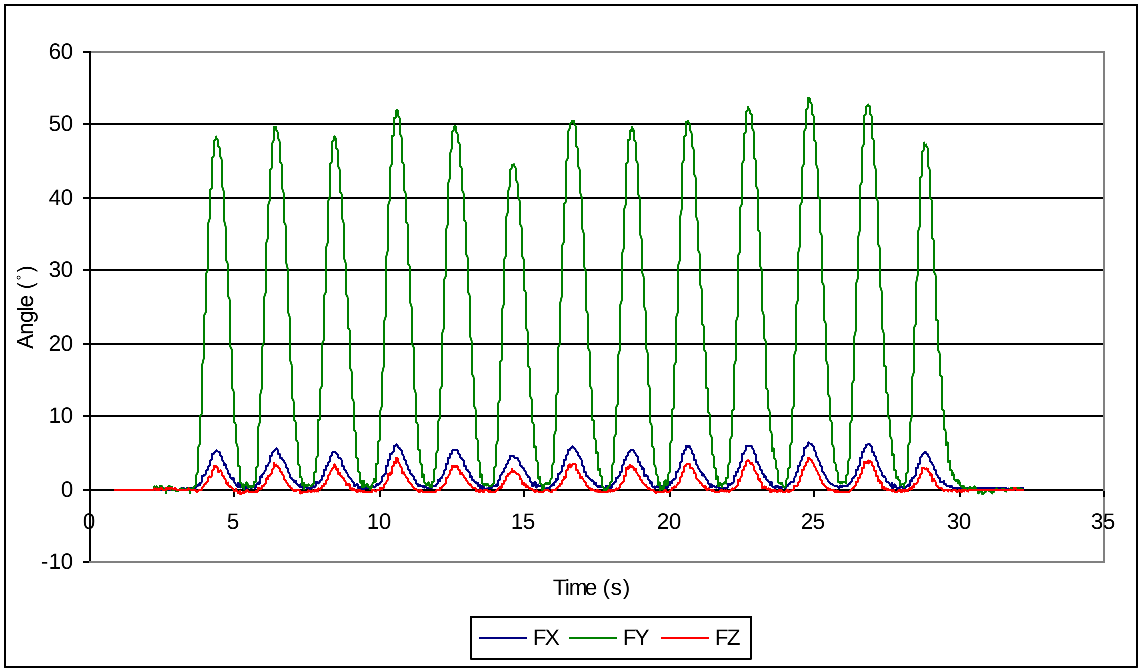
When compared to the data collected with both sensors aligned with the movement plane, 5° misalignment of the moving sensor led to a maximum error of between 5.79° and 2.57° in the X and Z axes respectively, as shown in Graph 5.2.2. The level of error increased with greater degrees of misalignment of the moving sensor. At 10° misalignment, the maximum error in the coupled axes had tripled compared to that measured with 5° misalignment. At 15° of misalignment of the moving sensor, the maximum error was approximately 4 times greater than at 5° misalignment. The effect was greatest in the X axis. In comparison to Graph 5.2.1, Graphs 5.2.2 to 5.2.4 show much higher coupled angles during the 2 dimensional hinged movements.

	FX (°)				FZ (°)			
	0°	5°	10°	15°	0°	5°	10°	15°
Set 1	1.52	6.40	14.39	22.16	2.78	4.22	7.77	11.32
Set 2	1.55	7.17	14.26	22.08	2.78	5.03	7.90	10.93
Set 3	1.66	7.28	14.54	23.99	2.62	4.44	7.91	12.95
Set 4	2.41	8.20	17.25	24.36	3.36	5.92	10.03	12.74
Set 5	1.11	8.04	18.02	26.02	0.17	5.27	10.78	14.02
Maximum	2.41	8.20	18.02	26.02	3.36	5.92	10.78	14.02
Minimum	1.11	6.40	14.26	22.08	0.17	4.22	7.77	10.93
Mean	1.65	7.42	15.69	23.72	2.34	4.98	8.88	12.39
Standard Deviation	0.47	0.73	1.80	1.65	1.25	0.68	1.42	1.26
Max. difference	-	***5.79***	***15.61***	***23.61***	-	***2.57***	***7.42***	***10.66***

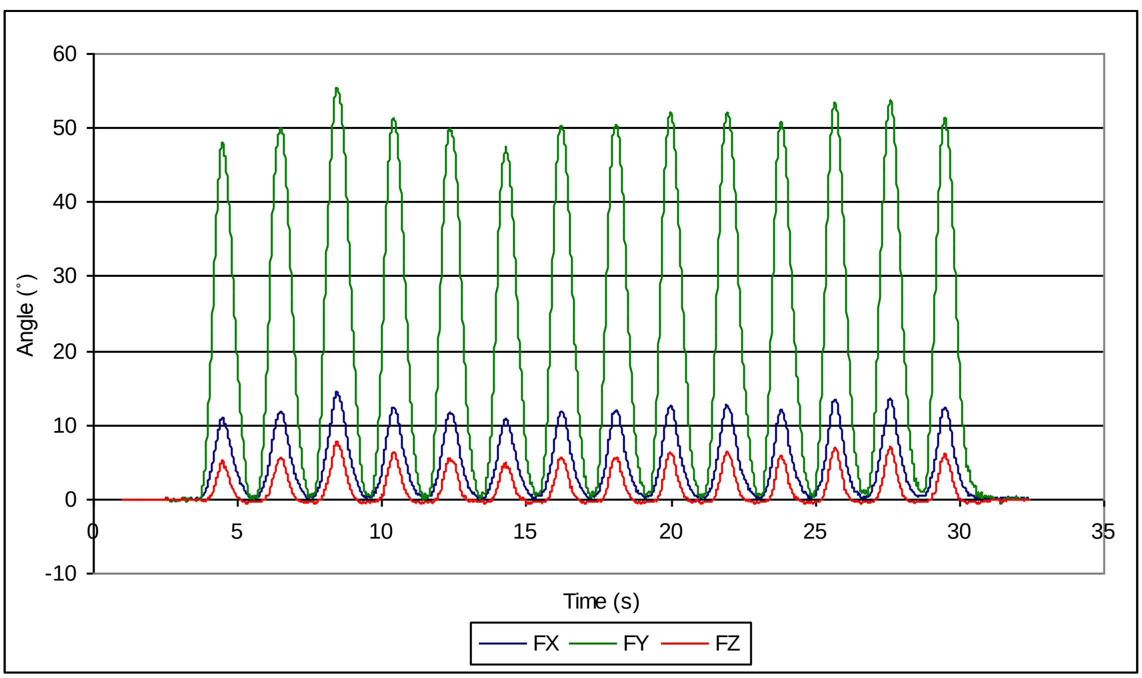
Table 5.2.1: Results of Configuration 1, comparing data of the movements' coupled axes from different degrees of misalignment with data collected when sensors were aligned with the plane of movement of the wooden hinged joint



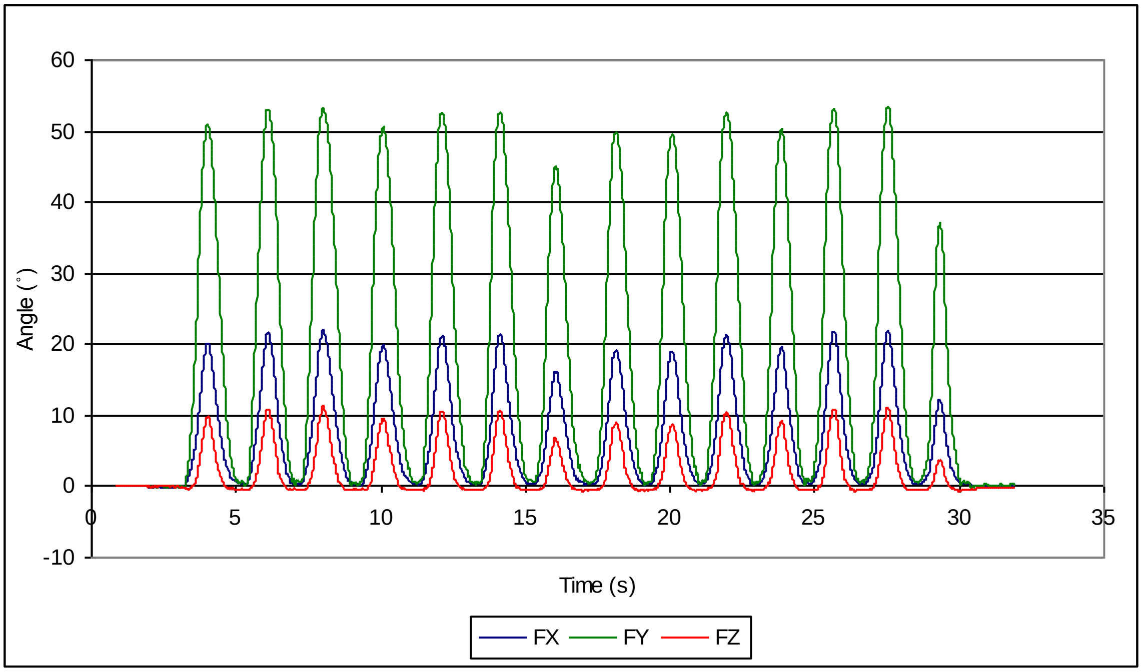
Graph 5.2.1: A typical graph of data collected when sensors were aligned with the plane of movement of the wooden hinged joint



Graph 5.2.2: A typical graph of data collected when the moving sensors were 5° misaligned with the plane of movement of the wooden hinged joint



Graph 5.2.3: A typical graph of data collected when the moving sensors were 10° misaligned with the plane of movement of the wooden hinged joint



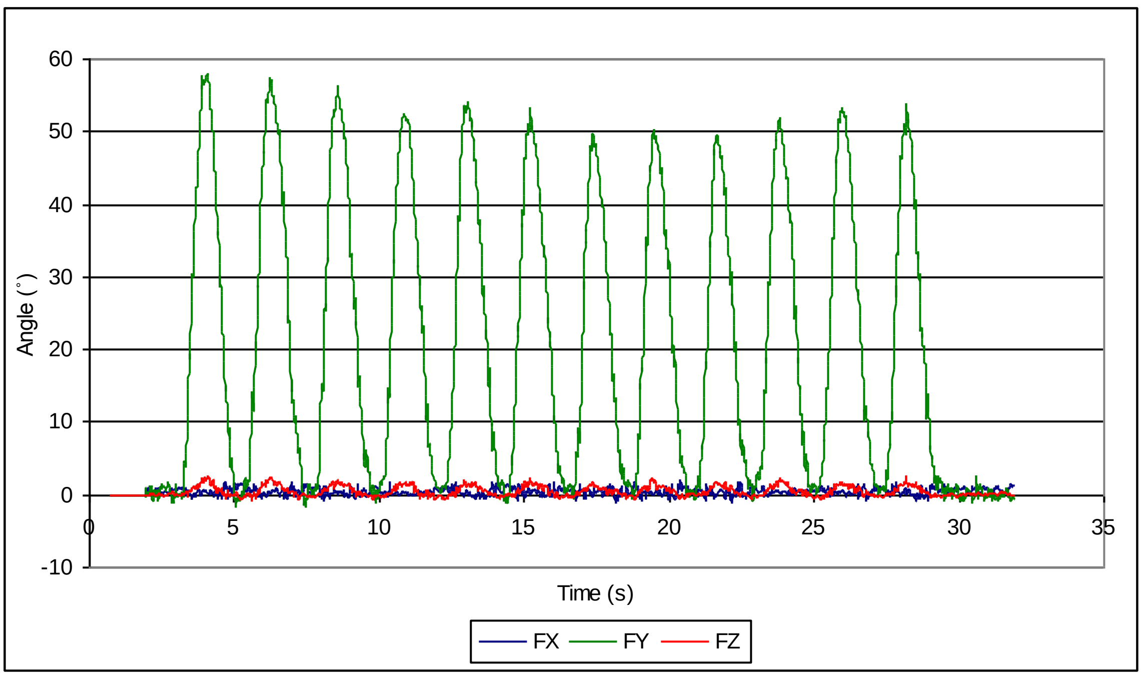
Graph 5.2.4: A typical graph of data collected when the moving sensors were 15° misaligned with the plane of movement of the wooden hinged joint

In the second configuration in which the reference sensor was misaligned with the moving plane of the wooden hinged joint, the results did not show much error (<0.4°) on the coupled axes even at 15° misalignment, as shown in Table 5.2.2.

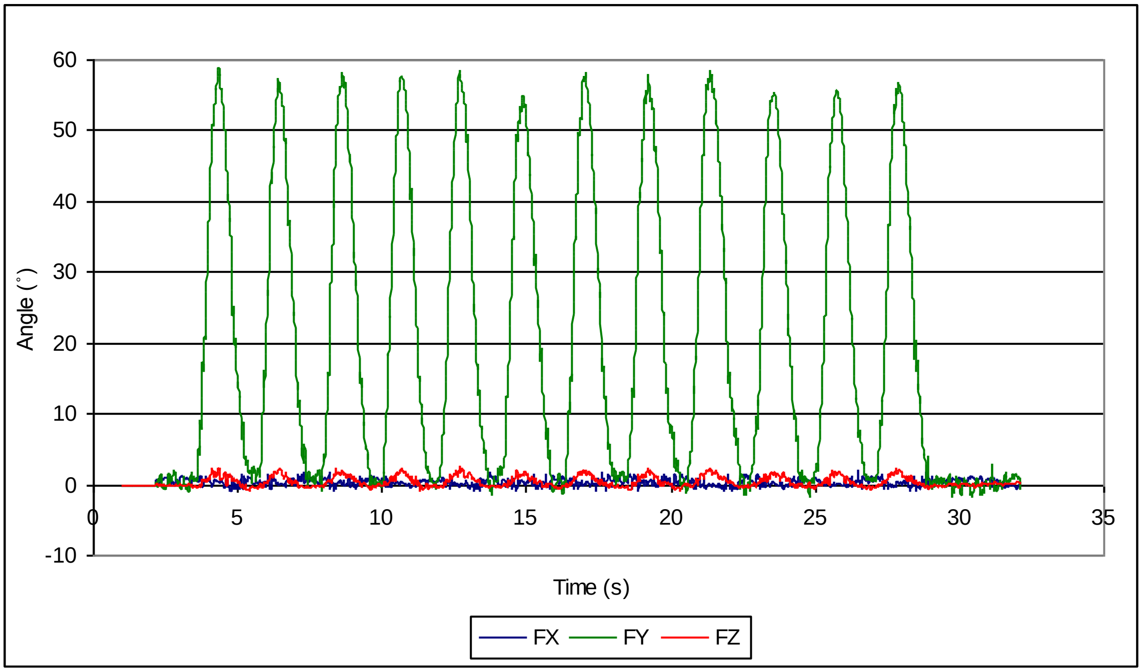
The maximum difference in angle when compared to data taken when the sensors were aligned to the moving plane ranged from 0.07° to 0.34°, which suggested that no change or effect occurred. From Graphs 5.2.5 to 5.2.7, it is apparent that the reference sensor did not affect the measurement even if it was 15° misaligned to the moving plane, when compared to data collected when sensors were aligned as in Graph 5.2.1, with the maximum error less than 0.35° in both X and Z axes.

	FX (°)				FZ (°)			
	0°	5°	10°	15°	0°	5°	10°	15°
Set 1	1.52	2.08	1.57	2.34	2.78	2.71	2.87	2.48
Set 2	1.55	2.14	1.35	2.13	2.78	2.54	3.02	2.64
Set 3	1.66	1.37	1.98	1.49	2.62	3.07	2.80	2.69
Set 4	2.41	2.16	2.03	1.87	3.36	2.93	2.50	3.09
Set 5	1.11	1.48	2.07	1.49	0.17	3.07	2.65	2.61
Maximum	2.41	2.16	2.07	2.34	3.36	3.07	3.02	3.09
Minimum	1.11	1.37	1.35	1.49	0.17	2.54	2.50	2.48
Mean	1.65	1.84	1.80	1.86	2.34	2.86	2.77	2.70
Standard Deviation	0.47	0.39	0.32	0.38	1.25	0.23	0.20	0.23
Max. difference	-	-0.24	-0.34	-0.07	-	-0.29	-0.33	-0.27

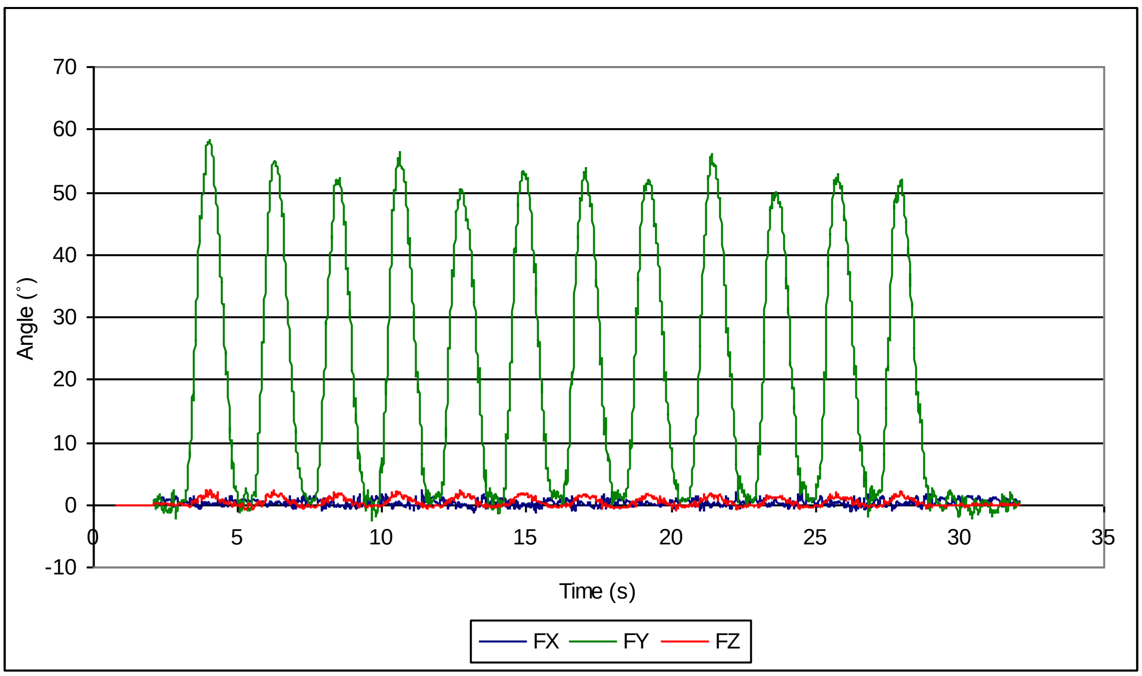
Table 5.2.2: Results of Configuration 2, comparing data of the movements' coupled axes from different degrees of misalignment with data collected when sensors were aligned to the plane of movement of the wooden hinged joint



Graph 5.2.5: A typical graph of data collected when the reference sensors were 5° misaligned with the plane of movement of the wooden hinged joint



Graph 5.2.6: A typical graph of data collected when the reference sensors were 10° misaligned with the plane of movement of the wooden hinged joint



Graph 5.2.7: A typical graph of data collected when the reference sensors were 15° misaligned with the plane of movement of the wooden hinged joint

5.2.3 Discussion

The results showed that it was critical for the moving sensor to be as closely aligned to the moving plane as possible as even 5˚ of misalignment produced approximately 2.57° to 5.78° of error. The error grew when the degree of misalignment increased, from 5° misalignment to 10° misalignment of the moving sensor, the error grew almost 3 fold; and from 5° misalignment to 15° misalignment, the error rose more than 4 fold. As illustrated in Figure 5.2.5, when the sensor was aligned to the plane of movement, there was only rotation recorded in the Y axis, while the X and Z axes experienced no rotation in this condition. However when the moving sensor was misaligned to the plane of movement by an angle of σ, rotation occurred in all 3 axes measuring the component of the movement as a function of misalignment σ rather than the rotation angle of the true planar movement. Hence the greater the misalignment to the plane of movement, the larger the errors would be expected.

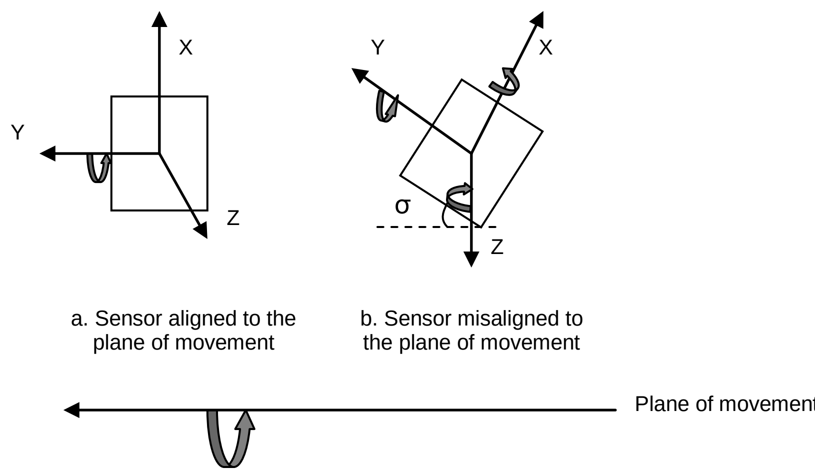


Figure 5.2.5: Illustration of the effects on the orientation measurement when a moving sensor is misaligned with the plane of movement

Correct alignment of the sensors therefore plays a significant role in reducing errors in the coupled axes during spinal motion measurement. Theoretically these errors due to sensor misalignment could be compensated for mathematically with the initial alignments of the sensors known, however the process could be complex and potentially erroneous (Van Herp et al. 2000), especially in 3 dimensional conditions with a moving coordinate.

The reference sensor however did not have much effect on the coupled axes even if it was 15˚ misaligned to the plane of movement. In this experiment the reference sensor was stationary, which means that it did not experience a change in rotation after being reset in a neutral position, and the rotation angles of the reference sensor remained at 0° throughout the data collection whether it was 5° or 15° misaligned to the movement plane. This could explain why it did not contribute much to error during measurement. However if the measurement is to be performed on humans, the reference sensor would not be stationary but moving along with the part of the body to which it is attached. Therefore, it was anticipated that it may be necessary to also align the reference sensor to the movement plane. For 3 dimensional movement measurements, the importance of this factor will be amplified.

In the ideal condition with both sensors aligned to the plane of movement, the axis that was aligned to the moving plane would experience a rotational change, while the other 2 axes would experience 0° changes. However this was not the case in the current study where there was 1-3° of angular movements in the coupled axes during the configuration where the sensors were aligned. This could be due to the accuracy of the drawn aligned angle (±1°) on the wooden hinge joint, the alignment of the sensor to that line and/or the non-rigid motion of the moving segment on the wooden hinged joint during movement. It was observed that the hinged joint used in these experiments did not produce a perfect 2 dimensional movement due to the nature of the mechanical parts. However, these errors in the coupled axes (1-3°) were small and did not affect the observations on the effects of misalignment for the 2 measurement configurations.

Therefore, it can be concluded that in order to minimise error during spinal motion measurement, it is essential to ensure that sensors are aligned to the body reference plane of movements as closely as possible as errors could arise in the other planes as an artefact, and this could lead to misleading results.

5.3 Sensor fixation methods for lumbar spinal posture and motion measurement

As discussed previously (Section 5.1), a secure sensor fixation method plays an important role in reducing errors caused by loose connection and skin artefacts in human posture and motion measurements. Various researchers have discussed the importance of having a secure sensor attachment (Burnett et al. 2008; Hindle et al. 1990; Lee and Wong 2002; Lee et al. 2003; Pearcy and Hindle 1989; Van Herp et al. 2000) in lumbar spinal motion measurement.

Burnett et al. (2008) placed a 150mm clear Perspex ruler horizontally on the skin of participants by using double sided tape and the sensors were attached to the ruler and secured with a Nylatex strap prior to their study which measured the lumbar ranges of axial rotation during flexion and extension movements using an electromagnetic tracking system (Fastrak). Based on repeated observation, Burnett et al. (2008) claimed that this attachment method ensured that the sensors replicated movements of the trunk.

Hindle et al. (1990) and Pearcy and Hindle (1989) advocated that the best sensor attachment method for reducing the effect of skin movement was by attaching the electromagnetic tracking sensor and source (3Space Isotrak, Polhemus) used in their study to L1 spinous process (sensor) using double sided tape and to the sacrum (source) with a moulded plastic plate, and both sensor and source were secured by placing a strap over them and around the participants' trunk.

Lee and Wong (2002) and Lee et al. (2003) used plastic screws to secure the sensor onto a mouldable plastic plate before threading a Velcro band through the plastic plate. The sensor was attached to participants by wrapping the Velcro band around their trunk. Both Lee and Wong (2002) and Lee et al. (2003) commented that this attachment method was the most secure arrangement for spinal motion measurement. Lee and Wong (2002) used an electromagnetic tracking system (Fastrak) and Lee et al. (2003) used gyroscopes in their study.

Van Herp et al. (2000) mounted the sensor and source of an electromagnetic tracking system (3Space Isotrak, Polhemus) to adjustable wedges and these were attached to the participants' skin by using double sided tape. The authors used the adjustable wedges to align the sensor and the source of the system to the anatomical planes of the body. The sensor and source were then held in place with an inextensible nylon strap. Van Herp et al. (2000) used this attachment method for spinal ranges of movement measurement.

The consensus amongst these authors was that a strap was essential to keep the sensors in place regardless of the type of attachment used prior to that procedure. However there are limited reported works on the effect of different types of sensor fixation methods.

As discussed in Section 2.3, due to the spinal structures, movement of the lumbar spine occur in 3 dimensions. Each planar movement is usually coupled with movements from the other 2 planes, with the directions and magnitudes of these coupled motions varying between individuals. Radiography is the most accurate method for measuring ranges of movement and their coupled motions due to its capability of measuring movement of each intervertebral segment. Conversely, skin surface measurements such as electromagnetic tracking systems and inertial measurement systems are prone to errors due to sensor misalignment, skin artefacts and loose sensor attachment. These factors complicate the interpretation of the results as the directions and magnitudes of the 'coupled motions' measured can be masked by these errors. During 3 dimensional spinal motion measurement using skin surface motion sensors, coupled motions could be a combination of true coupled motions of the spine and errors due to the methods of measurement. As it is extremely complicated to mathematically separate the true coupled motions with these errors after measurement, it is crucial to minimise such errors before the measurement. Studying the magnitude and direction of the couple motions of different sensor attachment methods could provide information on which attachment method resulted in the least probable error.

The objective of this experiment was to explore different sensor attachment methods on the lumbar spine for spinal motion measurement. The attachment method that produced the least error due to skin movement and loose connection was identified, these being the major factors that contribute to skin surface measurement errors. The procedures and results of this study are discussed in the following sections.

5.3.1 Methods

The protocols for this part of study were approved by the University of Brighton's Faculty of Health and Social Science Ethics and Governance Committee (see Appendix Section A1.1a). Two participants (both male) were recruited for this study by word of mouth. The participants were informed regarding the procedures and were given as long as they wished to decide if they would like to participate in the study prior to the data collection day. The study took place in the Human Movement Laboratory, Robert Dodd Annexe 1 building where participants were given a printed information sheet as shown in Appendix A1.3a and signed a consent form (as shown in Appendix Section A1.4a) after they had decided if they wished to continue with participation. The mean age of the participants was 26.5 years and the mean BMI was 22.67±0.45kg/m^2. Both participants were healthy, had no history of low back pain and had no limitation in performing normal daily activities.

Two electromagnetic tracking sensors (Fastrak) were used in this experiment. Before sensor attachment, the participants' L1 and S1 spinous processes were located in standing by palpation carried out by a trained physiotherapist. From the level of the posterior superior iliac spine (PSIS), S2 was identified; L1 and S1 were then located by palpating intervening vertebrae (Ng et al. 2002). The levels of the spinous processes were further verified using ultrasound imaging by scanning the spinous processes from S2 to L1.

In this experiment, 4 different spinal attachment configurations were evaluated as follows:

Configuration 1: Sensors were attached to the spinous processes by using double sided tape and secured with medical tape over the sensors as in Figure 5.3.1. Spirit levels were used to align the sensors to the horizontal plane.

Configuration 2: Clear plastic plates (103x48x1mm) were attached to the spinous processes using double sided tape to act as a base for the sensors. Sensors were then attached to the plastic plates also using double sided tape. Spirit levels were used to align the sensors to the horizontal plane. The configuration is shown in Figure 5.3.2. This was similar to the method used by Burnett et al. (2008) but without a strap.

Configuration 3: Clear plastic plates were attached to the spinous processes by using double sided tape to act as a base for the sensors, the sensors were attached to plastic plates threaded with an elastic Velcro strap before being attached to the plastic base with double sided tape. The straps were fastened around the participants' trunk for a more secure attachment, as shown in Figure 5.3.3. The strap was fastened to a level where the sensors were securely held in place while not causing discomfort to the participants. Spirit levels were again used to align the sensors to the horizontal plane. This configuration combined the fixation strategies used by Burnett et al. (2008); Lee and Wong (2002) and Lee et al. (2003).

Configuration 4: Clear plastic plates were attached to the spinous processes by using double sided tape to act as a base for the sensors, the sensors were attached to plastic plates with orthogonal secondary plates threaded with a Velcro strap before being attached to the plastic base with double sided tape. The straps were fastened around the participants' trunk for a more secure attachment. Spirit levels were used to align the sensors to both vertical and horizontal planes on the secondary plates of the sensor attachment platform, as shown in Figure 5.3.4. This configuration facilitated better sensor alignment to the body reference planes of movement, which was found to be critical in Section 5.2. This configuration used a similar concept as those reported by Van Herp et al. (2000), however instead of using adjustable wedges for alignment, the sensors were aligned on the secondary plate.

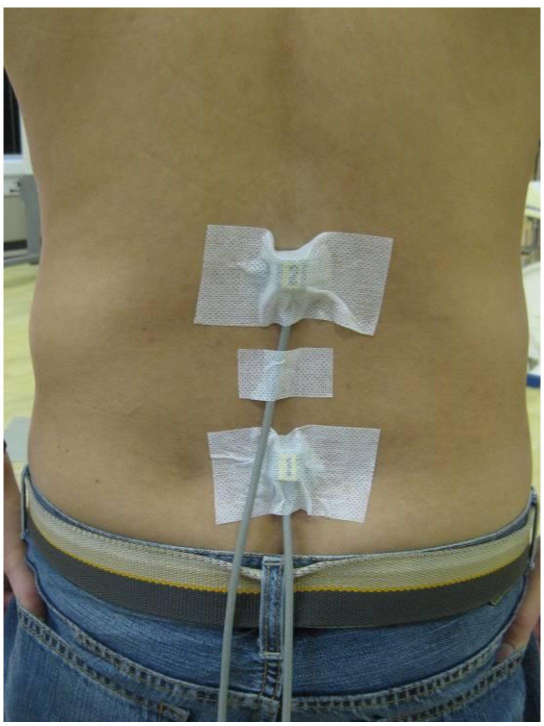


Figure 5.3.1: Configuration 1, sensors attached to L1 and S1 spinous processes

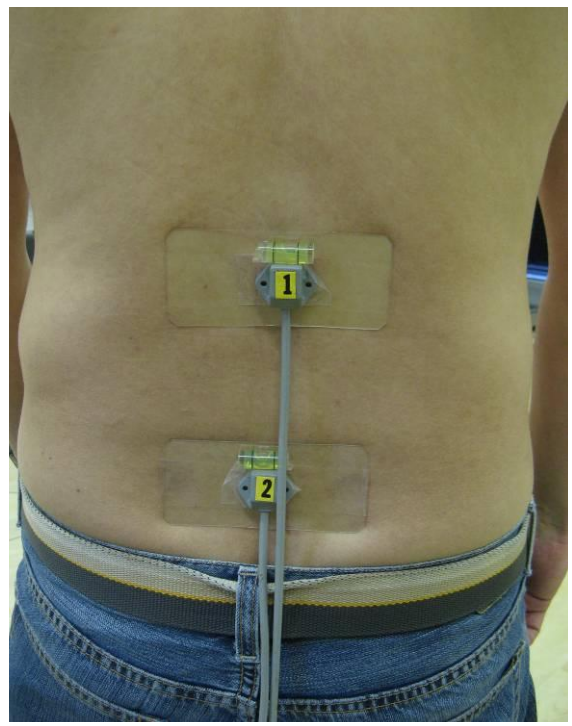
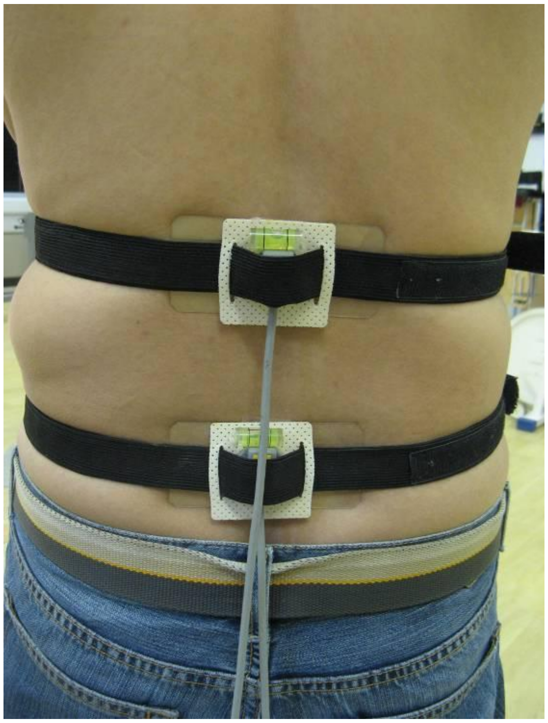


Figure 5.3.2: Configuration 2, sensors attached to L1 and S1 spinous processes



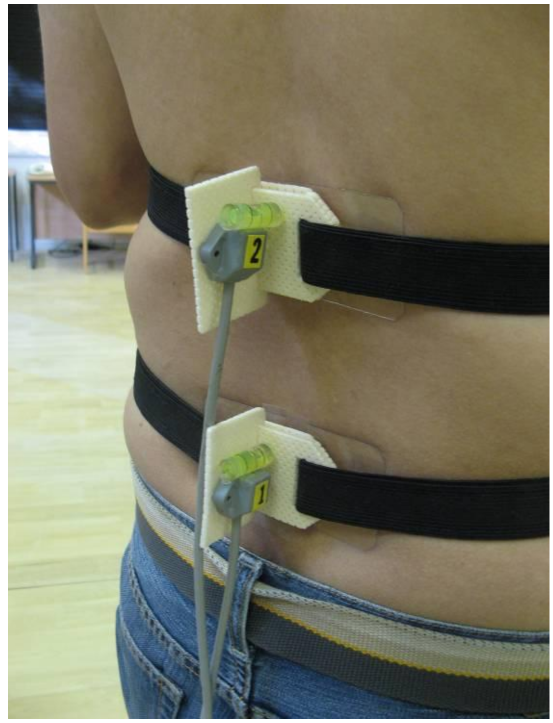


Figure 5.3.3: Configuration 3, sensors attached to L1 and S1 spinous processes

Figure 5.3.4: Configuration 4, sensors attached to L1 and S1 spinous processes

Participants performed 6 different movements in each configuration: flexion, extension, lateral flexion to both left and right sides, and axial rotation to both left and right sides. During flexion, participants were requested to bend forward trying to touch their toes with their hands; during extension, participants bent their spine backwards with their hands sliding down the back of their thighs with the movement; lateral flexion was performed with hands by the sides of body whilst bending sideways; and during axial rotation, participants placed their hands across their chest and rotated their spine. The participants were encouraged to move as far as they could with both feet placed shoulder width apart and their knees extended. Before each movement, participants stood for 5 seconds as the reference/neutral point and the participants performed each movement 3 times at a pace which was comfortable for them.

The data were collected at a sampling rate of 60 samples/second (non-selectable). The relative angles between the 2 sensors were calculated using a rotation matrix method as discussed in Appendix 6.1 and the results were compared between different configurations.

5.3.2 Results

Table 5.3.1 shows the mean angles of all 3 axes for 6 different movements taken with the 4 different attachment configurations. In this experiment, the X axis was referred to as the axial rotation axis, the Y axis referred to as the flexion-extension axis and the Z axis was referred to as the lateral flexion axis. Positive values referred to flexion, left lateral flexion and left axial rotation, while negative values denoted the opposite directions of these movements. The axis of the main plane of movement is formatted in bold in Table 5.3.1.

Flexion	FX	**FY**	FZ
Configuration 1	-20.1	**62.5**	23.6
Configuration 2	-4.2	**56.0**	6.6
Configuration 3	-3.9	**55.6**	-5.7
Configuration 4	-3.3	**50.7**	5.8

Extension	FX	**FY**	FZ
Configuration 1	-6.5	**-22.0**	-2.8
Configuration 2	-3.2	**-16.6**	2.8
Configuration 3	-1.8	**-16.3**	4.5
Configuration 4	-1.3	**-13.2**	2.1

Right lateral flexion	FX	FY	**FZ**
Configuration 1	-7.7	23.0	**-22.1**
Configuration 2	-3.7	14.8	**-25.2**
Configuration 3	-2.0	20.9	**-25.7**
Configuration 4	-3.0	14.8	**-28.5**

Left lateral flexion	FX	FY	**FZ**
Configuration 1	9.8	25.1	**34.1**
Configuration 2	3.3	21.3	**33.2**
Configuration 3	3.8	11.6	**28.2**
Configuration 4	-3.9	11.3	**31.0**

Right axial rotation	**FX**	FY	FZ
Configuration 1	**-5.5**	9.5	-14.3
Configuration 2	**-14.8**	-3.6	-9.9
Configuration 3	**-13.5**	-5.0	5.4
Configuration 4	**-10.6**	-5.0	-3.8

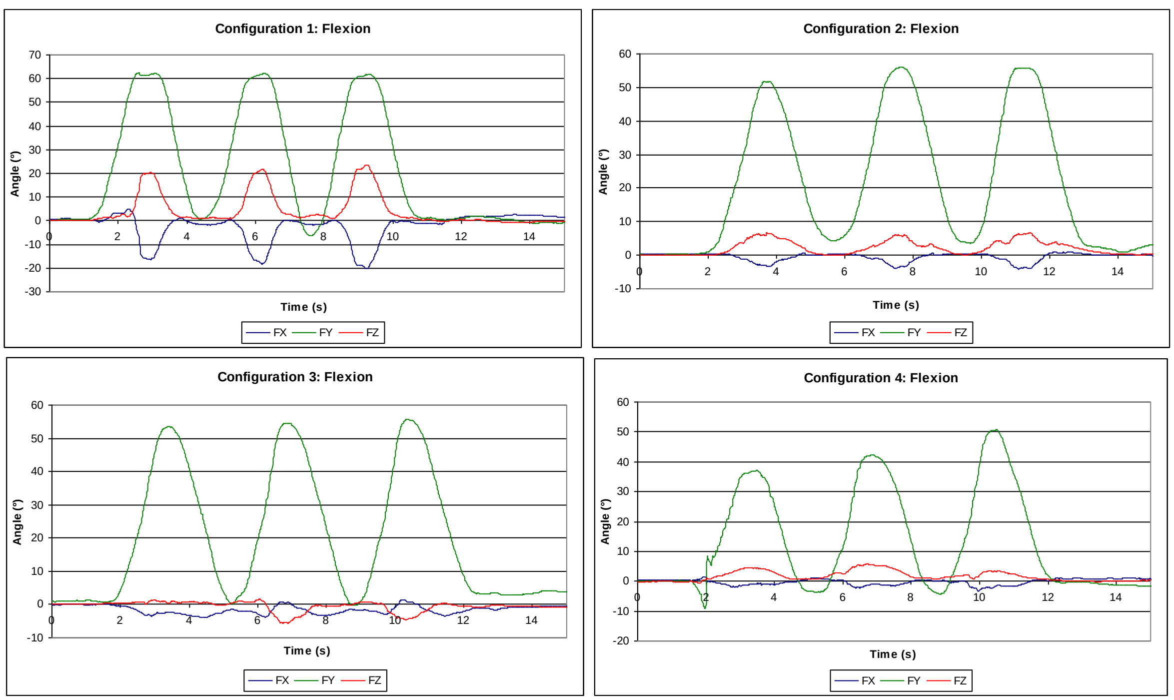
Left axial rotation	**FX**	FY	FZ
Configuration 1	**10.4**	-7.0	23.0
Configuration 2	**14.1**	-8.4	15.3
Configuration 3	**11.8**	-6.6	16.3
Configuration 4	**8.7**	4.1	17.5

Table 5.3.1: The mean angles (°) of the 3 axes during the 6 physiological movements collected with 4 different attachment configurations. FX was the axial rotation axis, FY was the flexion-extension axis, and FZ was the lateral axis.

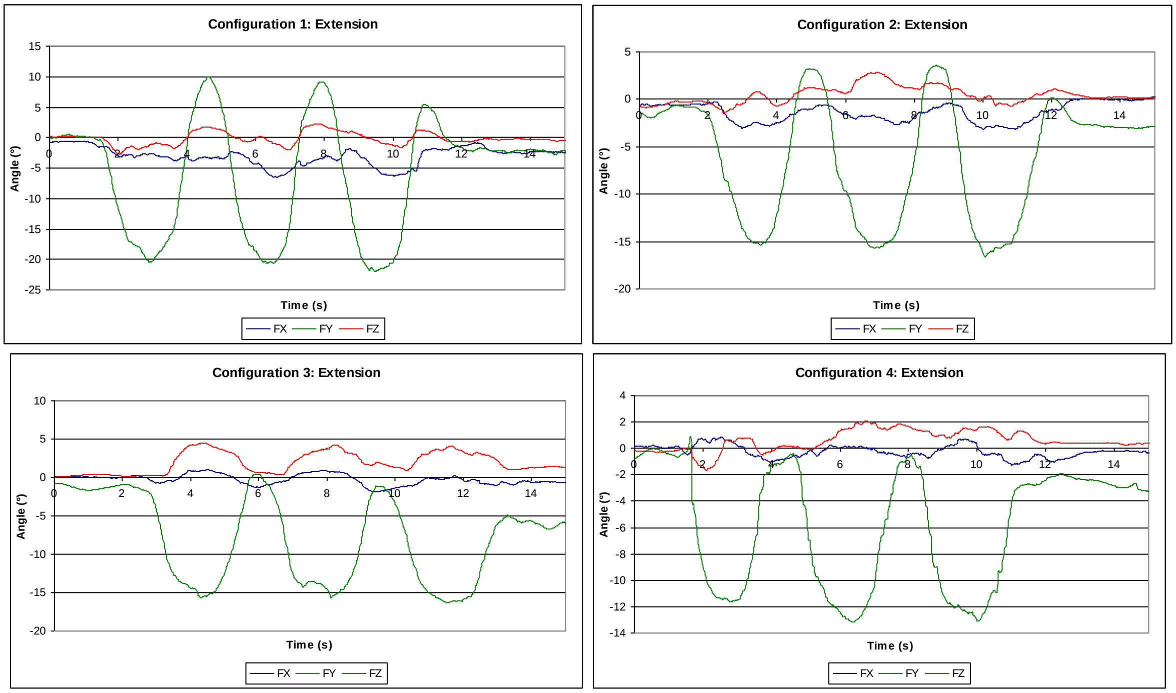
From the data collected, Configuration 1 produced larger angles on the coupled axes for all movements. During flexion, the average of main flexion movement was 62.5°, however this was coupled with 20.1° of right rotation and 23.6° of left lateral flexion. Configuration 3 and 4 produced the least coupled angles, which ranged from 3.3° to 5.8° during flexion. Another clear difference occurred during axial rotation. When the participants were performing right axial rotation, Configuration

1 produced 9.5° of flexion and 14.3° of right lateral flexion; followed by Configuration 2 which produced 3.6° of extension and 9.9° of right lateral flexion; the best results, which were those with the least "coupled motions", were obtained with Configuration 3, with 5.0° of extension and 5.4° of left lateral flexion, and Configuration 4 with 5.0° of extension and 3.8° of right lateral flexion. Results of left axial rotation showed Configuration 1 as having 7.0° to 23.0° of coupled angles; while Configuration 2 registered 8.4° to 15.3° of coupled angles; Configuration 3 and 4 again produced the lowest coupled angles, which ranged from 4.1° to 17.5°.

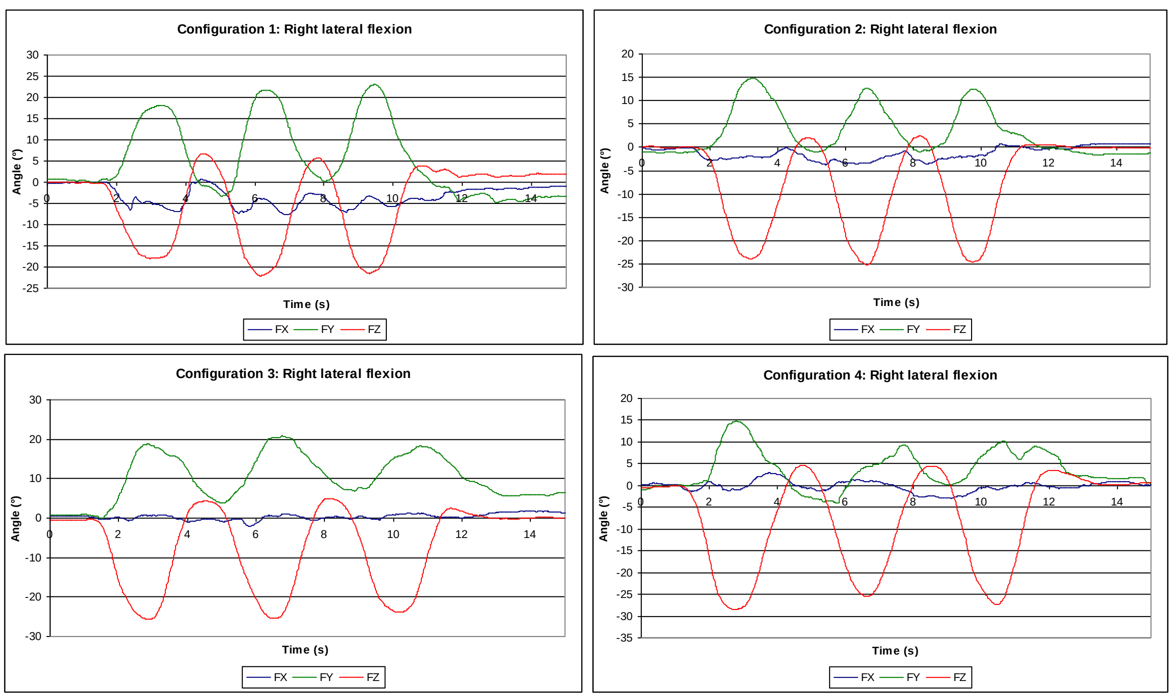
By referring to Graph 5.3.1 to Graph 5.3.6, it is clear that Configuration 1 produced much higher angles on the 2 coupled axes. Configuration 2 had less coupled movements compared to Configuration 1, but Configuration 3 and 4 produced least coupled movements in the results.



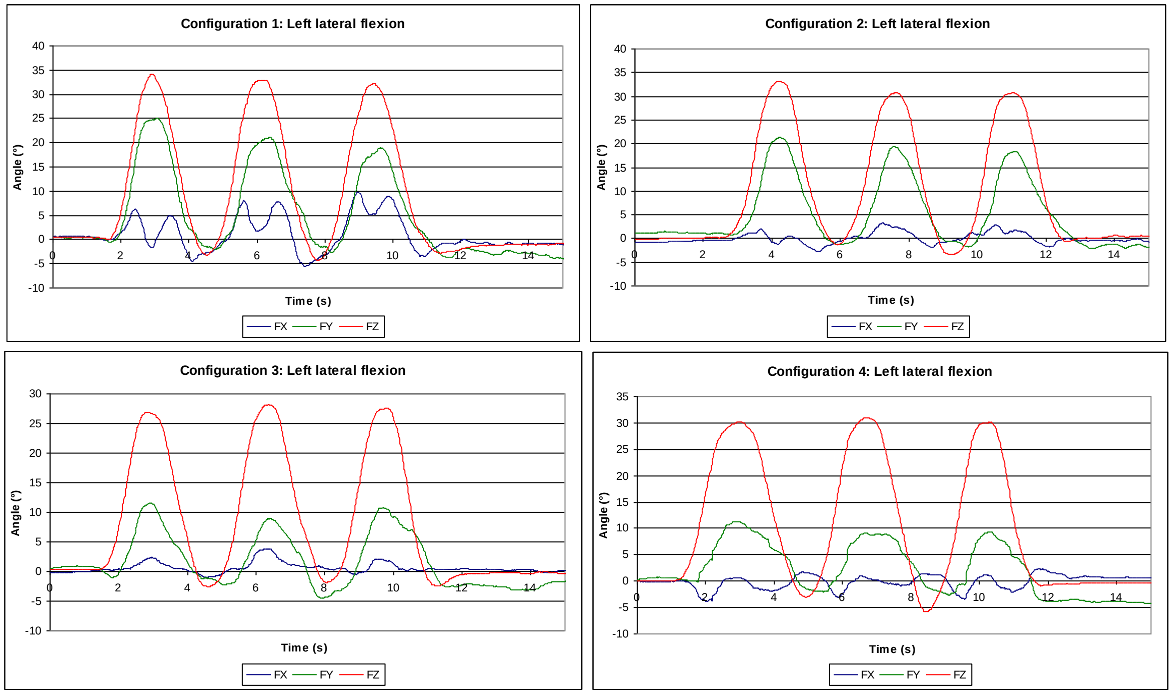
Graphs 5.3.1: Typical graphs of flexion collected with 4 different attachment configurations.



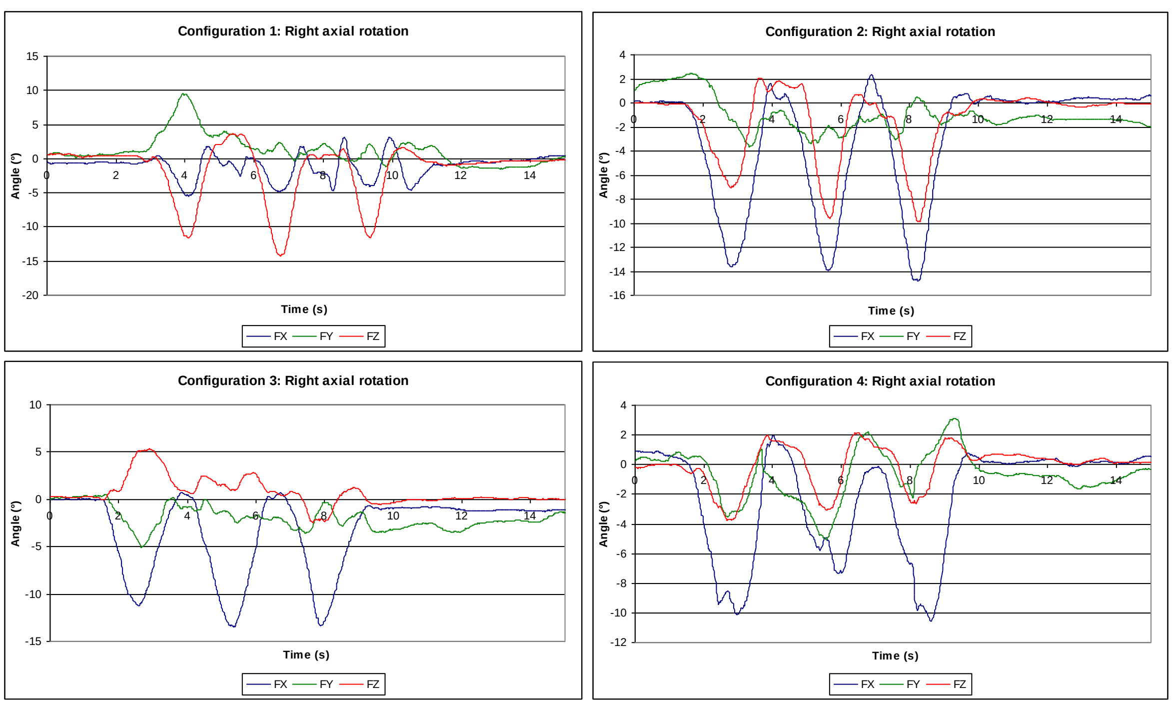
Graphs 5.3.2: Typical graphs of extension collected with 4 different attachment configurations.



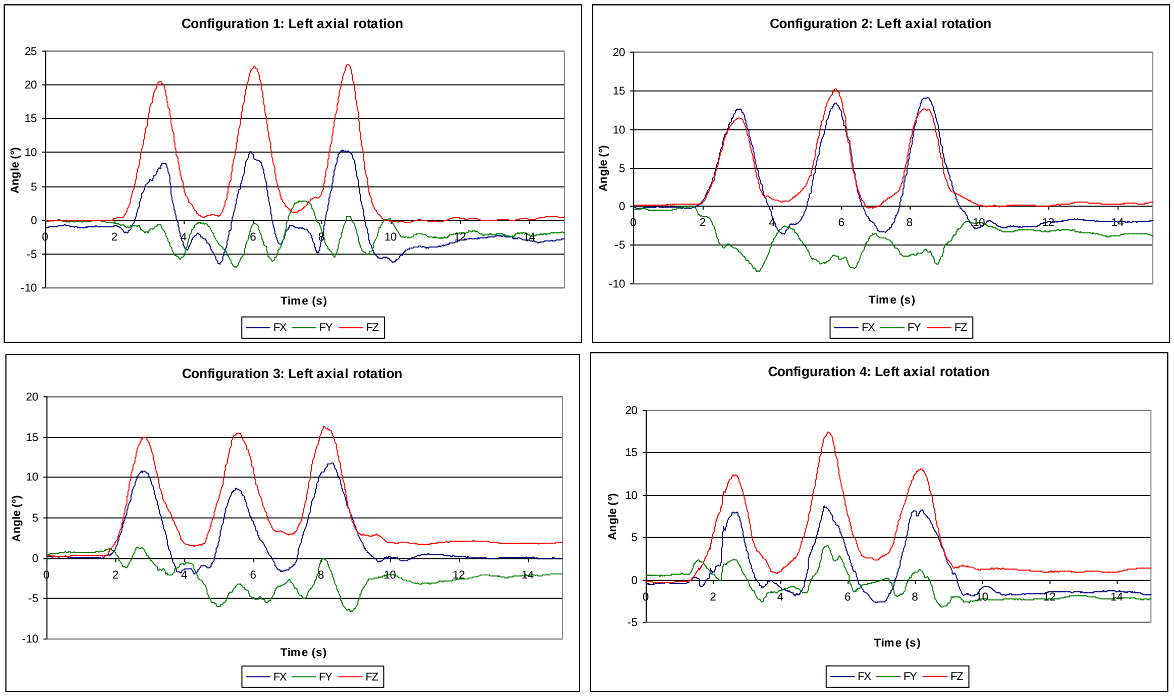
Graphs 5.3.3: Typical graphs of right lateral flexion collected with 4 different attachment configurations.



Graphs 5.3.4: Typical graphs of left lateral flexion collected with 4 different attachment configurations.



Graphs 5.3.5: Typical graphs of right axial rotation collected with 4 different attachment configurations.



Graphs 5.3.6: Typical graphs of left axial rotation collected with 4 different attachment configurations.

5.3.3 Discussion

Configuration 1 was the least secure attachment method, participants reported feeling the sensors were loose and felt to move during their physiological movement performance. It was also more difficult to align the sensors due to non-rigid attachment. From the results, Configuration 1 produced the largest values in the coupled axes during movements, these 'coupled motions' were a combination of true coupled motions and errors due to skin movement and loose sensor attachment. While in Configurations 3 and 4, the least errors were observed due to a more secure attachment. Configurations 2, 3 and 4 also provided a better platform for sensor attachment and better sensor alignment compared to Configuration 1.

Based on radiographical analysis (Pearcy 1985), normal lumbar movement produces little coupled motion (1° to 3°) during flexion and extension, 2° to 10° during lateral flexion and approximate 0° to 9° of coupled motion during axial rotation. Peach et al. (1998) on the other hand observed 3° to 4° of coupled motion during flexion, 8° to 11° during lateral flexion and 3° to 8° of coupled motion during axial rotation. With skin surface measurement, spinal lumbar motion is often reported to exhibit a higher range of coupled motion (Peach et al. 1998; Russell et al. 1993), which could be due to skin artefacts as a result of insecure sensor attachment. Configuration 1 in the current study reported high ranges of 'coupled motion' of 20° to 24° during flexion, which was almost 2 to 3 times of those reported by Peach et al. (1998) and a minimum of 7 times higher than those reported by Pearcy (1985). Configurations 3 and 4 recorded lower ranges of coupled motions (3° to 6°) during flexion when compared to Configuration 1, and Configuration 2 (4° to 7°). The high ranges of coupled motion in Configuration 1 was also observed during lateral flexion (7° to 25°) and axial rotation movements (7° to 23°), where these ranges of coupled motions were almost double those reported in Configurations 3 and 4. All 3 Configurations 2, 3 and 4 reported a maximum of 4° and 21° of coupled axial rotation and flexion during lateral flexion movement; and a maximum of 8° and 18° of coupled sagittal and lateral movements during axial rotation. This 'coupled motion' reported in Configurations 2, 3 and 4 of the current study were found to be slightly higher than those reported by Peach et al. (1998). These differences could be due to the individual factors of the participants, methods of measurement, equipment used and the study design in both studies. It could also be due to the motivation of the participants, the participants in the current study repeated the 6 physiological movements 4 times for the 4 different configurations, the performance of the participants in performing these movements after a few trials might have deteriorated due to tiredness. Another limitation of this experiment was only 2 participants were recruited for the experiment thus the ranges of movement and coupled movement might not be as represent able as studies measured with a larger sample, e.g. Peach et al. (1998).

There are many factors that could result in different ranges of movement for each configuration. Although the participants were requested to perform the movements as similarly as possible for all the configurations, it was not possible to ensure exactly the same amount of movement each time. During this study, there were no warm up procedures before the data collection took place, this could have led to a slight increase in range of movement in the later data due to the warming up of the spinal structures; or participants have been tired after undertaking a few trials and not move as much as before. Another possible source of error in the results could be due to the difficulties in the palpation of anatomical landmarks. McKenzie and Taylor (1997) reported that intra-examiner reliability in locating lumbar spinal levels by palpation ranged from 84% to 96% and inter-examiner reliability was 56%. In this experiment, the palpation was performed by the same physiotherapist for all participants and the lumbar spinal levels were verified with ultrasound scanning, which therefore minimised the error due to anatomical landmark identification.

There was no hindrance or discomfort reported by the participants with the use of plastic plate between the sensor and the skin, the participants also reported that Configurations 2, 3 and 4 did not affect natural movements.

In this experiment, it was found that Configurations 3 and 4 produced the most secure attachment method with the least errors reported in the coupled axes. However Configuration 4 would be impractical for spinal posture and motion measurement during normal daily activities due to the protruding nature of the attachment platform. Although Configuration 2 performed better than Configuration 1, it might not be as secure in spinal motion measurement during normal daily activities over a long period of time. Therefore Configuration 3 was concluded to be the best sensor attachment method for long term spinal motion measurement during normal daily activities. A secure sensor attachment method is important in skin surface measurement as skin movement and loose connections could induce large errors and thus impair the reliability of a study.

5.4 Summary and conclusions

To maximise the accuracy of 3 dimensional spinal motion measurement using skin surface motion sensors, it is important to understand the possible sources of error in order to explore possible methods of minimising these errors. In this chapter, the errors caused by misalignment of the sensors with the plane of movements and sensor attachment had been examined. It was found that it was especially important for the moving sensor to be aligned with the plane of movement as well as possible to minimise errors in the coupled axes, as well as providing better accuracy in detecting the main plane of movement. When the moving sensor was misaligned to the plane of movement, this caused the body frame of the sensor to be tilted from the main moving plane which hence resulted in the 3 axes of the sensors measuring a component of the movement rather than the true planar movement. The reference sensor was found to be not as critical in terms of alignment in this study. The reference sensor was absolutely stationary during the experiment and no change in rotation was experienced in any of the axes, therefore it did not contribute to errors in the coupled axes as seen in the earlier configuration. However for spinal motion measurement with human participants, the reference sensor may not be stationary and it may contribute certain errors to the results. Although post processing of the data may be possible in correcting errors due to misalignment, this type of algorithm is usually complex and erroneous especially in a 3 dimensional moving coordinate system. Hence, in order to produce valid spinal motion measurement data, it was essential to ensure minimisation of errors by achieving accurate alignment of the sensors.

Another factor to be taken into consideration is the security of sensor attachment as insecure attachment will produce variable errors through skin movement and loose fixation. The experiments discussed in this chapter indicated that a plastic plate between the sensor and the skin provided a more reliable and consistent platform for sensor attachment and alignment. The deployment of a Velcro strap provided further security of the sensors on the attachment locations.

From this chapter, it can be concluded that secure sensor attachment using base plates and external strapping coupled with ensuring accurately aligned sensors to the plane of movement would minimise errors often seen in external spinal motion measurement, and would consequently contribute to a more reliable and valid study.

Chapter 6. The validity of spinal posture and motion measurement using an inertial measurement system during static and dynamic movements

6.1 Overview

As discussed in Chapter 3, inertial measurements systems had been identified as possible 3 dimensional spinal posture and motion measurement instruments for use outside the laboratory setting over an extended period of time. As not many studies in measuring spinal posture and motion using inertial measurement systems have been reported, it was necessary to validate such systems for spinal posture and motion measurement before developing a protocol for long term spinal posture and motion monitoring study outside the laboratory.

In Chapter 4, inertial measurement systems were shown to be feasible in measuring 2 dimensional and 3 dimensional movements using hinged wooden models, the results were compared to data collected with an electromagnetic tracking system and found to be comparable. The work discussed in Chapter 5 showed that it is important to ensure the security of sensor attachment and ensure accuracy of alignment in order to minimise errors in skin surface based measurement. In this chapter, the validity of motion measurement using inertial measurement systems on the human spine is examined using an electromagnetic tracking system, the 'gold standard' in skin surface spinal motion measurement as a reference.

The objective of this study was to examine the feasibility and validity of spinal posture and motion measurements and monitoring using an inertial measurement system.

Within the study reported in this chapter, spinal postures and a range of different functional activities were measured and identified utilising the inclination data from accelerometers as demonstrated in Section 4.3. The methods and results are discussed below in detail.

6.2 Participants and recruitment

This part of study was approved by the University of Brighton's Faculty of Health and Social Science Ethics and Governance Committee. A copy of the letter of approval can be found in Appendix Section A1.1a.

Participants for this study were recruited by posting recruitment posters on the University of Brighton's student website, studentcentral (the University's virtual learning environment) and also advertised through email within the University. A copy of the recruitment poster is attached in Appendix Section A1.2a. Interested participants who contacted the researcher were given information about the study's nature, its procedures and a copy of a participant information sheet by email. A copy of the information sheet for this study is provided in Appendix Section A1.3a. An appointment for data collection was made after the participants had agreed to participate. Interested participants were given as much time as they would like to decide if they were interested in participating, they were also assured that they could change their mind regarding participation at any time even if an appointment for data collection had been made. Interested participants were free to raise any questions or concerns regarding the study at any time by contacting the researcher by telephone or email. Participants who agreed to participate were requested to wear 2 piece clothing (shirt/t-shirt with trousers/skirts/shorts) on the day of data collection to ensure the attachment of sensors to the lumbar spine would cause minimal inconvenience to the participants.

The study was conducted in the Human Movement Laboratory, Robert Dodd Annexe 1 building. Participants were given a printed information sheet and a verbal explanation of the nature and procedures of the study on arrival at the Human Movement Laboratory on the day of data collection. Participants were then given as much personal time as they wished to decide if they still wished to continue with their participation in the study. The participants signed a consent form (as shown in Appendix Section A1.4a) if they decided to continue with the study, on the understanding that they could withdraw from the study at any time without penalty or prejudice, or the need to provide a reason for withdrawal. Participants were given the opportunity to raise any questions or concerns regarding the study at any time.

During the process of identifying the anatomical landmarks of the participants and the attachment of sensors, there were certain levels of undress required in order to expose the lumbar spine as the sensors needed to be attached to the first lumbar and first sacral spinous processes of participants. These procedures were performed in a private area of the laboratory to ensure privacy. The sensors stayed underneath the participants' clothing during the whole process of data collection. The detailed procedure of anatomical landmark identification and sensor attachment is discussed in Section 6.3 below.

Participants experienced no pain or discomfort during this study. There was no known risk associated with the method of data collection, or with the equipment used in this study. Participants had the right to request access to their own personal measurement information and results through the researcher, either via a request on the day of data collection or by telephone or email at a subsequent time.

A total of 30 participants were recruited for this study, 4 were excluded from the study on the basis of the exclusion criteria described below. A power analysis showed that a sample size of 26 would be sufficient to reveal any significant differences between 2 different measurement systems (power = 0.974, $p < 0.05$). The power analysis was completed using a paired t-test based on the means and standard deviations of ranges of motion provided by a previous study carried out by Van Herp et al. (2000). The study by Van Herp et al. (2000) was chosen for the power calculation in this study based on the validity of the results reported by the authors. They performed the study with a large sample size (100 participants), and had taken precautions in dealing with possible errors due to skin movement and sensor alignment. Furthermore the authors (Van Herp et al. 2000) utilised an electromagnetic tracking system in their study, which corresponded to 1 of the instruments used in the current study. The power analysis for this study was performed for all 6 movements (flexion, extension, left and right lateral flexion; and left and right rotation) with the sample size required for detecting changes in flexion being the largest amongst all the 6 movements. For flexion, the range of motion for an age group of 20 to 49 years was reported to be 58.2° ± 6.9° (Van Herp et al. 2000). The effect size was estimated to be 0.725 if the least clinically meaningful difference to be detected was 5° in this study. For $p < 0.05$, a sample size of 26 yields a power of 0.974.

In this study, healthy participants who had no back pain which required medical attention in the past 12 months prior to data collection were recruited in order to validate the feasibility of inertial sensors in 3 dimensional spinal posture and motion measurement. Participants who had difficulties and limitations in performing daily physical activity and any condition that could affect normal spinal posture and motion patterns were excluded from the study as this could complicate and deflect the initial aim of the study. Health concerns that could limit the activity tolerance were also a determinant in recruitment.

As discussed in Section 2.2, as the spine ages, the intervertebral discs, vertebral end plates, vertebral bodies and the zygapophyseal joints go through biochemical and structural changes (Bogduk 2005). These changes can affect the mechanical properties of the spine as well range of movement. Therefore, a young adult group of between 20 to 44 years of age (Soanes and Stevenson 2006) were recruited for the study as this study was to focus on measuring and monitoring spinal posture and motion of an age group that is more prone to non-specific low back pain.

The inclusion and exclusion criteria for the study are summarised as follows.

Inclusion criteria were:

- 20 to 44 years of age (both genders)
- body mass index (BMI) between 18.5kg/m^2 to 30kg/m^2
- no history of back pain or leg pain that could be related to a spinal problem or requiring medical attention/treatment in the past 12 months.

Exclusion criteria were:

- underweight or obese (body mass index, BMI < 18.5kg/m^2 for those who were underweight and BMI > 30kg/m^2 for those who were obese (WHO 2006))
- difficulties and limitations in performing daily physical activities;
- pregnancy;
- any known musculoskeletal disorders;
- any neurological or orthopaedic disorders;
- rheumatoid arthritis;
- joint dislocation;
- serious observable abnormality in spinal posture; and
- injury, surgery, infection, bone fracture, dislocation, or diseases related to the spine; that may affect normal spinal posture and motion patterns
- cancer or other serious conditions;
- asthma;
- coronary heart disease; that may decrease activity tolerance
- leg length discrepancy of more than 20mm as this was found to affect the symmetry of the spinal structures and thus affecting normal spinal posture and movement patterns (Kakushima et al. 2003, Lee and Turner-Smith 2003)
- allergy or hypersensitivity to the adhesive tapes used in this study.

The general information relating to the 26 participants (12 males and 14 females) in this study is summarized in Table 6.2.1. All the participants were either students or staff of the University.

Participant	Gender	Age (year)	Height (m)	Weight (kg)	BMI (kg/m^2)
1	M	29	1.83	85	25.38
2	M	25	1.83	86	25.68
3	M	22	1.69	63	22.06
4	M	36	1.72	68	22.99
5	M	22	1.77	70	22.34
6	F	41	1.51	46	20.17
8	F	43	1.69	77	26.96
9	F	38	1.78	76	23.99
10	F	42	1.73	69	23.05
11	M	25	1.78	76	23.99
12	M	22	1.77	70	22.34
13	F	42	1.63	55	20.70
15	F	25	1.71	62	21.20
17	F	28	1.71	56	19.15
18	F	24	1.59	46	18.20
20	F	25	1.72	68	22.99
21	M	21	1.78	70	22.09
22	M	34	1.79	79	24.66
23	M	24	1.66	73	26.49
24	F	27	1.77	61	19.47
25	M	23	1.83	63	18.81
26	F	27	1.76	62	20.02
27	F	21	1.60	50	19.53
28	F	24	1.68	55	19.49
29	F	22	1.71	55	18.81
30	M	22	1.81	87	26.56
Minimum		21.00	1.51	46.00	18.20
Maximum		43.00	1.83	87.00	26.96
Mean		28.23	1.73	66.46	22.20
Standard deviation		7.42	0.08	11.65	2.68

Table 6.2.1: General information relating to the 26 participants in the study to examine the feasibility of inertial measurement systems in spinal posture and motion measurement, M refers to male and F refers to female

6.3 Methods

On the day of data collection, after participants had agreed to continue with participation and signed the consent form, measurements of height, weight and lower limb length were taken and questions regarding participants' general health were recorded (refer to Appendix Section A1.5). The length of the lower limb was measured with a tape measure from the anterior superior iliac spine (ASIS) to the medial malleolus (Beattie et al. 1990) in standing, as shown in Figure 6.3.1. Participants' shoulder width was also measured using a tape measure; the measurement was taken between the participants' left and right lateral borders of the acromion processes, with participants standing with both their hands resting at the sides of their body. Markers were then put on the floor to indicate participants' shoulder width for participants to stand with their feet at this distant during the physiological movement measurements.

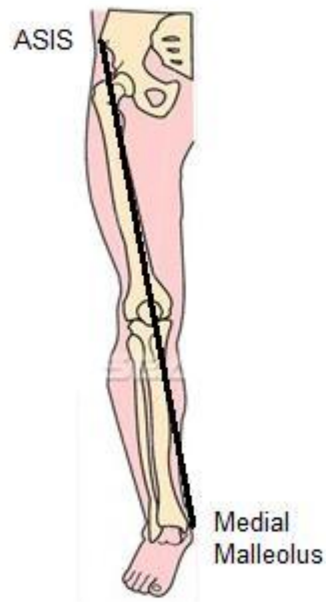


Figure 6.3.1: The length of the lower limb was measured from ASIS to the medial malleolus using a tape measure

There were 3 main types of activities involved in this study: physiological movements, static postures and functional activities. Details of the 3 main activities are discussed in the following pages. Two types of measurement systems were used in this study, which were the inertial measurement systems (Xsens) and electromagnetic tracking systems (Fastrak). Two sensors were used for each measurement system. The electromagnetic tracking sensors (Fastrak) were used to measure physiological movements only while inertial sensors (Xsens) were used to measure all 3 types of activities. Both the Fastrak and Xsens systems were used to measure physiological movements separately, as the 2 systems were found to interfere with each other if placed close to each other on the same spinal segment. The Fastrak system was used as a reference system to validate spinal movement measurement obtained from the Xsens system. The Xsens sensors were set to collect data at 100 samples/second in order to provide high resolution data even during the monitoring of dynamic activities, and 60 samples/second was the fixed sampling rate for the Fastrak sensors.

The procedure started with the attachment of 2 Fastrak sensors to the spinous processes of L1 and S1 of the participants. The sensors were attached to the participants' spine by using the method discussed in Section 5.2 (Configuration 3) and as shown in Figure 6.3.2. The spinous processes were located by palpating the participants' spine in a standing posture; the procedure was carried out by a trained physiotherapist. S2 was located at the level of posterior superior iliac spine (PSIS), by palpating intervening vertebrae from S2, L1 and S1 were identified and marked with skin markers. The locations of the bony landmarks were verified by checking the iliac crest level aligned at approximately L4-L5 (Black et al. 1996; Ng et al. 2001). To further validate the locations, ultrasound imaging was used to determine the anatomical points by scanning the spinous processes from S2 to L1.

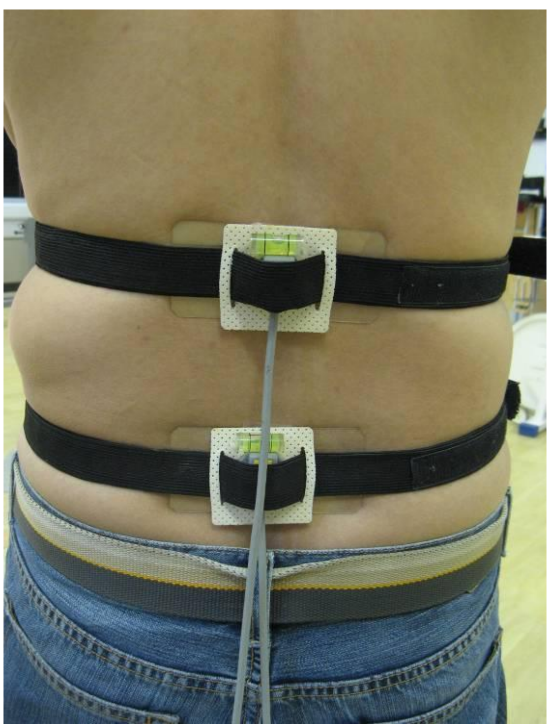


Figure 6.3.2: Attachment of Fastrak sensors to the L1-S1 spinous processes

Figure 6.3.3: Attachment of Xsens sensors to the L1-S1 spinous processes

After sensors were attached to the participants, participants were requested to perform 6 physiological movements, 6 static postures and 4 functional activities as tabulated in Figure 6.3.4.

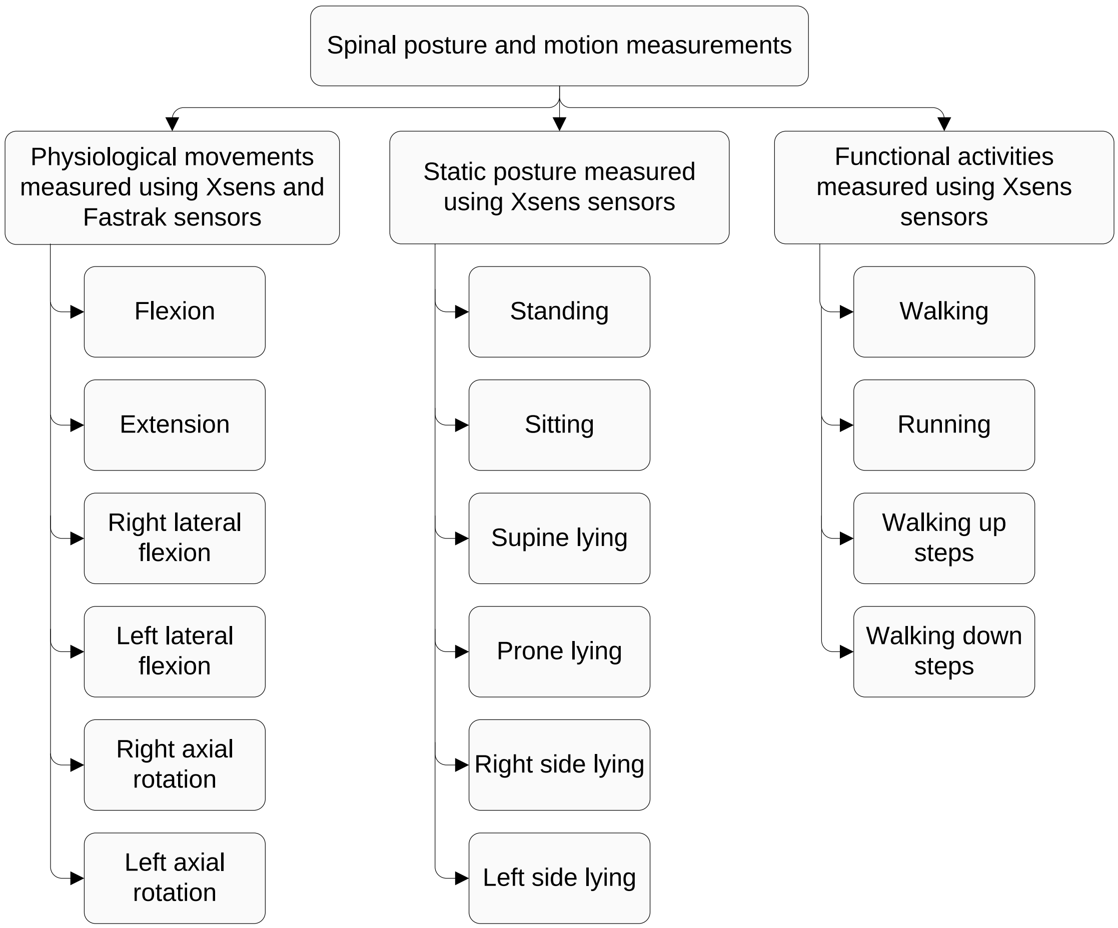


Figure 6.3.4: The breakdown of the 3 main types of activities measured in the study to validate inertial measurement systems in spinal posture and motion measurement

Data collection started with 6 physiological movements, which were flexion, extension, lateral flexion to both left and right sides, and axial rotation to both left and right sides. The descriptions of these movements are described below.

Physiological movements

Flexion. Participants bent forward with both hands placed in front of their thighs and tried to touch their toes.

Extension. Participants placed their hands on the back of their thighs and bent backwards sliding their hands down the back of their thighs with the movement.

Lateral flexion. Participants placed their hands by the side of their thighs, bent sideways and slid their hands along the sides of their thighs.

Axial rotation. Participants crossed their arms across their chest and rotated their trunk.

Pelvic movement of the participants was not passively restricted in this study; however they were requested to limit pelvic movement as much as possible. Participants were requested to perform all 6 physiological movements with their knees extended. Before data collection started, participants were encouraged to perform each of the physiological movements once to familiarise themselves with the procedure. They were encouraged to move to their full range of movement whilst standing with their feet shoulder width apart as guided by markers on the floor. The participants performed the movements at their chosen pace to ensure comfort. They were requested to perform each movement 3 times, and a 30 second period was allowed for the data collection for each movement, the mean value of the 3 cycles was taken for comparison. Before performing each movement, they were requested to stand upright for 5 seconds to enable a reference or neutral position to be established for the physiological movements.

After performing the 6 physiological movements, the Fastrak sensors were detached and Xsens sensors were attached to the participants using the same attachment method as for the Fastrak sensors, as shown in Figure 6.3.3. The data logger for the Xsens system was worn around the participants' waist. Bluetooth function was selected for wireless operation. The participants were requested to repeat the same 6 physiological movements as described for the Fastrak sensors.

Participants were next requested to perform 6 different static postures as explained below. They were asked to stay in each posture for 20 seconds and 10 seconds was allowed for the transition from one posture to another. A plinth and a pillow were used for all the lying postures to improve comfort.

Static postures

Sitting. Participants were provided with a stool with no armrest or backrest, the stool provided support from the ischial tuberosities to the middle of the thighs. The height of the stool was adjusted for participants to 110% of the distance from the apex of the fibular head to the floor, this arrangement could allow participants to rest their feet on the floor (Shum et al. 2005). Participants rested both feet on the floor and put both hands on their lap, with eyes looking forward and sat in an upright sitting posture.

Standing. Participants stood with their feet shoulder width apart with both hands by the sides of the body and with their eyes looking forward.

Supine lying. Participants lay on their back with both legs straight and both hands placed by the side of body. A pillow was provided to support the participants' head and neck.

Prone lying. Participants lay on their abdomen with both legs straight and both hands by the sides of their body. The head was supported by a pillow and turned sideways to allow for breathing.

Side lying. Participants lay on their right and left sides by placing both hands in front of their chest and bending both hips and knees slightly. A pillow was provided to support their head and neck.

Next, the participants were requested to perform 4 different functional activities, which were walking, running on a treadmill and walking up and down steps, the descriptions on these activities are shown below. The participants were asked to perform each functional activity for approximately 30 seconds.

Functional activities

Walking. Participants walked at their chosen comfortable speed on a treadmill with both hands moving freely with the rhythm.

Running. Participants ran at their chosen comfortable speed on a treadmill with both hands moving freely with the rhythm.

Walking up and down stairs. Participants walked up and down a custom built 4 step stair platform (width x depth x height of 455x335x105mm each step) without a hand rail at their normal comfortable speed. Both hands moved freely at the sides of their body.

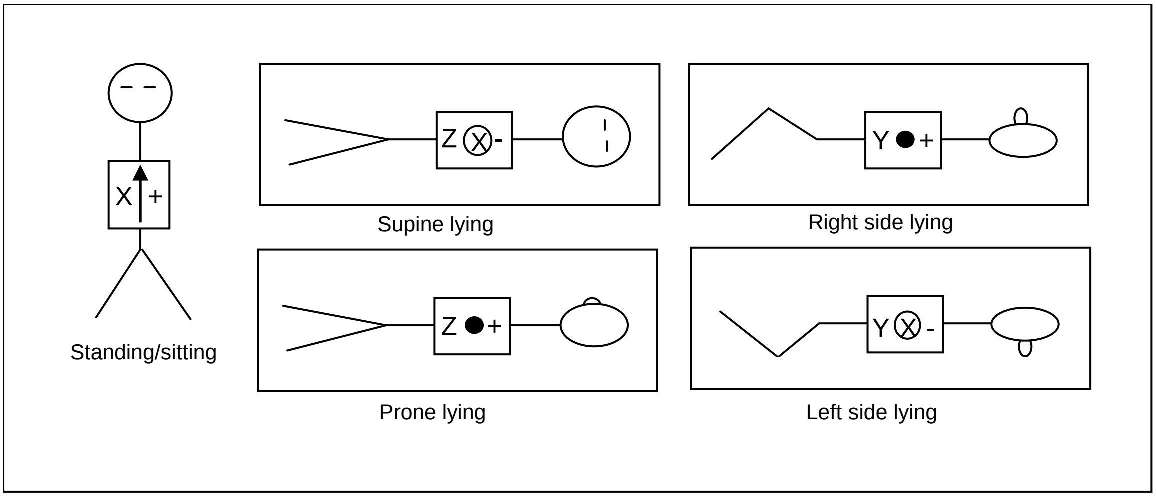
The participants were given as much time as they wished to rest in between each session of data collection. After performing all 4 functional activities, Xsens sensors were detached from the participants. Before the participants left the Human Movement Laboratory, their experience of and comfort during the whole data collection process were discussed with the researcher to enable any improvement in future work.

Data analysis.

All the data from this study were analysed using MATLAB and Microsoft Excel; statistical analysis was performed using SPSS (Statistical Package for the Social Sciences) software.

For physiological movements, the relative angles between L1 and S1 using both measurement systems were calculated using direction cosine matrices and expressed in anatomical rotation angles using Euler angles solutions as discussed in Appendix A6.1, for the sensor at L1 with respect to the sensor at S1. Descriptive analysis was performed on all variables and the relative angles of the 6 physiological movements between the 2 measurement systems were compared using regression analysis, Bland and Altman method (1986) and paired t-tests.

Identification of the different static postures was achieved utilising the capability of accelerometers in inclination measurement during static conditions via their gravitational component. When the X axis, a_X of both inertial sensors was approximately 1g, it was classified as an upright posture which included standing or sitting. Participants were classified as lying prone when the Z axis, a_Z was approximately 1g; as lying supine when a_Z was approximately -1g; as lying on left side when the Y axis, a_Y was approximately -1g; and lying on right side when a_Y was approximately 1g. The value of acceleration (g) for identifying different static postures varied between postures and also the location of sensor being attached, however if the value fell within -0.8g > acceleration (g) > 0.8g, it would be treated similarly with the conditions defined above. A summary of the discriminating approach and a pictorial representation are presented in Table 6.3.1.



	a_X	a_Y	a_Z
Standing	≈ +1g		
Sitting	≈ +1g		
Supine lying			≈ -1g
Prone lying			≈ +1g
Right side lying		≈ +1g	
Left side lying		≈ -1g	

Table 6.3.1: The discrimination approach to identifying different static postures using accelerometers

From Table 6.3.1, it can be observed that standing and sitting produce almost similar accelerometer data, therefore a separate step, by calculating the lumbar curvature/lumbar lordosis angle was used to differentiate between these 2 postures. Lumbar curvature angle was calculated based on inclination values provided by the accelerometers.

The lumbar curvature angle was calculated using the Cobb method which is often employed in radiographic measurement of lumbar lordosis (Been et al. 2007; Harrison et al. 2001; Lord et al. 1996). Harrison and colleagues (2001) tested the reliability of 4 different methods in radiographic analysis of lumbar lordosis and recommended the Cobb method and the tangent method as the most reliable and practical methods. The Cobb method used the relative angle between the lines of the superior or inferior endplates to measure curvature, while the tangent method used the lines drawn through the posterior superior and posterior inferior corners of the vertebral bodies, the angle created at the intersection of these lines being the relative curvature angle (Harrison et al. 2001). In this study, the tangent method was not chosen due to the vertical axis of the sensor, the X axis, although capable of giving inclination data of the spine with respect to the vertical axis, the direction of tilt (flex or extend) was not able to be differentiated as the value would always be positive if the participant was in upright postures. When the sensitive axis of the accelerometer was pointing above the horizontal axis, the reading was always positive leading to a potential mis-calculation of curvature angle. Consequently the Cobb method was selected as the most suitable method to be used in this study.

Figure 6.3.5 below shows how the lumbar curvature angle (LC) was calculated using inclination information from the Z axis, the horizontal axis of the accelerometer pointing from anterior aspect to posterior aspect of the spine. When the Z axis of the sensor on L1 spinous process was pointing below the horizontal axis due to lumbar curve of L1, the accelerometer produced a negative inclination value, $-LC_2$; and when the Z axis of the sensor on S1 spinous process was tilted above the horizontal axis, a positive inclination, LC_1 was produced. Therefore, lumbar curvature, LC can be expressed as follows:

$$LC = LC_1 + LC_2 \qquad \text{E 6.3.1}$$

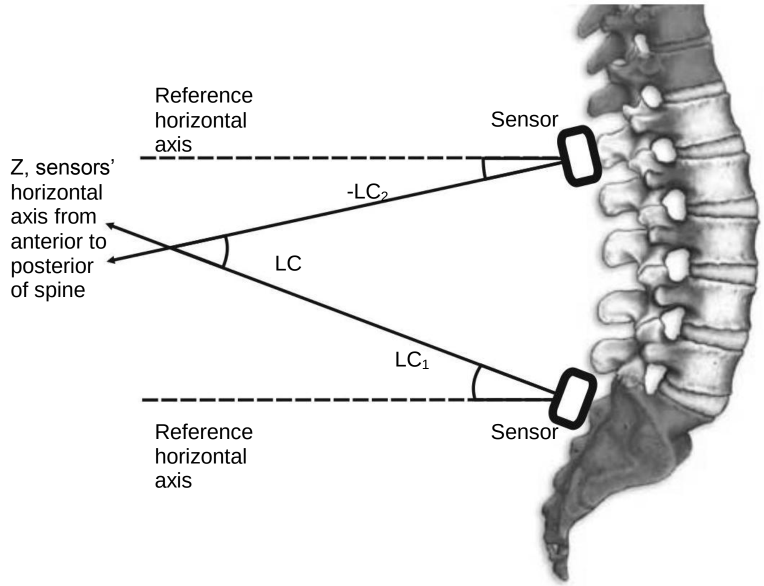


Figure 6.3.5: Illustration on how lumbar curvature angle was calculated with inclination data from accelerometers for differentiation between standing and upright sitting

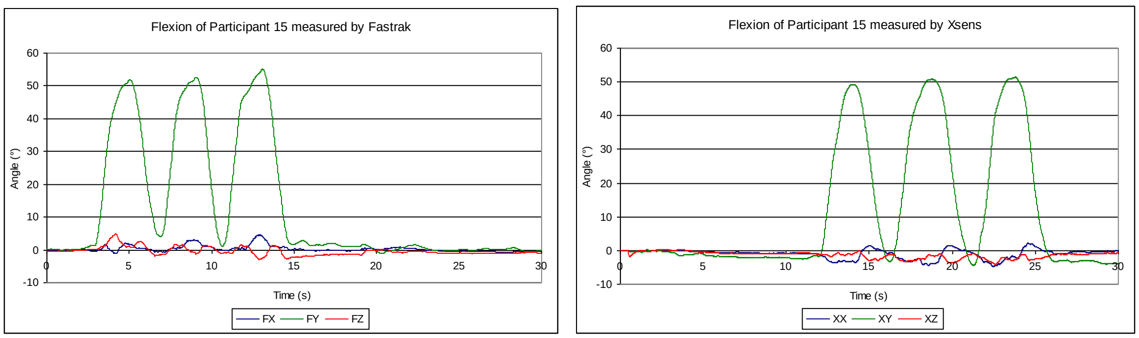
The lumbar curvature angle during standing and sitting was calculated using equation E 6.3.1 and the values were compared using paired t-test.

The amplitudes of the accelerometer data were calculated on all axes and compared among the functional activities to examine their differences. Frequency components of different functional activities were analysed using Fast Fourier transform (FFT) with MATLAB software. FFT is an algorithm to compute a sequence of values into components of different frequencies. The frequency and amplitude of different functional activities were analysed to determine the characteristics of these movements.

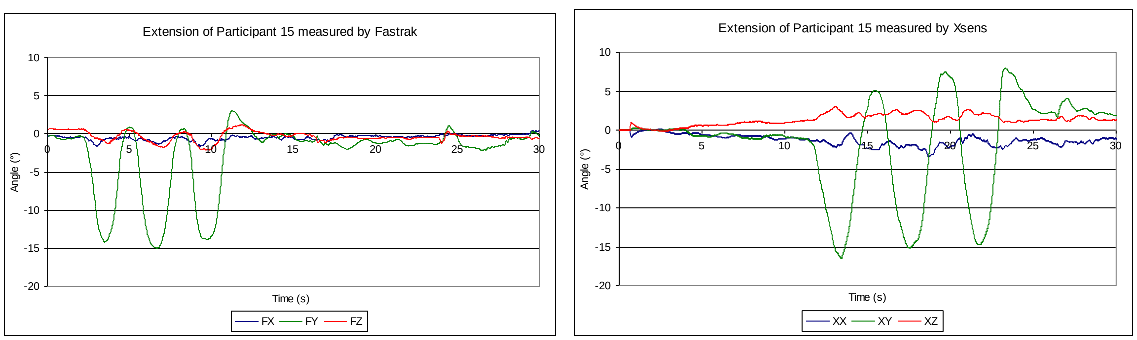
6.4 Results

Physiological movements

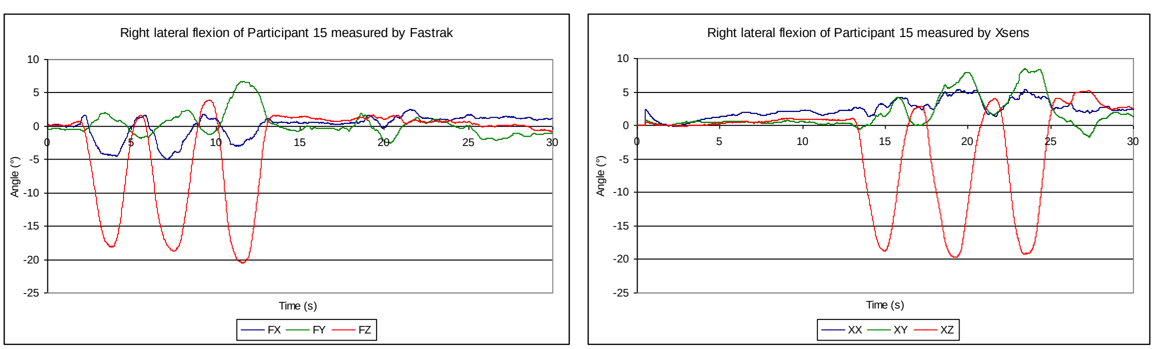
Graphs 6.4.1 to 6.4.6 show plots of typical plotted results recorded during the 6 physiological movements with the results collected with Fastrak sensors on the left and with Xsens sensors on the right; both were adjusted to have the same scale range for easy visual comparison. The letter 'F' placed in front of the X, Y and Z axes indicates that these data were taken using Fastrak sensors; while the ‘X’ letter found in front of the X, Y and Z axes indicates that the data were measured using Xsens sensors. Flexion and extension are represented in the Y axis; lateral flexion in the Z axis; and axial rotation was recorded in the X axis. These graphs were taken from the results of Participant 15 of the study.



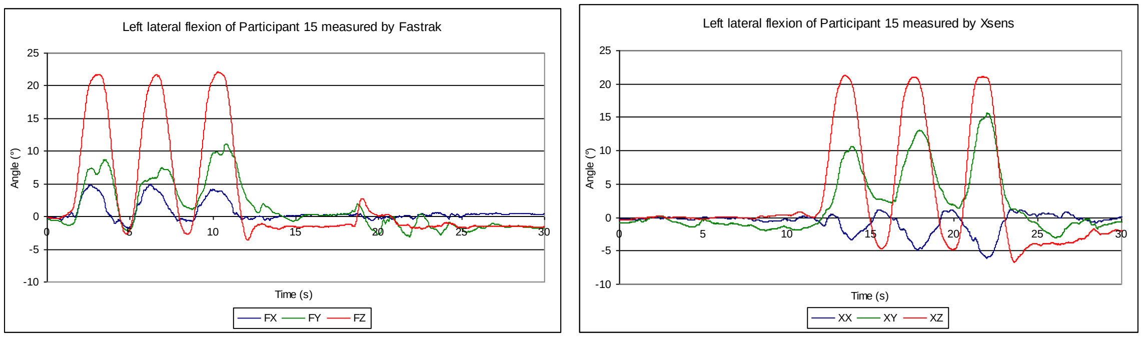
Graph 6.4.1: Typical plotted results for flexion (positive rotation on Y axis) measured by Fastrak (left) and Xsens (right)



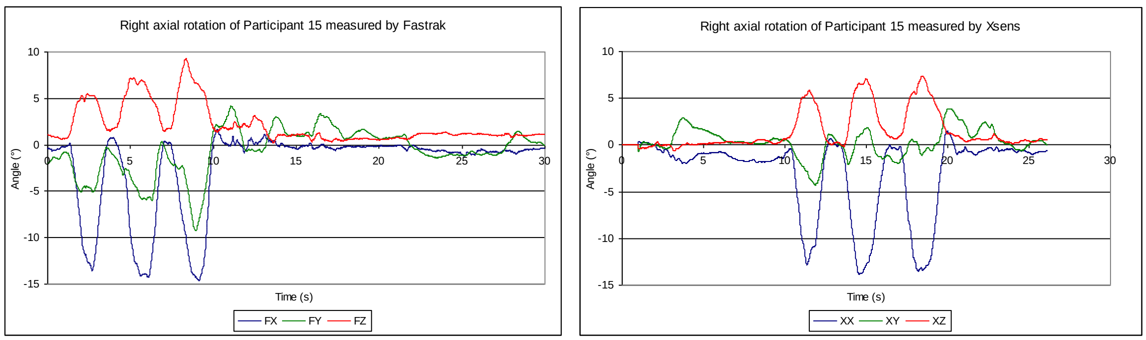
Graph 6.4.2: Typical plotted results for extension (negative rotation on Y axis) measured by Fastrak (left) and Xsens (right)



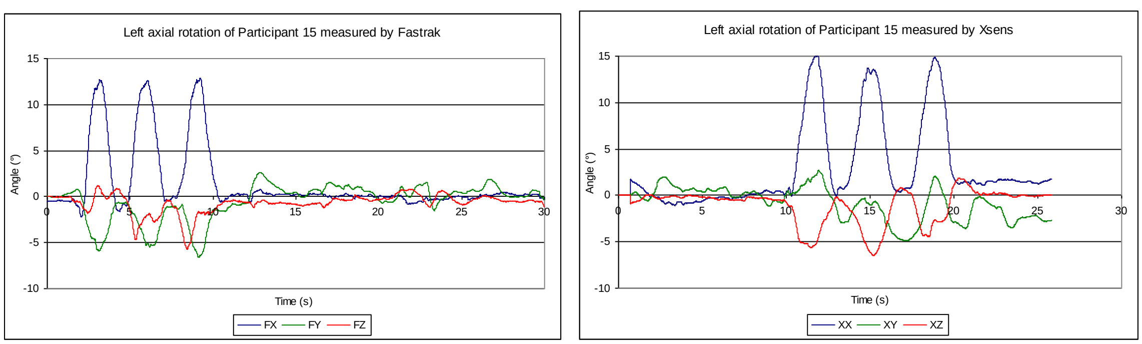
Graph 6.4.3: Typical plotted results for right lateral flexion (negative rotation on Z axis) measured by Fastrak (left) and Xsens (right)



Graph 6.4.4: Typical plotted results for left lateral flexion (positive rotation on Z axis) measured by Fastrak (left) and Xsens (right)



Graph 6.4.5: Typical plotted results for right axial rotation (negative rotation on X axis) measured by Fastrak (left) and Xsens (right)



Graph 6.4.6: Typical plotted results for left axial rotation (positive rotation on X axis) measured by Fastrak (left) and Xsens (right)

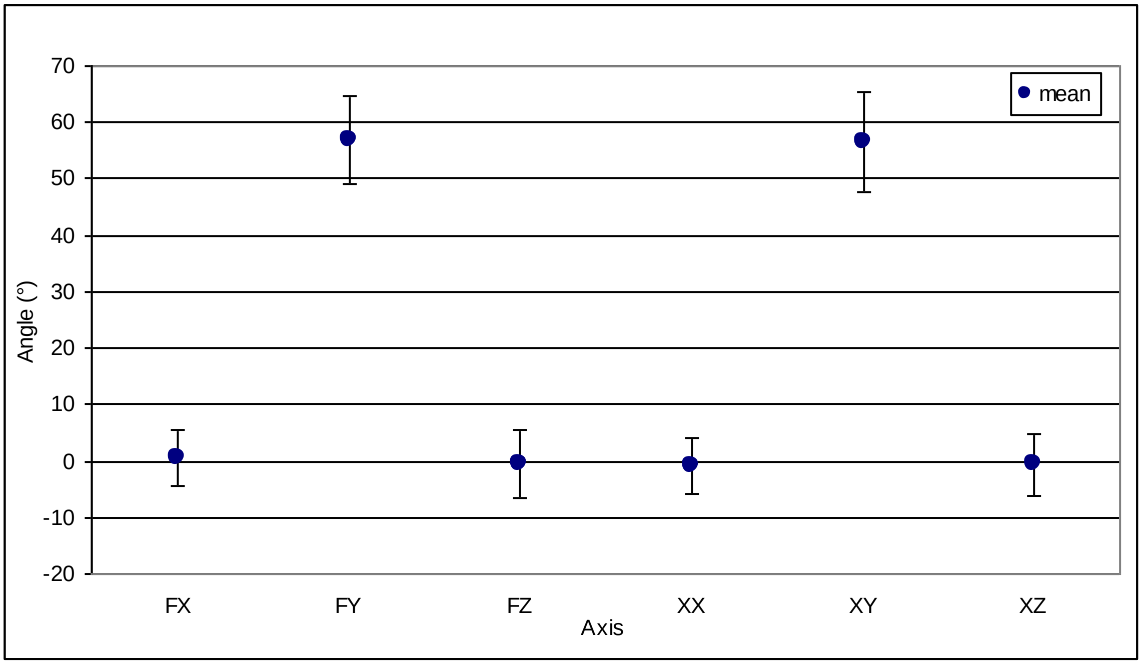
From the graphs above, it can be seen that both Fastrak and Xsens systems were producing ranges of movement similar to each other. This showed that the Xsens system was capable of measuring similar spinal movement ranges and patterns as the Fastrak system, which was the reference system in this study. Different physiological movements were able to be identified by looking at the orientation results computed by the gyroscope data. During flexion, a positive rotation was observed on the Y axis; negative rotation was found on the Y axis during extension. Positive rotation on the Z axis indicated left lateral flexion and negative rotation on the same axis represented right lateral flexion. On the X axis, positive rotation was found during left axial rotation and negative rotation was identified as right axial rotation.

From Table 6.4.1, it was observed that the mean values of the 6 physiological movements between the 2 measurement systems were highly comparable to each other. During flexion the mean angle measured by Fastrak sensors was 56.9° and by Xsens was 56.6°. During extension, the mean angle was 26.7° by Fastrak and 26.2° by Xsens. For lateral flexion, they were found to be 26.1° and 25.8° on the right and left sides by Fastrak; 27.3° and 26.6° on right and left sides by Xsens. As for axial rotation, the mean angles were 14.8° and 15.5° measured by Fastrak; and 14.2° and 16.1° by Xsens on the right and left sides respectively. The possible causes for these slight differences between the 2 measurement systems are discussed in Section 6.5. For the detailed physiological movements results of all participants, please refer to Appendix Tables A2.1 to A2.6.

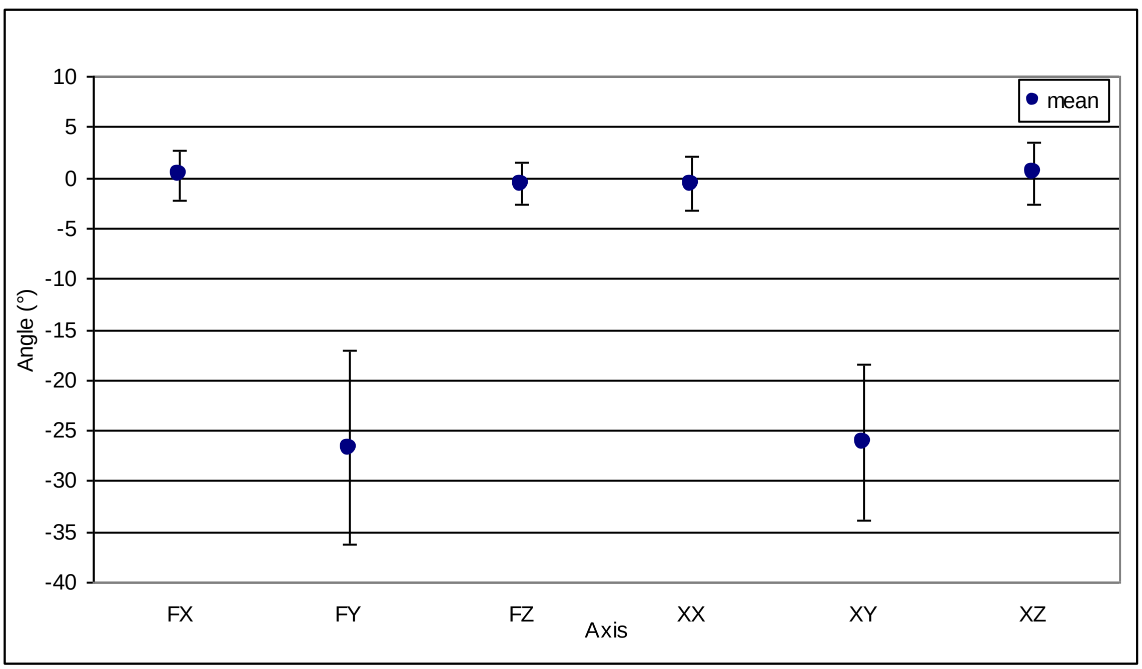
	Fastrak (°)				Xsens (°)			
	Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation
Flexion	44.6	75.6	56.9	7.8	40.0	71.3	56.6	8.9
Extension	-52.7	-9.0	-26.7	9.6	-44.9	-13.1	-26.2	7.7
Right lateral flexion	-47.2	-14.7	-26.1	7.1	-44.2	-13.2	-27.3	7.2
Left lateral flexion	15.2	43.3	25.8	6.7	14.6	41.2	26.6	6.7
Right axial rotation	-23.0	-7.0	-14.8	3.8	-24.6	-8.0	-14.2	3.6
Left axial rotation	9.4	23.7	15.5	3.5	7.1	22.5	16.1	3.2

Table 6.4.1: Descriptive data of anatomical movements measured by electromagnetic tracking systems (Fastrak) and inertial measurement systems (Xsens)

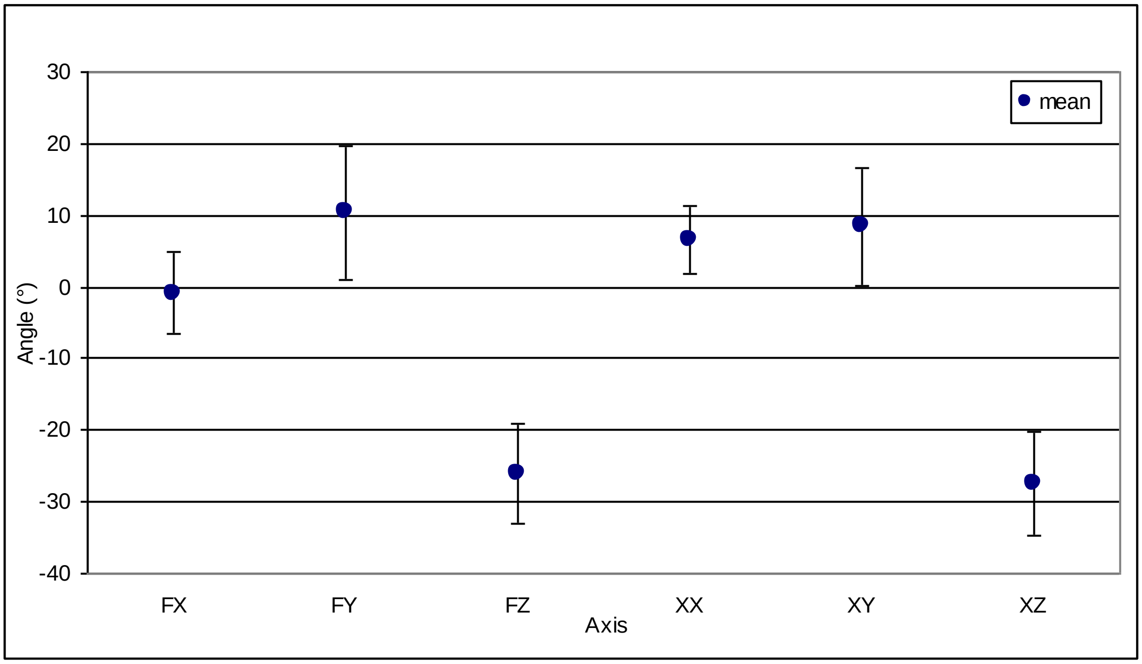
Graphs 6.4.7 to 6.4.12 below show the distributions of the means and standard deviations of the 6 physiological movements between the Fastrak and Xsens systems in all 3 axes, the main movement axis and the 2 coupled axes of both measurement systems.



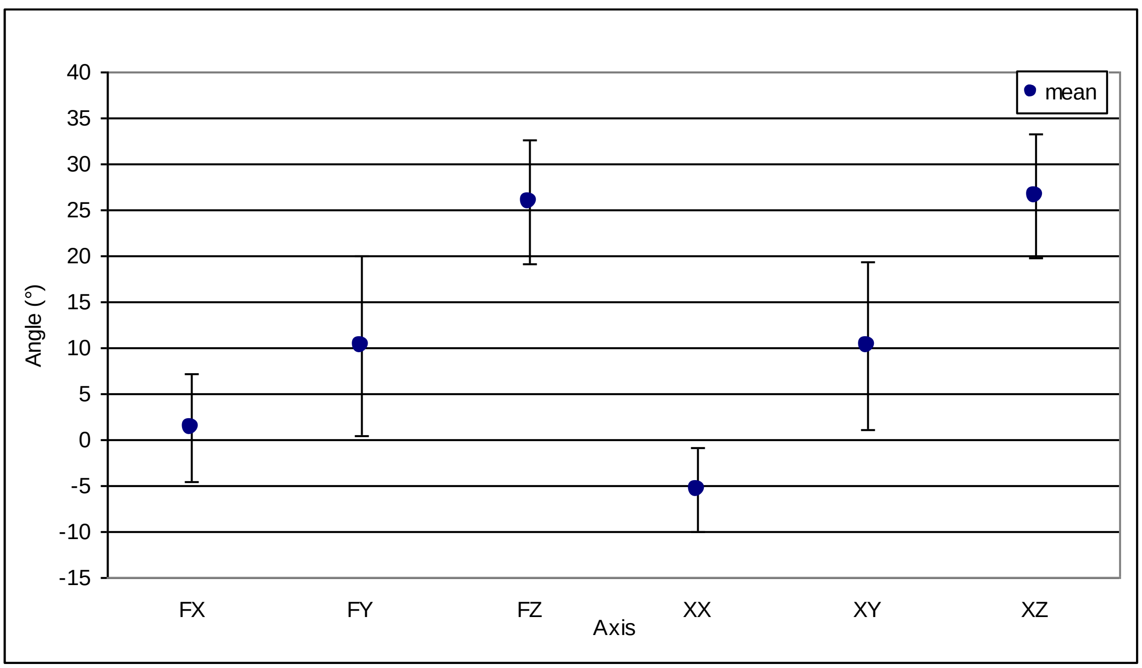
Graph 6.4.7: The distribution of means and standard deviations of flexion on all 3 axes between measurements taken with Fastrak (F) and Xsens (X) sensors



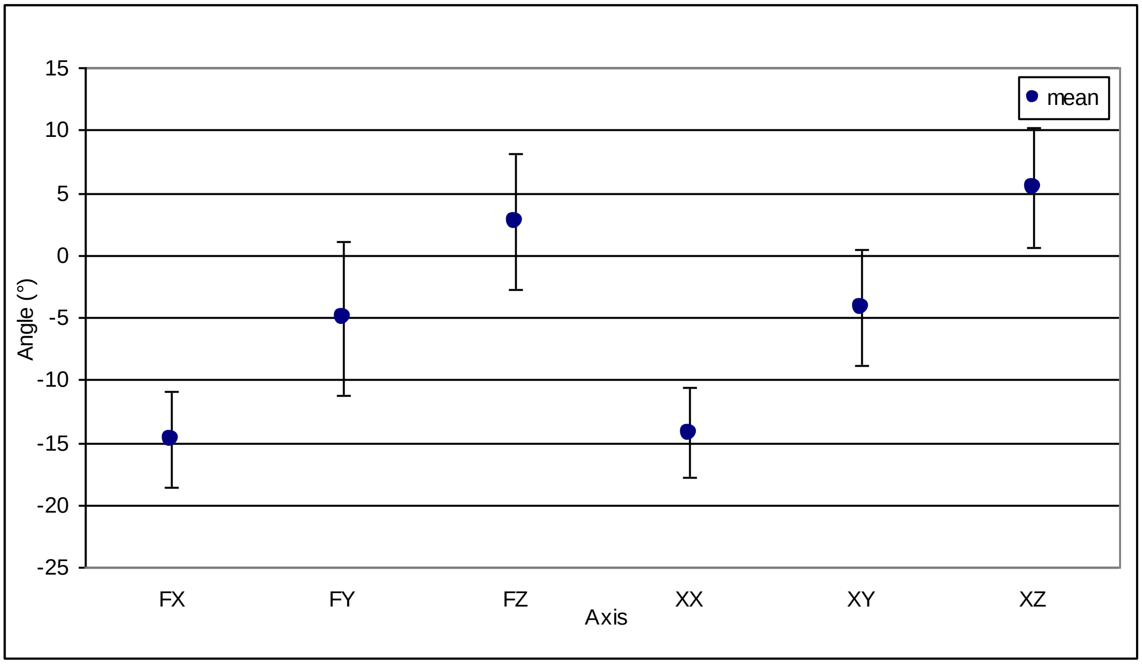
Graph 6.4.8: The distribution of means and standard deviations of extension on all 3 axes between measurements taken with Fastrak (F) and Xsens (X) sensors



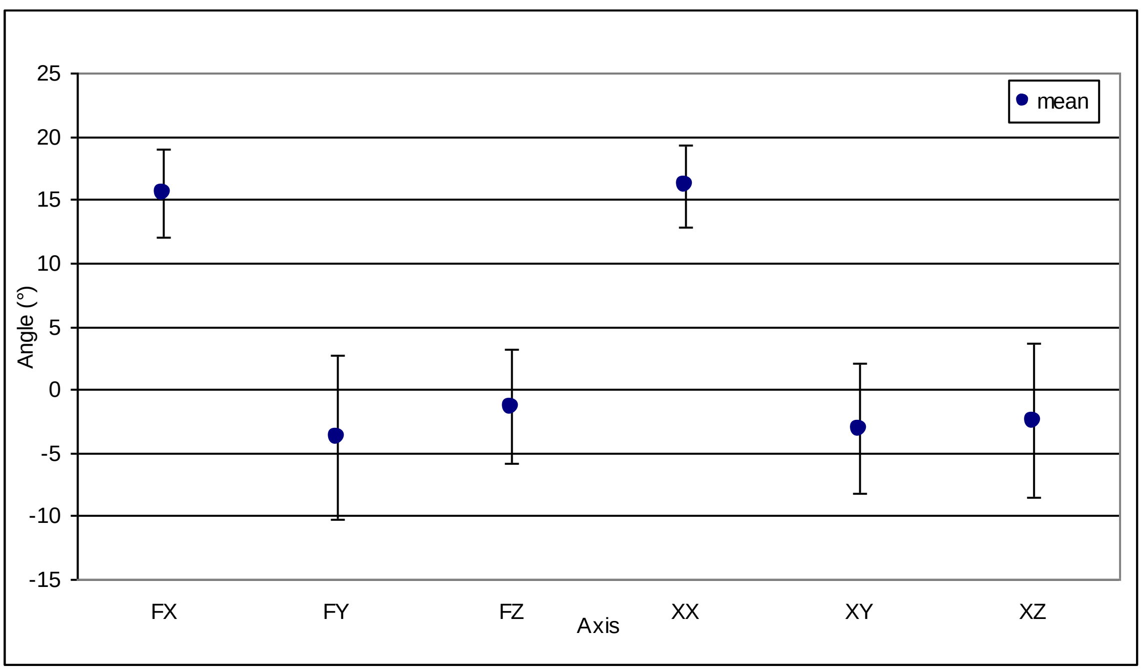
Graph 6.4.9: The distribution of means and standard deviations of right lateral flexion on all 3 axes between measurements taken with Fastrak (F) and Xsens (X) sensors



Graph 6.4.10: The distribution of means and standard deviations of left lateral flexion on all 3 axes between measurements taken with Fastrak (F) and Xsens (X) sensors



Graph 6.4.11: The distribution of means and standard deviations of right axial rotation on all 3 axes between measurements taken with Fastrak (F) and Xsens (X) sensors



Graph 6.4.12: The distribution of means and standard deviations of left lateral rotation on all 3 axes between measurements taken with Fastrak (F) and Xsens (X) sensors

Table 6.4.2 shows the tabulated data of Graphs 6.4.7 to 6.4.12. The main planes of movements are highlighted in bold and the other 2 axes show the degree of coupled motion for every physiological movement.

		Fastrak (°)				Xsens (°)			
	Axis	Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation
Flexion	X	-11.8	6.7	0.5	4.8	-8.1	7.8	-0.8	5.0
	Y	***44.6***	***75.6***	***56.9***	***7.8***	***40.0***	***71.3***	***56.6***	***8.9***
	Z	-7.4	12.2	-0.6	5.9	-11.8	8.8	-0.6	5.5
Extension	X	-5.5	3.6	0.2	2.4	-4.0	3.8	-0.6	2.7
	Y	***-52.7***	***-9.0***	***-26.7***	***9.6***	***-44.9***	***-13.1***	***-26.2***	***7.7***
	Z	-4.0	4.2	-0.6	2.1	-3.9	8.0	0.4	3.1
Right lateral flexion	X	-10.7	9.5	-0.9	5.8	-4.4	14.3	6.5	4.8
	Y	-6.1	32.9	10.4	9.3	-8.5	23.0	8.4	8.2
	Z	***-47.2***	***-14.7***	***-26.1***	***7.1***	***-44.2***	***-13.2***	***-27.3***	***7.2***
Left lateral flexion	X	-17.1	8.1	1.3	5.9	-14.7	3.1	-5.5	4.6
	Y	-4.8	33.2	10.2	9.8	-7.3	31.1	10.3	9.1
	Z	***15.2***	***43.3***	***25.8***	***6.7***	***14.6***	***41.2***	***26.6***	***6.7***
Right axial rotation	***X***	***-23.0***	***-7.0***	***-14.8***	***3.8***	***-24.6***	***-8.0***	***-14.2***	***3.6***
	Y	-18.8	9.1	-5.0	6.1	-11.3	6.5	-4.2	4.7
	Z	-7.1	16.9	2.6	5.4	-6.4	14.0	5.4	4.8
Left axial rotation	***X***	***9.4***	***23.7***	***15.5***	***3.5***	***7.1***	***22.5***	***16.1***	***3.2***
	Y	-12.0	12.7	-3.8	6.4	-18.9	5.2	-3.1	5.1
	Z	-8.3	11.9	-1.4	4.5	-11.9	12.7	-2.5	6.1

Table 6.4.2: Descriptive data of anatomical movements on all axes measured by electromagnetic tracking systems (Fastrak) and inertial measurement systems (Xsens), the main plane movements are highlighted in bold while the values on the other two axes were the angle of coupled motions.

Beside the main plane of movement, coupled movements were observed during all physiological movements. As shown in Table 6.4.2, the magnitude of coupled movements during flexion and extension were smaller (mean values between -0.8° to 0.5°) when compared to movements that were coupled with lateral flexion (mean values between -5.5° to 10.4°) and axial rotation (mean values between -5.0° to 5.4°). The magnitude (Table 6.4.2) and direction (Table 6.4.3) of the coupled movements differed between participants. However during lateral flexion, more than 85% of the participants demonstrated coupled flexion (mean values between 8.4° to 10.4°) and during axial rotation, more than 77% of the participants presented coupled extension (mean values between 3.1° to 5.0°). More than 73% of the participants possessed coupled lateral flexion in the opposite direction of the axial rotation movement, e.g. when the participants rotated the lumbar spine to the left side, a mean of 2.5° of right lateral flexion together with a mean value of 3.1° of extension was seen coupled with this main plane of movement. This reverse direction of coupled movement phenomenon between lateral flexion and axial rotation was also seen in main plane lateral flexion movements, e.g. when participants engaged in right lateral flexion, a mean value of 6.5° of coupled left axial rotation and 8.4° of coupled flexion were identified.

		Coupling movements % of participants (number of participants)					
		Flexion	**Extension**	**Right lateral flexion**	**Left lateral flexion**	**Right axial rotation**	**Left axial rotation**
Main plane of movement	**Flexion**			53.8 (14)	46.2 (12)	50.0 (13)	50.0 (13)
	Extension			50.0 (13)	50.0 (13)	57.7 (15)	42.3 (11)
	Right lateral flexion	84.6 (22)	15.4 (4)			7.7 (2)	92.3 (24)
	Left lateral flexion	88.5 (23)	11.5 (3)			88.5 (23)	11.5 (3)
	Right axial rotation	11.5 (3)	88.5 (23)	11.5 (3)	88.5 (23)		
	Left axial rotation	23.1 (6)	76.9 (20)	73.1 (19)	26.3 (7)		

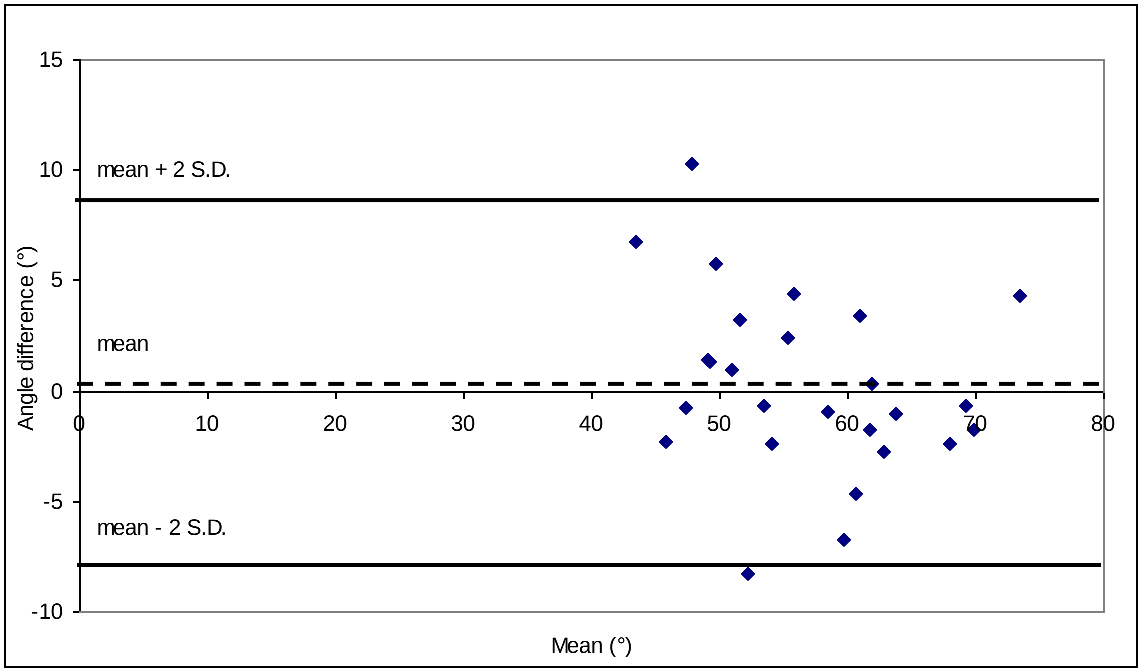
Table 6.4.3: Summary of percentage of participants (number of participants) engaging in different coupled movement

By comparing the overall ranges of the movements recorded by Xsens and Fastrak systems, the regression R^2 was found to be 0.999, with a gradient m of 1.01 and an intercept c at -0.09. The correlation and regression analysis in Table 6.4.4 shows the 2 measurement systems had a significant association with p values of less than 0.005 for all movements.

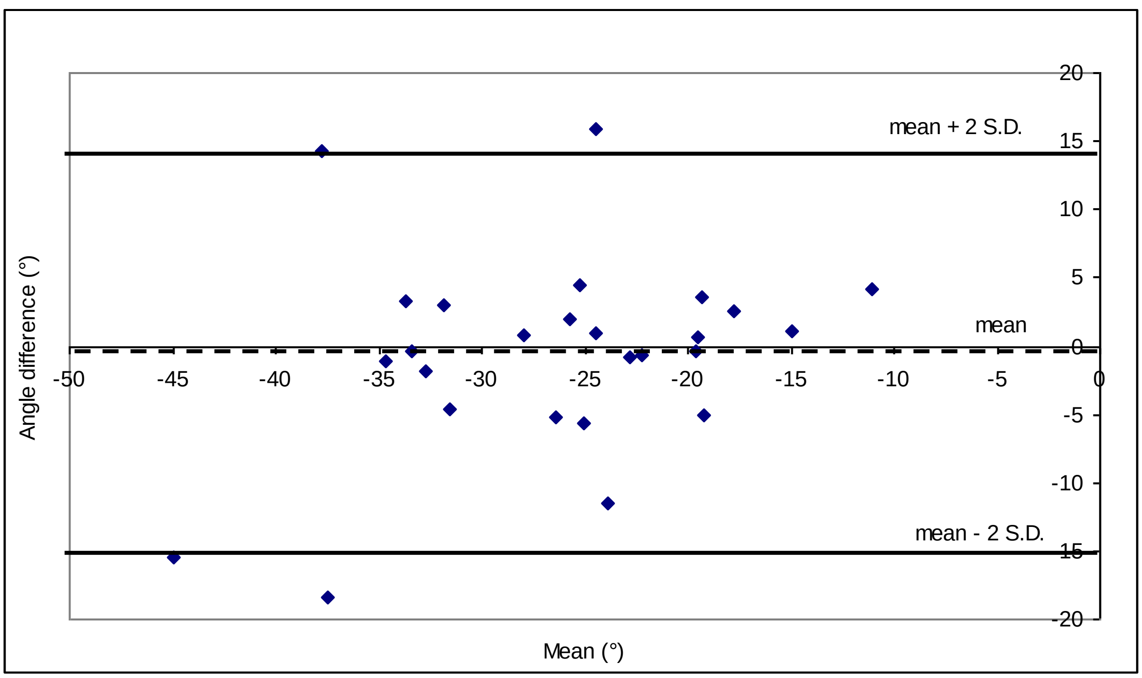
	Correlation coefficient	Sig. (p)	Regression R^2	Sig. (p)	Gradient, m	Intercept, c
Flexion	0.8876	<0.0001	0.7878	<0.0001	1.0158	-1.1823
Extension	0.6573	0.0003	0.4321	<0.0001	0.5252	-12.1410
Right lateral flexion	0.8535	<0.0001	0.7285	<0.0001	0.8724	-4.5890
Left lateral flexion	0.9000	<0.0001	0.8101	<0.0001	0.9035	3.2985
Right axial rotation	0.6657	0.0002	0.4199	<0.0001	0.6297	-4.9271
Left axial rotation	0.5411	0.0043	0.2633	0.0040	0.5028	8.3462

Table 6.4.4: Correlation and regression analysis of physiological movements measured by an electromagnetic tracking system (Fastrak) and an inertial measurement system (Xsens)

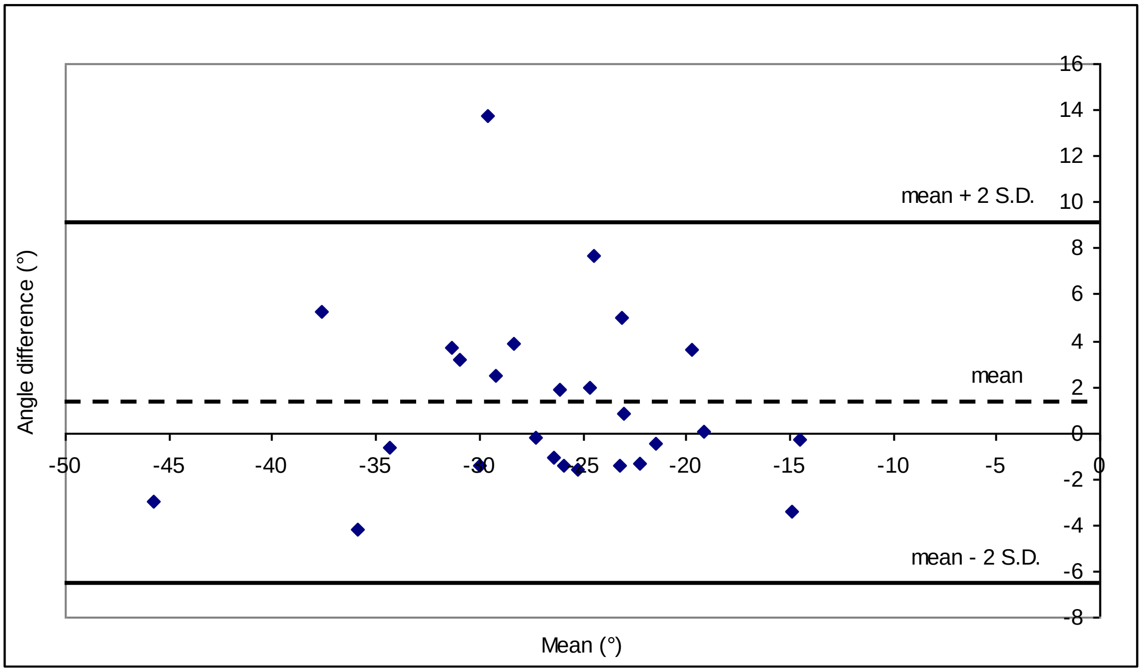
In Graphs 6.4.13 to 6.4.18, the distribution of angle difference of all 26 participants in 6 physiological movements between Fastrak and Xsens systems are plotted using the Bland and Altman method (1986). The x-axis of the graphs represents the mean values of the 2 measurement systems and the y-axis shows the angle differences between the 2 measurement systems. From these plotted graphs, it can be observed that most differences fell within ±5°. As the least clinically meaningful difference to be detected was 5° in this study (Section 6.2), Graphs 6.4.13 to 6.4.18 show that the Fastrak and Xsens systems produced good agreement in physiological movement measurement with mean differences of < ±1.3°. These results had strengthened the observations from regression analysis that both Xsens and Fastrak systems strongly agreed with each other in spinal motion measurement.



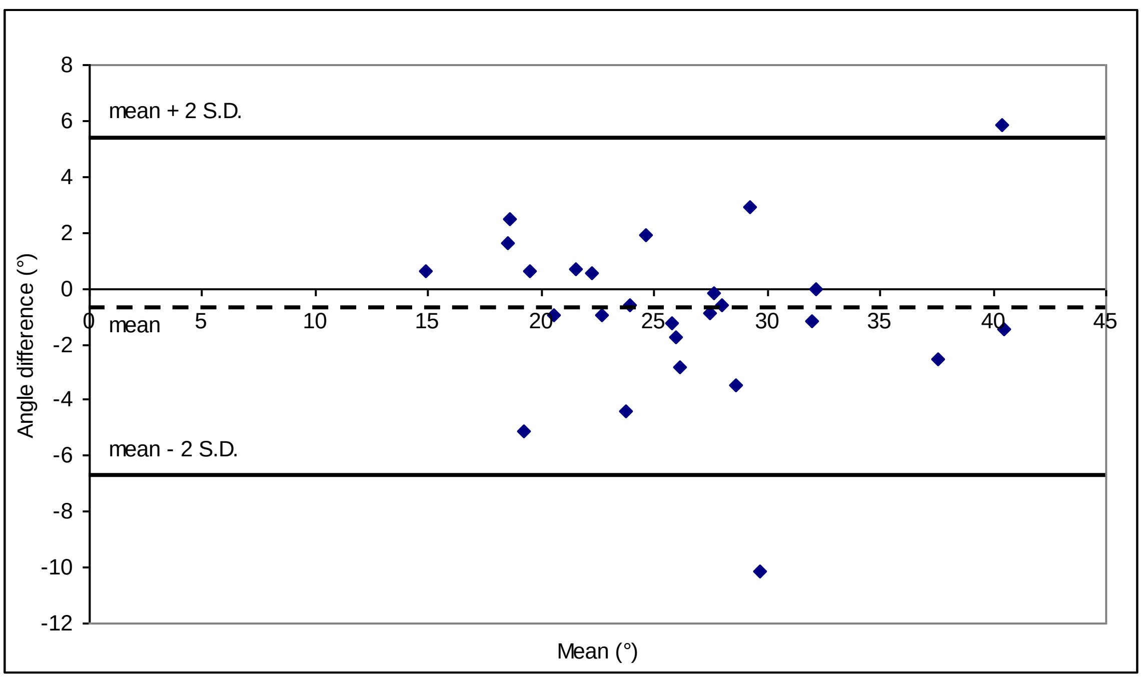
Graph 6.4.13: The distribution of angle differences for all 26 participants in flexion between Fastrak and Xsens measurement systems, mean difference was 0.28° and standard deviation was 4.10°



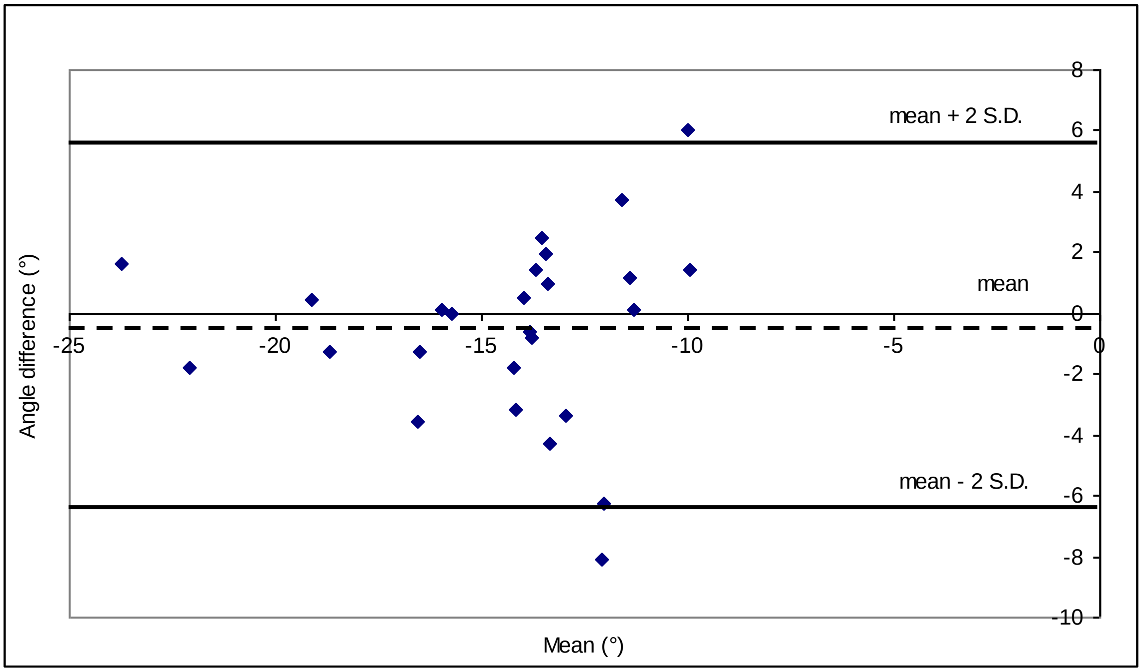
Graph 6.4.14: The distribution of angle differences for all 26 participants in extension between Fastrak and Xsens measurement systems, mean difference was 0.56° and standard deviation was 7.36°



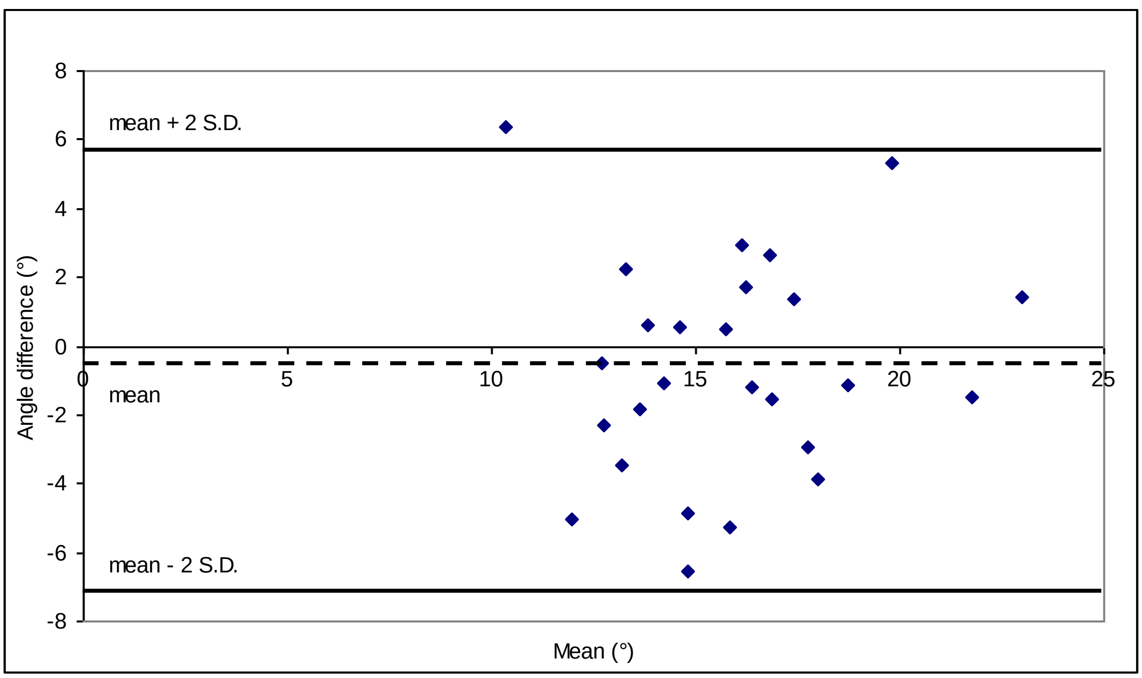
Graph 6.4.15: The distribution of angle differences for all 26 participants in right lateral flexion between Fastrak and Xsens measurement systems, mean difference was 1.26° and standard deviation was 3.90°



Graph 6.4.16: The distribution of angle differences for all 26 participants in left lateral flexion between Fastrak and Xsens measurement systems, mean difference was -0.81° and stand deviation was 3.01°



Graph 6.4.17: The distribution of angle differences for all 26 participants in right axial rotation between Fastrak and Xsens measurement systems, mean difference was -0.55° and standard deviation was 3.03°



Graph 6.4.18: The distribution of angle differences for all 26 participants in left axial rotation between Fastrak and Xsens measurement systems, mean difference was -0.66° and standard deviation was 3.22°

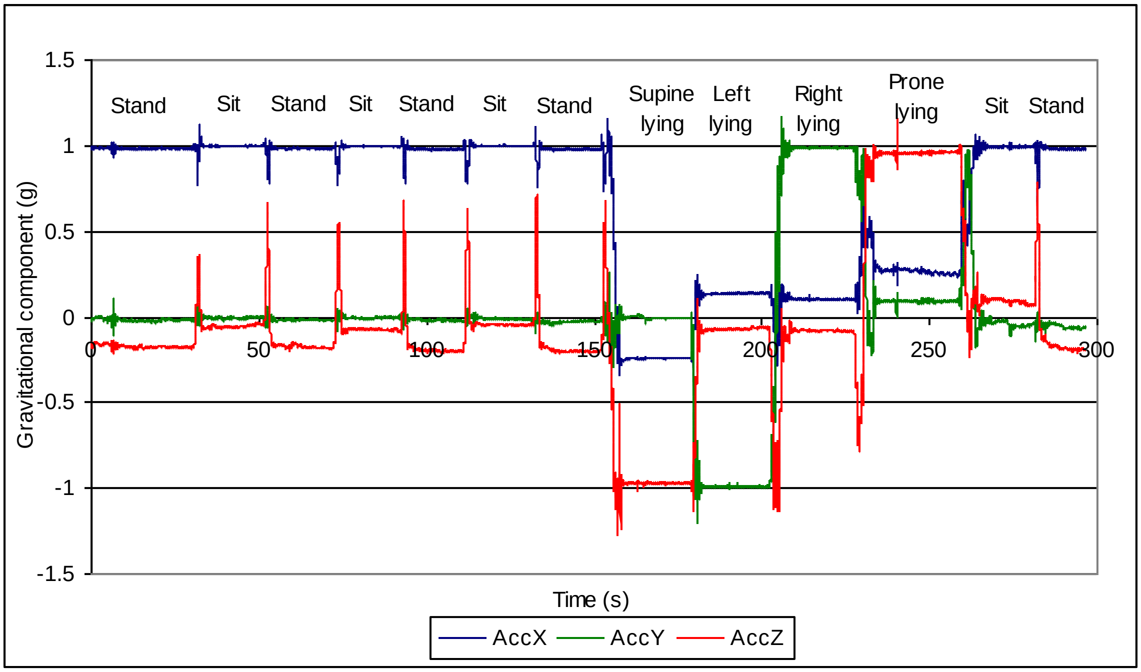
Table 6.4.5 below shows the results of paired t-tests between the Xsens and Fastrak systems for the 6 physiological movements. It was found that the p values for all movements were greater than 0.05, hence showing there was no significant difference between the 2 different measurement systems. From the ranges of physiological movements recorded by both Xsens and Fastrak systems, it was shown that there was a distinct association between both Xsens and Fastrak systems by regression analysis; that data produced by the Xsens system strongly agreed with those recorded by the Fastrak system through Bland and Altman method; and that there was no significant difference between the 2 measurement systems with the results of pair t-test. This analysis indicated that the inertial measurement system (Xsens) is a valid measurement system for spinal motion measurements, when compared to the electromagnetic tracking system (Fastrak).

	Paired differences					t	df	Sig. (p)
	Mean	Standard deviation	Standard error mean	95% Confidence interval of the difference				
				Upper	Lower			
Flexion	0.2809	4.1041	0.8049	-1.3768	1.9386	0.3490	25	0.7300
Extension	-0.5556	7.3615	1.4437	-3.5289	2.4178	-0.3848	25	0.7036
Right lateral bend	1.2622	3.8699	0.7590	-0.3009	2.8253	1.6630	25	0.1088
Left lateral bend	-0.8089	3.0070	0.5897	-2.0234	0.4057	-1.3716	25	0.1824
Right axial rotation	-0.5461	3.0260	0.5935	-1.7684	0.6761	-0.9203	25	0.3662
Left axial rotation	-0.6588	3.2211	0.6317	-1.9598	0.6423	-1.0428	25	0.3070

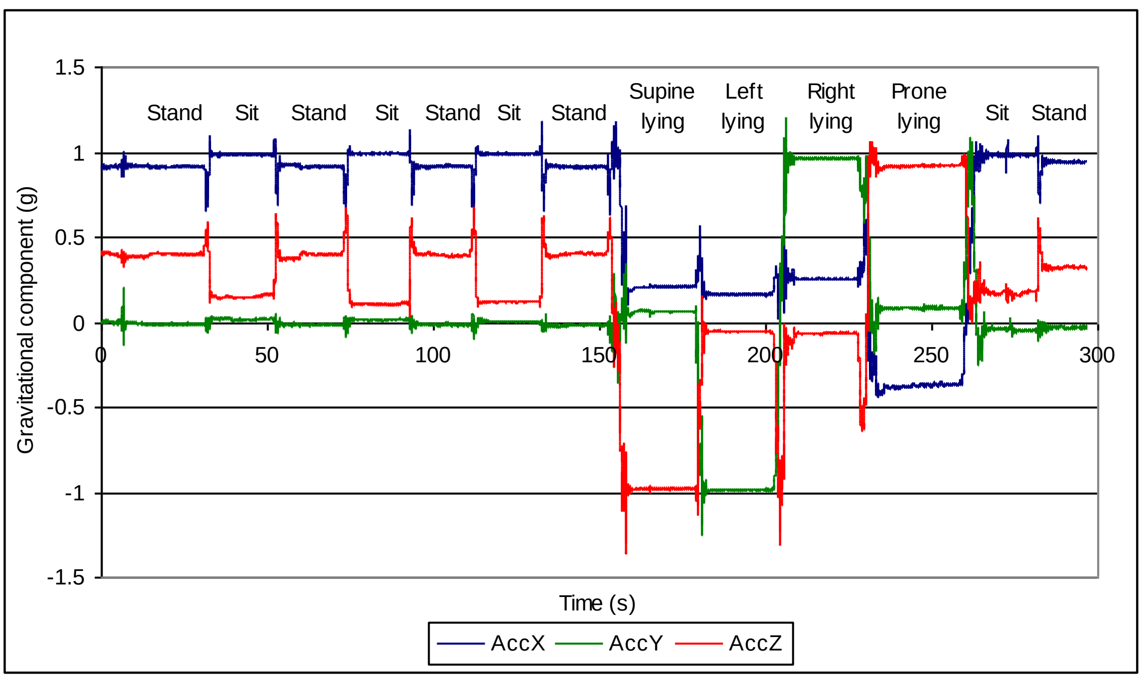
Table 6.4.5: Paired t-test analysis of physiological movements measured by electromagnetic tracking systems (Fastrak) and inertial measurement systems (Xsens)

Static postures

Accelerometer data was used to analyse the differences between static postures. As described in Section 6.3, the value of the acceleration was able to be used to differentiate different static postures based on the gravitational component measured during static conditions. Graphs 6.4.19 and 6.4.20 below show typical plotted results for static postures for the lumbo-sacral spine, these graphs were taken from the results of Participant 27 of the study. Raw results on static postures of all 26 participants can be found in Appendix Tables A2.7 to A2.13.



Graph 6.4.19: Typical plotted gravitational component data on L1 spinous process during static postures, data was taken from Participant 27



Graph 6.4.20: Typical plotted gravitational component data on S1 spinous process during static postures, data was taken from Participant 27

By utilising the capability of accelerometers as tilt sensors when the acceleration of body movement was zero or relatively small when compared to gravity, different postures were able to be differentiated. The tilt angles of each axes were calculated by using the equations A6.17 and E A6.18 as discussed in Appendix A6.2, however for better illustration, the analysis and discrimination of different postures were expressed using the gravitational component, g, where 1g corresponded to 90° and 0g indicated 0° with respect to the horizontal axis.

As can be seen from Tables 6.4.6 and 6.4.7, standing and upright sitting postural data were very similar and hard to differentiate with only 2 sensors on the lumbar spine. However a trend was observed between the 2 postures. Due to the lumbar curve, the sensor on S1 always produced a higher tilt angle on the X axis (less acceleration in g) against the vertical reference axis during standing than sitting as sitting flexed the lumbar curve and caused the X axis of the sensor to align closer to the vertical axis (indicated as an output closer to 1g). The sensor on L1 showed a similar trend between standing and sitting, however it was less obvious than that shown by the sensor on S1 in most cases. This phenomenon is shown in Graphs 6.4.19 and 6.4.20. The tilt angle of the Z axis (the axis pointing from anterior to posterior aspects of the spine) can also be used in differentiating between upright standing and sitting. During standing, when the lumbar curve was more obvious, both sensors indicated a tilt but in opposite directions, however during sitting when the lumbar curve was flexed, the Z axes of both sensors tended to be aligned with the horizontal axis, which produced a near zero tilt angle with respect to the ground.

	Gravitational component on S1 (g)			**Gravitational component on L1 (g)**		
Standing	**XX**	**XY**	**XZ**	**XX**	**XY**	**XZ**
Minimum	0.8182	-0.0387	0.1500	0.9301	-0.0523	-0.3612
Maximum	0.9882	0.0884	0.5662	0.9927	0.0384	-0.1122
Mean	0.9369	0.0212	0.3331	0.9655	-0.0066	-0.2480
Standard deviation	0.0348	0.0303	0.0869	0.0155	0.0214	0.0606

Table 6.4.6: Descriptive analysis of gravitational component data during standing

	Gravitational component on S1 (g)			Gravitational component on L1 (g)		
Sitting	**XX**	**XY**	**XZ**	**XX**	**XY**	**XZ**
Minimum	0.8670	-0.0633	-0.1591	0.9745	-0.0677	-0.2205
Maximum	0.9988	0.0745	0.4940	0.9996	0.0239	0.1131
Mean	0.9856	0.0040	0.0654	0.9932	-0.0109	-0.0632
Standard deviation	0.0251	0.0357	0.1365	0.0069	0.0224	0.0829

Table 6.4.7: Descriptive analysis of gravitational component data during sitting

To further differentiate upright standing and sitting, lumbar curvature angles of the 2 postures were calculated using equation E 6.3.1. Table 6.4.8 shows the descriptive data for the lumbar curvature angles of all 26 participants in upright standing and sitting. From the results, it can be seen that the mean value of lumbar curvature angle during standing was much higher than in sitting, 33.3° against 6.7°. This indicated that when participants were in sitting, the lumbar spine was flexed at an average of 26.6° more than when in standing.

	Lumbar curvature angle (°)		Lumbar curvature angle (°) during standing	
	Standing	**Sitting**	**Male**	**Female**
Minimum	22.4	-9.5	22.4	27.7
Maximum	42.9	22.4	39.0	42.9
Mean	33.3	6.7	31.9	34.5
Standard Deviation	4.8	7.0	5.5	3.8

Table 6.4.8: Descriptive analysis of lumbar curvature angles during upright standing and sitting; and lumbar curvature angle between male and female participants during upright standing

Table 6.4.9 below is the result of a paired t-test of lumbar curvature angles between standing and sitting. It was found that the 2 postures were significantly different in terms of lumbar curvature angle, with a p value of less than 0.001. The difference between standing and sitting in lumbar curvature angle was obvious; hence the lumbar curvature angle is a valid method for differentiating between standing and sitting postures.

	Paired Differences					t	df	Sig. (p)
	Mean	Standard Deviation	Standard Error Mean	95% Confidence Interval of the Difference				
				Upper	Lower			
Standing - Sitting	26.642	7.526	1.476	23.603	29.682	18.051	25	<0.001

Table 6.4.9: Paired t-test analysis of lumbar curvature angles between upright standing and sitting

The lumbar curvature angles of different genders during upright standing is also summarised in Table 6.4.8. Females were found to possess higher lumbar curvature angles than male participants. However this difference was found to be small with a mean difference of 2.6° and the t-test suggested that this difference between genders was not significant (p = 0.173), as shown in Table 6.4.10.

	Independent Samples Test								
	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (p)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Upper	Lower
Male - Female	3.465	0.075	-1.404	24	0.173	-2.589	1.845	-6.396	1.218

Table 6.4.10: Independent t-test analysis of lumbar curvature angles between male and female participants in standing

Tables 6.4.11 to 6.4.14 show the gravitational component data for lying postures. The Z axis data was used to differentiate between supine and prone lying. When the Z axes of both sensors were reading approximately 1g the participants were lying on their abdomen while -1g meant that the participants were lying on their back. The Y axis, which was the axis pointing from the right to the left of the spine for both sensors, was used to discriminate between right and left side lying, 1g referred to right side lying and -1g was identified as left side lying. During static postures, gyroscope data were not useful for analysis purposes as there was no meaningful data (near zero) produced as would be expected due to no rotational movement along the sensitive axes occurred at static conditions.

	Gravitational component on S1 (g)			Gravitational component on L1 (g)		
Supine lying	**XX**	**XY**	**XZ**	**XX**	**XY**	**XZ**
Minimum	0.0781	-0.1013	-0.9988	-0.2410	-0.0889	-0.9985
Maximum	0.4229	0.1517	-0.9068	0.0302	0.1045	-0.9677
Mean	0.2510	0.0132	-0.9638	-0.1110	0.0252	-0.9887
Standard deviation	0.0838	0.0641	0.0238	0.0744	0.0378	0.0094

Table 6.4.11: Descriptive analysis of gravitational component data during supine lying

	Gravitational component on S1 (g)			Gravitational component on L1 (g)		
Prone lying	**XX**	**XY**	**XZ**	**XX**	**XY**	**XZ**
Minimum	-0.4806	-0.1364	0.8624	0.0348	-0.1526	0.9251
Maximum	-0.1546	0.1458	0.9838	0.3511	0.0932	0.9990
Mean	-0.3199	0.0282	0.9372	0.2464	-0.0257	0.9633
Standard deviation	0.0790	0.0658	0.0291	0.0894	0.0595	0.0209

Table 6.4.12: Descriptive analysis of gravitational component data during prone lying

	Gravitational component on S1 (g)			Gravitational component on L1 (g)		
Left side lying	**XX**	**XY**	**XZ**	**XX**	**XY**	**XZ**
Minimum	-0.1306	-1.0001	-0.1456	0.0259	-1.0004	-0.2722
Maximum	0.2578	-0.9582	0.2371	0.2293	-0.9499	0.2270
Mean	0.0910	-0.9853	0.0162	0.1045	-0.9865	0.0075
Standard deviation	0.0967	0.0121	0.1089	0.0545	0.0128	0.1319

Table 6.4.13: Descriptive analysis of gravitational component data during left side lying

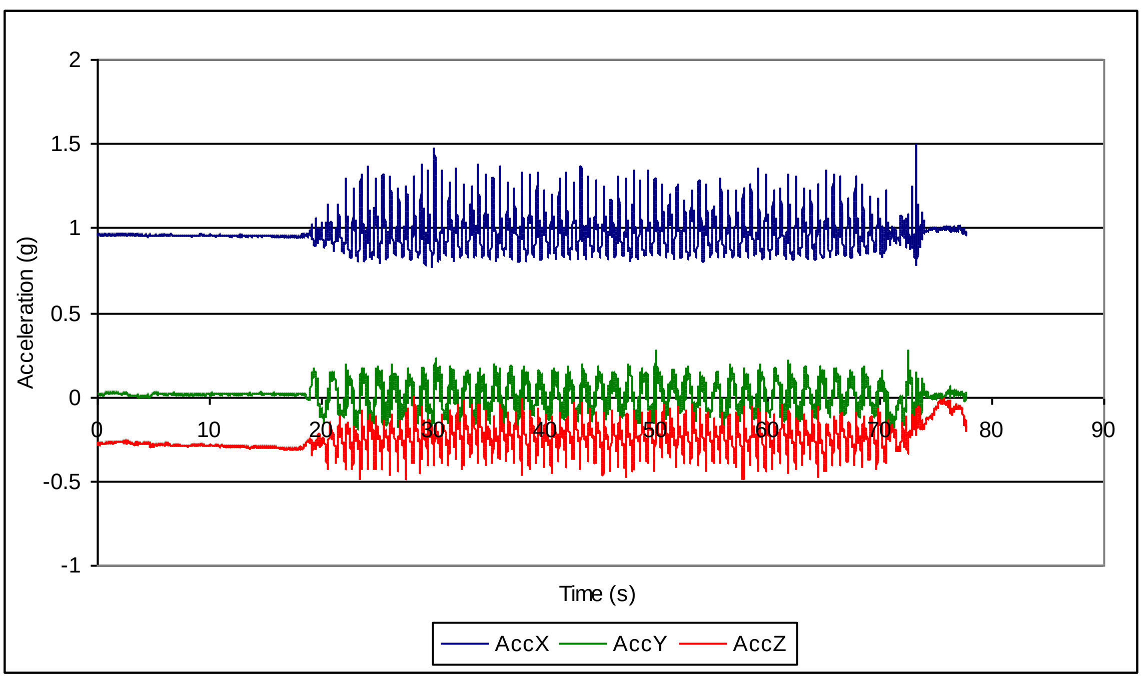
	Gravitational component on S1 (g)			Gravitational component on L1 (g)		
Right side lying	**XX**	**XY**	**XZ**	**XX**	**XY**	**XZ**
Minimum	0.0299	0.8802	-0.4288	0.0277	0.9237	-0.3396
Maximum	0.2914	0.9988	0.1477	0.2763	0.9960	0.3206
Mean	0.1362	0.9786	-0.0422	0.1144	0.9792	-0.0157
Standard deviation	0.0848	0.0267	0.1181	0.0652	0.0177	0.1356

Table 6.4.14: Descriptive analysis of gravitational component data during right side lying

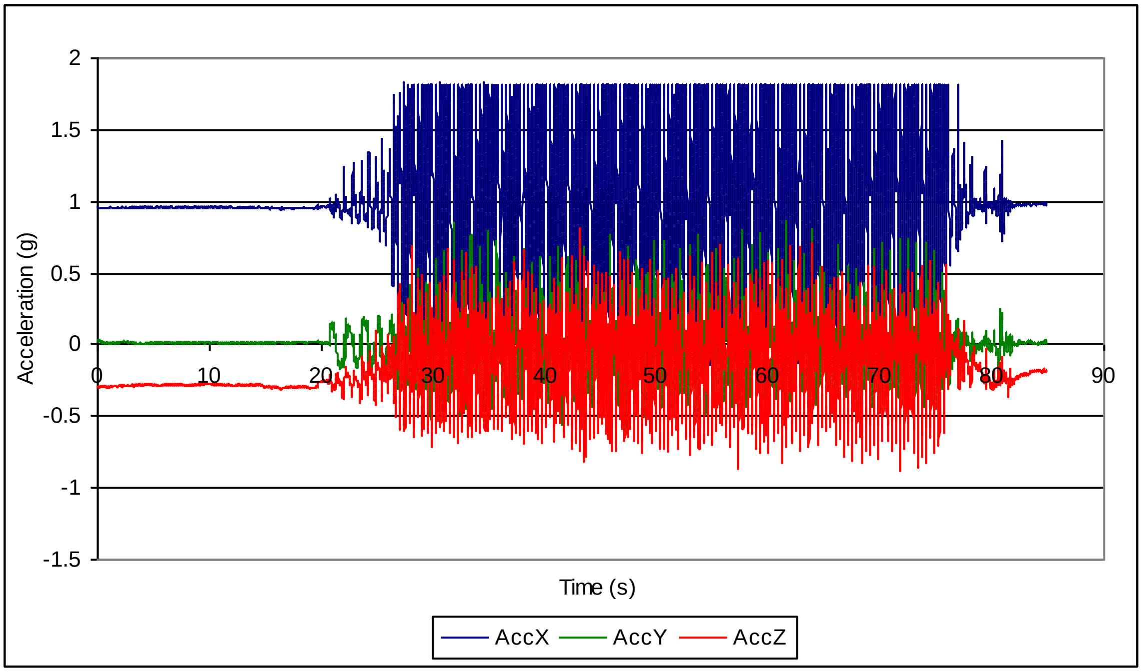
Functional activities

Different functional activities were analysed by utilising the data from the accelerometers, where the amplitude and frequency properties of these activities were examined. Graph 6.4.21 is a typical plotted acceleration result of all 3 axes during walking; the sensors on L1 and S1 produced similar data during the functional activities. When compared to Graph 6.4.22, it can be seen that the amplitude during walking was much lower than running, especially on the X (vertical) axis. However during walking up and down the steps as shown in Graph 6.4.23, the acceleration amplitudes in all axes were very similar to the data obtained during level walking and therefore it was not possible to differentiate these activities by looking at this parameter.

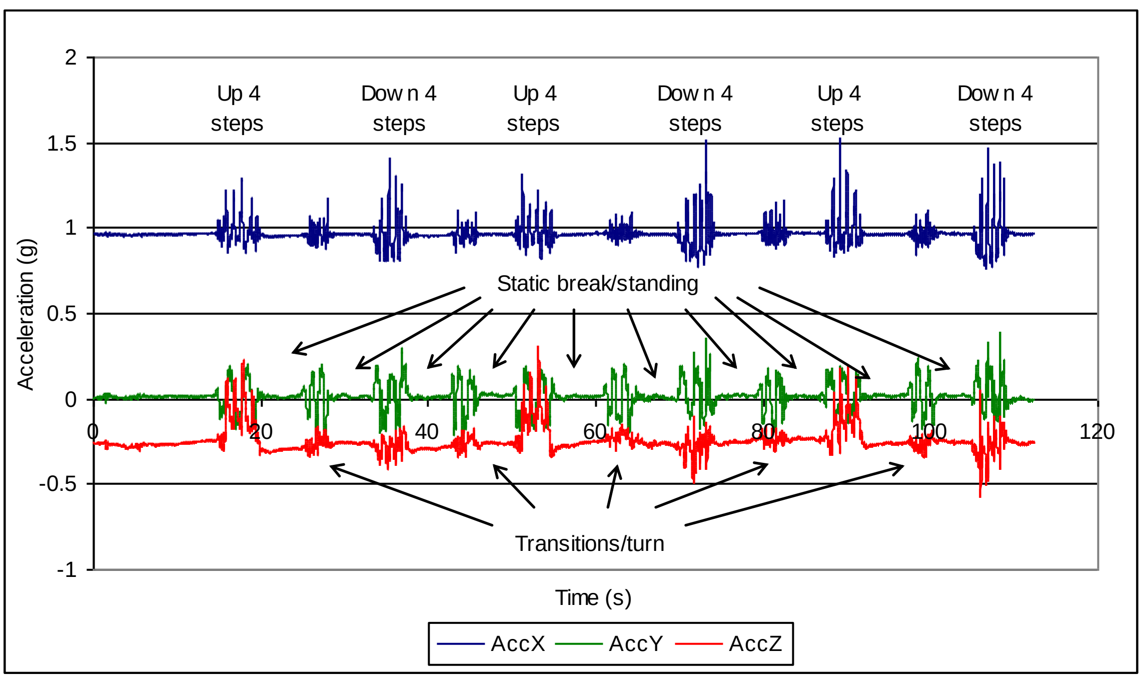
Please refer to Appendix Tables A2.14 to 2.21 for raw results on functional activities for all 26 participants.



Graph 6.4.21: Typical plotted acceleration results for walking, data obtained from sensor on L1 spinous process of Participant 11



Graph 6.4.22: Typical plotted acceleration results for running, data obtained from sensor on L1 spinous process of Participant 11



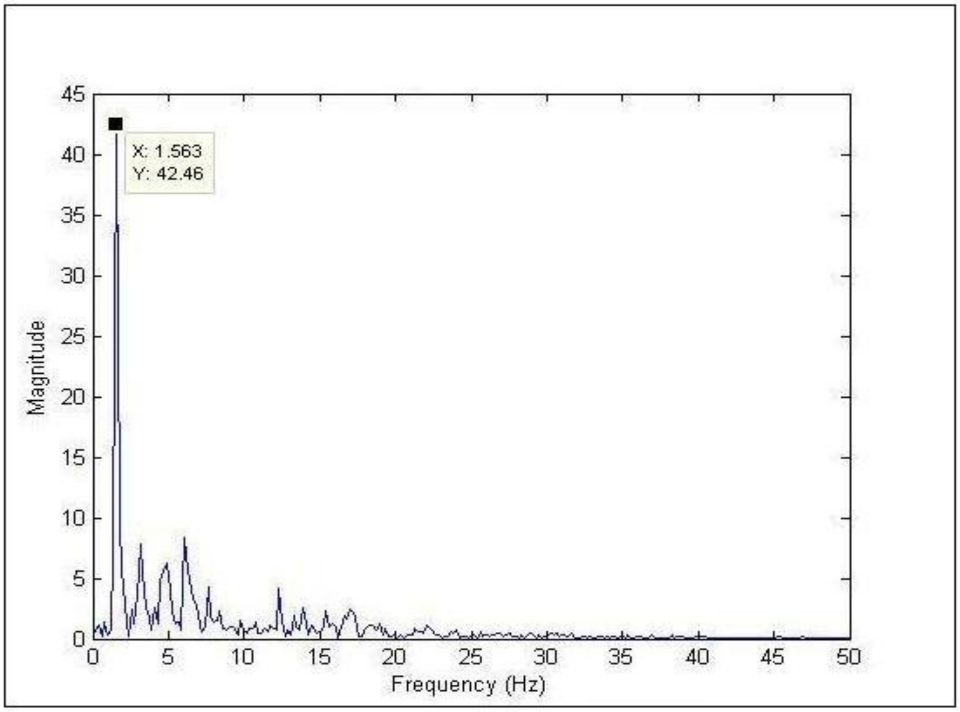
Graph 6.4.23: Typical plotted acceleration results for walking up and down steps, data obtained from sensor on L1 spinous process of Participant 11

Table 6.4.15 summarises the amplitude analysis of the 4 different functional activities. During running, the vertical axis, X produced a minimum acceleration of 1.85g, while the other 2 axes showed minimum accelerations of 0.94g and 0.97g respectively. The mean accelerations during running ranged from 2.20g to 2.44g. The accelerations produced during walking were much lower, at a maximum of 1.34g on X axis, 1.17g on Y axis and 1.13g on Z axis, which yielded a mean values between 0.72g to 0.93g. Walking up and down the steps showed similar data to walking and the differences were not significant enough in differentiating these movements.

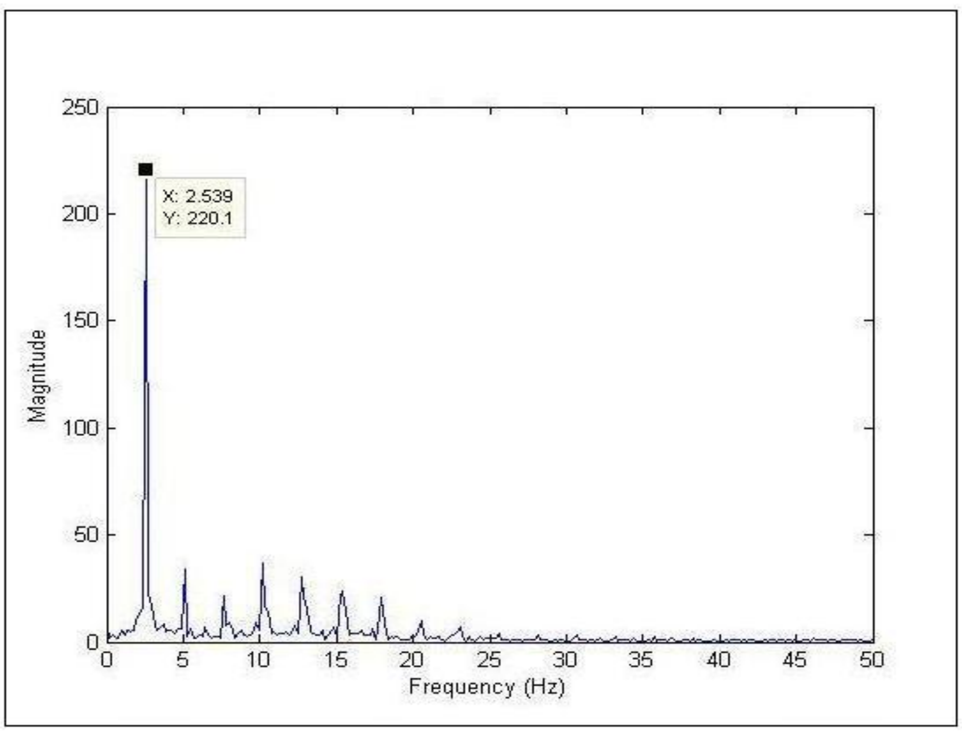
	Acceleration during walking (g)			Acceleration during running (g)			Acceleration during walking up steps (g)			Acceleration during walking down steps (g)		
	XX	XY	XZ	XX	XY	XZ	XX	XY	XZ	XX	XY	XZ
Minimum	0.49	0.37	0.40	1.85	0.94	0.97	0.41	0.31	0.42	0.56	0.40	0.37
Maximum	1.34	1.17	1.28	3.16	3.75	3.33	1.37	1.00	1.08	1.72	2.34	1.62
Mean	0.93	0.73	0.72	2.44	2.42	2.20	0.84	0.59	0.67	1.08	0.87	0.69
Standard deviation	0.19	0.22	0.18	0.36	0.87	0.64	0.23	0.15	0.16	0.26	0.35	0.24

Table 6.4.15: Descriptive analysis of amplitude of acceleration data during level walking, running and walking up and down steps

The frequency components of the accelerations during walking and running were analysed by using Fast Fourier transform (FFT) with MATLAB software. Graphs 6.4.24 and 6.4.25 show the typical frequency plots for running and walking. A frequency analysis was not performed on the walking up and down steps data as the samples of these activities were too small to produced meaningful data.



Graph 6.4.24: Typical plotted frequency analysis results for walking, data obtained from sensor on L1 spinous process of Participant 11



Graph 6.4.25: Typical plotted frequency analysis results for running, data obtained from sensor on L1 spinous process of Participant 11

The frequency with the highest magnitude was recorded for comparison. Table 6.4.16 below is the summary of the frequency analysis for walking and running. It can be seen that during walking, the peak frequencies ranged from 1.37Hz to 1.95Hz on the vertical axis, X; while during running, the peak frequencies were higher and ranged from 2.34Hz to 2.93Hz on the X axis. The magnitudes of the peak frequencies, which signified the frequency's relative strength, were again greater during running when compared to walking. The Y axis, which was the axis pointing from right lateral to left lateral was not used for differentiating the 2 movements as this axis was not as significant during these movements as the body experienced little motion laterally during walking and running.

	Walking						Running					
	Frequency (Hz)			Magnitude			Frequency (Hz)			Magnitude		
	XX	XY	XZ	XX	XY	XZ	XX	XY	XZ	XX	XY	XZ
Minimum	1.367	0.781	1.367	15.74	8.65	11.25	2.344	1.172	2.344	129.00	21.00	18.45
Maximun	1.953	11.130	1.953	89.77	38.91	53.98	2.930	15.630	10.740	322.60	114.70	136.00
Mean	1.687	3.193	1.690	36.87	18.50	30.16	2.663	5.041	2.922	224.36	49.67	64.47
Srandard deviation	0.122	2.889	0.122	15.33	6.83	9.75	0.160	4.235	1.387	44.97	17.29	24.37

Table 6.4.16: Frequency and magnitude analysis data for level walking and running

6.5 Discussion

From this study, the inertial measurement system was shown to be a valid 3 dimensional tool for spinal posture and motion measurement.

Physiological movements

Spinal movements were measured in the study with both an inertial measurement system (Xsens) and an electromagnetic tracking system (Fastrak). The electromagnetic tracking system was used as the reference system in spinal motion measurement in this study as this system has been proved to be an accurate method in spinal motion measurement (Pearcy and Hindle 1989), and it was also a skin surface measurement technique which was more directly relevant for comparison with the inertial measurement system used in this study. When compared to the Fastrak results, Xsens data was highly correlated and showed to strongly agree and produced no significant difference from the other system.

The manufacturer's data claims that the Xsens MTx system has a static accuracy of 0.5° for roll and pitch, 1° for yaw and 2° RMS dynamic accuracy; and that the Fastrak system has a static accuracy of 0.8mm RMS for sensor position and 1.5° for sensor orientation. This could result in the differences between the 2 systems as measured in this study (mean difference of 0.3° to 1.2°), comparing favourable with the manufacturers claimed accuracy.

Ideally, in order to ensure the 2 different measurement systems are measuring the same movement, both systems should be attached to the measuring object at the same segment and conduct data collection with both systems at the same time. During the data collection for spinal movements in this study, both systems were not used simultaneously to measure the movements; this was because the magnetic interference between the 2 systems would have invalidated the recorded data. This manifested itself as noise on the Fastrak data when the 2 systems' sensors were placed within 100mm of each other, as discussed in Section 4.2. Participants would also need to stand with the sensors as close as 50mm from the electromagnetic source to reduce the interference if both sensors were used at the same time. However this was not viable as it would have affected participants' movements.

Although participants were encouraged to move through their full range of movement and perform these movements as similarly as possible for data collection with both the Fastrak and Xsens systems, it was not possible to ensure exactly the same amount of movement each time. This might be achievable if the researcher guided the participants to the same levels of movement each time using other means of reference, such as a marker on participants' leg to indicate where the participants should flex to each time in order to produce same range of flexion.

However the current study was set out to measure the end range of physiological movements, in order to be able to compare the ranges measured in the current study to those reported in the literature to provide further evidence to support the validity of the current results, therefore the above approach was not utilised in the study. The motivation of the participants and tiredness may have affected the repeatability of the ranges of movements in the 2 data collection sessions. A warm up procedure was not included in the study before the data collection; however participants were encouraged to perform each of the 6 physiological movements once to familiarise themselves with the procedure. The spinal structures might have further warmed up during the second session of physiological movement measurement and this may also contribute to differences in the results when comparing the 2 measurement systems. However, it is considered that the differences in movements recorded by the 2 measurement systems were small enough not to affect the overall results of this study.

Another possible source of error in the spinal movement measurements was the identification of anatomical landmarks by palpation (McKenzie and Taylor 1997). In this study, the palpation was performed by the same trained physiotherapist, and the locations of the landmarks were validated with ultrasound scanning to minimise this error.

The Xsens sensors were relatively large, having dimensions of 38x53x21mm, and consequently it was possible that the sensors were actually placed across the level of T12/L1 or L1/L2 during data collection. This may also have contributed to differences in the range of movements recorded. In this study, the Xsens sensors were always attached with the most bottom edge of the sensor aligned with the inferior border of L1 spinous process; and the uppermost edge of the sensor aligned with the superior aspect of the S1 spinous process. This was to ensure consistency of the lumbar levels for spinal measurement, this greatly minimised the differences in placement location however may not eliminate the possibility completely.

When comparing the ranges of the 6 physiological movements' data of this study to Table 2.3.3 in Chapter 2, which are also shown in Table 6.5.1 below, the current study produced the most similar results to the study carried out by Van Herp et al. (2000). The range of flexion was found to be in close range (maximum difference of less than 6°) with studies carried out Pearcy (1985) and Lee and Wong (2002). The ranges of extension and lateral flexion were comparable to those measured by Hindle et al. (1990) and Russell et al. (1993). As for axial rotation, ranges were similar to results reported by Hindle et al. (1990), Russell et al. (1993) and Peach et al. (1998). This provided further confidence in the results obtained by both the electromagnetic tracking system (Fastrak) and inertial measurement system (Xsens) used in this present study.

	Ranges of physiological movements (°)					
	Flexion	**Extension**	**Right lateral bend**	**Left lateral bend**	**Right axial rotation**	**Left axial rotation**
Fastrak	56.9	26.7	26.1	25.8	14.8	15.5
Xsens	56.6	26.2	27.3	26.6	14.2	16.1
Pearcy et al. (1985) Biplanar radiography	51.0	16.0	18.0	17.0	5.0	4.0
Hindle et al. (1990) Electromagnetic tracking system	69.4	24.6	28.3	28.3	14.7	14.7
Russell et al. (1993) Electromagnetic tracking system	70.8	25.0	27.1	27.1	15.3	15.3
Peach et al. (1998) Electromagnetic tracking system	71.6	-	29.7	30.8	16.6	15.6
Van Herp et al. (2000) Electromagnetic tracking system	56.9	28.2	25.5	25.9	15.7	14.0
Lee and Wong (2002) Electromagnetic tracking system	58.1	15.6	21.3	19.9	7.6	9.8
Lee et al. (2003) Gyroscopic system	48.6	18.7	16.3	16.3	8.9	8.4

Table 6.5.1: Comparison of the mean values of ranges of movements measured by electromagnetic tracking systems (Fastrak) and inertial measurement systems (Xsens) in the current study with previous studies carried out by various authors

Lee et al. (2003) also measured spinal movements using gyroscopes in their study. Although the experimental set up in their study was similar to the current study, the ranges of movements in their study were found to be lower and closer to those measured by Pearcy's study (1985). These differences may be due to individual factors such as differences in gender, body mass index, body structure, occupation and lifestyles of the participants. As discussed in Section 2.3 in Chapter 2, there are many influential factors in spinal motion measurements; even with the same experimental set up with a similar group of participants, the same range of movement might not be able to be replicated. In the studies performed by Lee et al. (2003), they again showed gyroscopes to be a valid tool in spinal motion measurements.

Coupled movements were seen in all physiological movements, the magnitude and direction of the coupled movements were different from individual to individual. These coupled movements could be the true coupled movements combined with possible errors due to sensor misalignment, skin movements or loose sensor attachment (as shown in Chapter 5). In this study, these errors were minimised by aligning the sensors as close to the plane of movements with a secure sensor attachment method.

The main trends in coupled motion in the current study are summarised as follows:

Flexion	there was minimal and insignificant coupled lateral flexion and axial rotation (<1°)
Extension	similar to flexion, there was minimal and insignificant coupled lateral flexion and axial rotation (<1°)
Right lateral flexion	coupled with flexion and left axial rotation
Left lateral flexion	coupled with flexion and right axial rotation
Right axial rotation	coupled with extension and left lateral flexion
Left axial rotation	coupled with extension and right lateral flexion

Similar trends in coupled motions were reported by Hindle et al. (1990). Pearcy et al. (1985), Peach et al. (1998) and Lee et al. (2003) similarly did not observe any significant coupled motion during flexion and extension. During lateral flexion, all 3 studies by Russell et al. (1993), Peach et al. (1998) and Lee et al. (2003) reported the same observation as the current study, in which lateral flexion was always coupled with contralateral axial rotation and flexion was always seen to accompany these movements. Russell et al. (1993) found that axial rotation was coupled with contralateral lateral flexion, as also seen in the current study; however Peach et al. (1998) and Lee et al. (2003) observed opposing trend, in which same direction of lateral flexion was found coupling the axial rotation movements.

Although Hindle et al. (1990), Russell et al. (1993) and Lee et al. (2002) discussed the direction of coupled movements observed in their studies, the magnitude of those movements were not tabulated in their papers, therefore, their data were not compiled into Table 6.5.2 for comparison. Data from Pearcy (1985) and Peach et al. (1998) were readjusted to have the same axes and direction of movement as the current study, which were flexion/extension rotated around the Y axis, lateral flexion on the Z axis and axial rotation on the X axis. Positive values referred to flexion, left lateral flexion and left axial rotation, while negative values denoted movements in the other direction to those reported as positive values.

	Axis	Fastrak	Xsens	Pearcy (1985)	Peach et al. (1998)
Flexion	**X**	0.5	-0.8	-1.0	-2.9
	Y	***56.9***	***56.6***	***52.0***	***71.6***
	Z	-0.6	-0.6	2.0	-4.2
Extension	**X**	0.2	-0.6	3.0	-
	Y	***-26.7***	***-26.2***	***-16.0***	***-***
	Z	-0.6	0.4	-1.0	-
Right lateral bend	**X**	-0.9	6.5	3.0	7.7
	Y	10.4	8.4	-2.0	9.2
	Z	***-26.1***	***-27.3***	***-18.0***	***-30.8***
Left lateral bend	**X**	1.3	-5.5	-5.0	-7.9
	Y	10.2	10.3	-10.0	10.5
	Z	***25.8***	***26.6***	***17.0***	***29.7***
Right axial rotation	***X***	***-14.8***	***-14.2***	***-5.0***	***-15.6***
	Y	-5.0	-4.2	0.0	3.2
	Z	2.6	5.4	9.0	-8.2
Left axial rotation	***X***	***15.5***	***16.1***	***6.0***	***16.6***
	Y	-3.8	-3.1	0.0	4.1
	Z	-1.4	-2.5	-10.0	7.4

Table 6.5.2: Comparison of 3 dimensional spinal movements measured by Fastrak and Xsens with studies reported by Pearcy (1985) and Peach et al. (1998)

When comparing the magnitude of coupled movements of the current study with Pearcy's (1985), Pearcy showed an average of -1° to 3° of axial rotation and -1° to 2° of lateral flexion during flexion and extension movements of the lumbar spine, however in the current study the mean coupled lateral flexion and axial rotation were negligible. During lateral flexion, Pearcy (1985) reported a coupled extension movement, as opposed to what was observed in current study and studies by Russell et al. (1993) and Peach et al. (1998). Pearcy (1985) also did not observe any coupled extension during axial rotation as was seen in the current study. However the current study showed similar trends in contralateral coupled axial rotation with lateral flexion, and vice versa with study reported by Pearcy (1985). In Pearcy's (1985) study, only 10 to 11 male participants were recruited for each movement, the small sample size may be one of the affecting factors, which may indicate a weak representation of the general population. The difference in magnitude and direction of coupled motion between the current study and Pearcy's study (1985) could also be due to a different experimental set up and the equipment used. Pearcy (1985) performed his study with biplanar radiography that measured intervertebral movements, while the current study utilised an electromagnetic tracking system and an inertial measurement system that measured whole lumbar spine movements with skin fixation. The current study did not restrict pelvic movement as in the study carried out by Pearcy (1985) which could restrain the natural movements of the participants. In general, it is hard to reach a conclusion when comparing the magnitude of coupled motion between studies as these movements differ between individuals, though this study has shown to be capable of measuring 3 dimensional kinematics of the spine by providing a valid observation when compared to those reported in the literature. The direction and magnitude of reported coupled movements can be used as a reference when accessing abnormal spinal kinematics during movement analysis. For instance, if an individual produced 30° of coupled right lateral flexion during left axial rotation, the magnitude would be considered abnormally high when compared to those reported in the literature, and thus additional attention from the researcher or examiner may be necessary to further understand the cause of such movement.

Static postures

Different static postures were successfully classified by using the tilt angle measurement capability of the accelerometers. Veltink et al. (1996) reported similar detection of static postures in their study where they were able to classify standing, sitting and lying. However they could not identify which side the participants were lying on as there was no sensor used in the lateral axis, while standing and sitting were differentiated using an accelerometer attached to 1 thigh of the participants. Culhane et al. (2004) and Lyon et al. (2005) used a threshold classification to detect sitting, standing and lying postures with 1 uniaxial accelerometer on the sternum and another on the thigh with the sensitive axis of both sensors pointing along the vertical axis. In their studies (Culhane et al. 2004; Lyon et al. 2005), the 3 postures were reported to be discriminated with success rate of above 90%. However, as only uniaxial sensors were used, no information on different lying posture can be further classified. Foerster and Fahrenberg (2000) reported a high success detection rate (96.8%) in classifying different postures using reference pattern based classification. In the study by Foerster and Fahrenberg (2000), the postures tested were recorded prior to the actual data collection to serve as a reference postures/patterns. Although the authors (Foerster and Fahrenberg 2000) reported low rates of misclassification in their study, this could be due to the actual data collection occurring immediately after the reference posture measurements, therefore participants might have exhibited more similar postures than if they had returned for follow up after an extended period of time. Participants might also perform differently when engaging in different postures in the laboratory environment than in normal daily life, the reference system may not be robust in detecting posture in real life conditions, however a further study carried out in the normal daily life would be needed to further validate the discriminative algorithm.

Of all the postures, upright standing and sitting were more difficult to differentiate by monitoring at the tilt angle of individual sensors alone with no sensor attached to the leg. But by attaching 2 inertial sensors to the lumbar spine, monitoring the lumbar curve can facilitate the procedure. The lumbar curve is concave posteriorly from T12 to the lumbosacral joint, during standing, the lumbar spine takes up a lordotic posture and therefore the sensor on S1 showed a positive tilt angle on the Z axis and the sensor on L1 showed a negative tilt angle. These values were reversed or became closer to zero during sitting due to a decrease in lordosis. However these patterns are dependent on individuals and therefore a better discriminative process is needed. Calculating the lumbar curvature angle during standing and sitting was shown to be an effective measure in identifying standing and upright sitting postures. Data in this study showed that the mean lumbar curvature angle in standing was almost 5 times more lordosed than in sitting. Female participants showed a slightly higher lumbar curvature angle (average of 2.6°) compared to male participants however this difference was not significant (p=0.173). Table 6.5.3 compares the lumbar curvature angles measured in the current study with those reported by other studies.

	Lumbar curvature angle (°)		Measurement Method	Measurement Segment	Participants	No. of Sample	Gender (No)	Age range or mean (years)
	Standing	Sitting						
Current Study	33.3 ± 4.8	6.7 ± 7.0	Inertial measurement systems	L1-S1 spinous processes	Healthy	26	M12, F14	21 - 43
Lord et al. (1997)	49.0 ± 15.0	34.0 ± 15.0	Radiography	Superior endplates of L1-S1	Patients	109	M70, F39	21 - 83
Dolan et al. (1988)	31.2	10.8	Inclinometers	L1-L5 spinous processes	Healthy	11	M8, F3	25 - 59
Harrison et al. (2001)	58.6 ± 16.4	-	Radiography	Inferior endplate of T12 - superior endplate of S1	Patients	30	-	-
Ng et al. (2001)	24.0 ± 8.0	-	Inclinometers	T12/L1-L1/S1	Healthy	35	M35	29.9
Ng et al. (2002)	25.0 ± 8.0	-	Inclinometers	T12/L1-L1/S1	Healthy	15	M15	20 - 37
Mannion et al. (2004)	31.7 ± 7.3	-	Accelerometers (Spinal Mouse)	T12-S1 spinous processes	Healthy	20	M9, F11	41.8
Mannion et al. (unpublished data)	30.0	-	Electromagnetic tracking systems	L1-S1 spinous processes	Healthy	103	M64, F39	19 - 59
Vialle et al. (2005)	60.2 ± 10.3	-	Radiography	Superior endplates of L1-S1	Healthy	300	M190, F110	20 - 70
Damasceno et al. (2006)	60.9 ± 10.7	-	Radiography	Superior endplates of L1-S1	Healthy	350	M143, F207	18 - 50
Been et al. (2007)	51.0 ± 11.0	-	Radiography	Superior endplates of L1-S1	Patients	106	M56, F50	20 - 50

Table 6.5.3: Comparison lumbar curvature angles of the current study with lumbar curvature angles reported in the literature

Dolan et al. (1988) utilised inclinometers in lumbar curvature measurement and reported that the lumbar curvature angle during upright sitting was almost 3 times lower than erect standing; these values were found to be in close range as reported by the current study. The study carried out by Lord et al. (1997) that measured lumbar lordosis changes between standing and upright sitting using radiography found that the average lumbar lordosis in standing was about 45% greater than in sitting. Although the values between current study and study carried out by Lord et al. (1997) were of different ranges of lumbar curvature angle, both studies agreed that the lumbar curvature angles in standing are much higher than in sitting.

Studies that measured spinal curvature/lumbar lordosis angle using radiography (Been et al. 2007; Damasceno et al. 2006; Harrison et al. 2001; Lord et al. 1997; Vialle et al. 2005) reported much higher standing lumbar curvature angles than the current study, with mean angles ranging from 49° to 61° being recorded. The difference could be due to the different methods of measurement used. The current study measured the lumbar curvature angle over the spinous processes of L1 and S1, however radiographic studies calculated the lumbar curvature angles between the superior endplate of the vertebral body of L1 or inferior endplate of T12 and the superior endplate of S1, as shown in Figure 6.5.1.

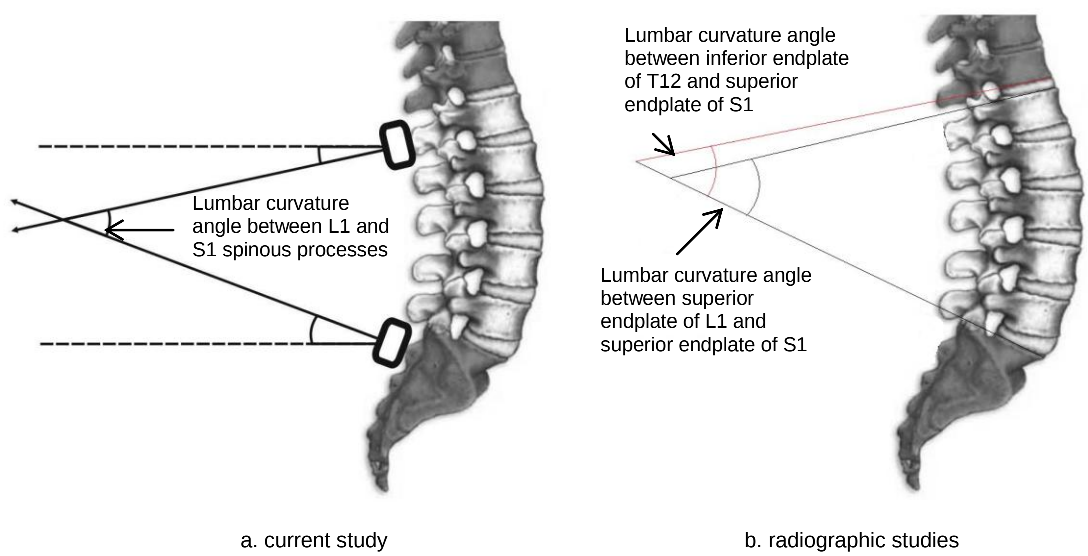


Figure 6.5.1: Illustration of the different methods in lumbar curvature angle measurement, a. shows the method used in the current study, which was over the L1 and S1 spinous processes and b. shows the method used in radiographic studies, either between the superior endplate of L1 or the inferior endplate of T12 and superior endplate of S1

The major possible causes of error in lumbar curvature angle measurement using skin surface technique include security of sensor attachment and alignment, and difficulties in anatomical landmark identification. However these errors were minimised in the current study by carefully aligned the sensors and monitored their positions from time to time, by using a secure sensor attachment method, and the use of ultrasound imaging to confirm levels of spinous processes identified by palpation. Radiographic methods in lumbar curvature measurement are also prone to errors, such as intraobserver and interobserver variability. In a normal procedure, the examiners would need to draw lines or digitise anatomical points on the radiographs in order to determine the angle of the vertebral endplate. However endplates do not usually lie perpendicular to the vertebral body, and often have a ridge that may distort the experimenters' choice in choosing the points of the line (see Figure 6.5.2), this could cause further discrepancies in the results (Harrison et al. 2001; Polly et al. 1996).

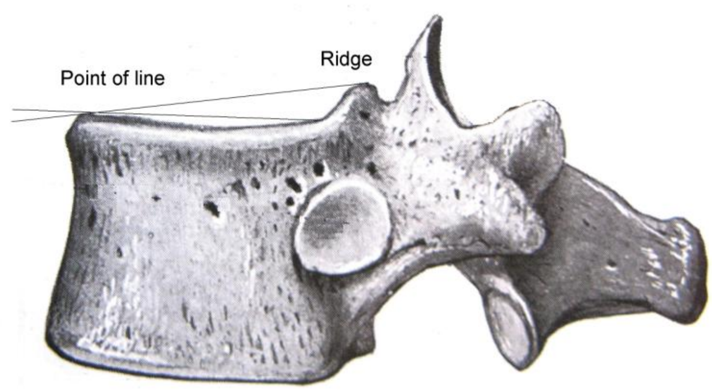


Figure 6.5.2: Illustration of possible discrepancy due to the point of line chosen for the calculation of lumbar curvature angle measurement in radiographic study

Different techniques used in determining lumbar curvature from a radiograph could also contribute to the variability of reported angles. Harrison et al. (2001) studied 4 different methods (Centroid, Cobb, TRALL and Posterior Tangent) in lumbar curvature measurement. Even using the same radiographs, the 4 different measurement methods produced a mean lumbar curvature angle that ranged from 41.2° (TRALL method) to 66.1° (Posterior Tangent method) (Harrison et al. 2001).

Measurement errors could also occur due to the participants' position and performance during radiographic imaging and radiograph quality (Mannion et al. 2004). In radiographic methods, participants are often requested to raise their hands during imaging in order to expose the spine; however raising the arms may increase the lumbar lordosis and this may be another possible reason for the differences between the current study and radiographic results.

The gender and age of participants in the studies could also contribute into the difference in lumbar curvature angles. Damasceno et al. (2006) and Vialle et al. (2005) reported that females exhibited significantly higher lumbar curvature angles than males with a difference of approximately 4° to 5°. Damasceno et al. (2006) also observed significantly higher lumbar curvature angles in older participants (age group of 31 to 50 years compared to an age group of 18 to 30 years) with a mean difference of approximately 4°. From the standard deviations of the radiographic studies, it can be observed that the range of lumbar curvature angles were considerably higher in those studies. Damasceno et al. (2006) reported a mean lumbar curvature angle of 60.9°, with a range of 33° to 89°; while Vialle et al. (2005) reported the average lumbar curvature angle of 60.2° with a range of 30° to 89°. The current study gave a range of lumbar curvature angles between 22° and 43°, however the sample size of this study was relatively small and this is likely to have reduced the range of angles observed.

When comparing the lumbar curvature angles measured in the current study with those measured using other skin surface methods, the values obtained in the current study were in close agreement with values reported by studies carried out by Dolan et al. (1988) and Mannion et al. (2004 and unpublished data) that utilised inclinometers, accelerometers (Spinal Mouse system) and electromagnetic tracking systems. The current study produced higher lumbar curvature angles (8° to 9°)

than the values reported by Ng et al. (2001; 2002) possibly due to different measurement methods and different levels of lumbar segments used for measurement. Ng et al. (2001; 2002) recruited only male participants in their studies while the current study had a balance mix of both genders, although this may not contribute much to the differences between the 2 studies as the current study did not find a significant difference in lumbar curvature angles between the 2 genders. Though, the findings of the current study did show a slightly higher angle in female participants, similar to the observations reported by Damasceno et al. (2006) and Vialle et al. (2005). Based on the results of the current study, it was concluded that the inertial measurement system was a feasible and valid system for use in spinal posture measurement and discrimination of posture.

Functional activities

During functional activities, running was identifiable by the amplitude of the acceleration signal from the vertical axis, which ranged from 1.85g to 3.16g, while level walking was found to result in an amplitude of between 0.49g to 1.34g, and walking up and down steps showed an amplitude similar to level walking, which was between 0.41g to 1.72g. Similar results were reported by Bhattacharya et al. (1980) that 0.9g to 5.0g was observed in the low back during running; and Cappozzo (1982) reported -0.3g to 0.8g amplitude in the vertical axis during walking. However with level walking and step walking, accelerations in the lumbar spine did not show drastic characteristics that could be used to differentiate between these activities in the current study. In this study the accelerometers used had a specified range of ±2g, thus it was not possible to record any acceleration higher than this range. A cut off at approximately ±1.8g was seen in most of the running results, as shown in Graph 6.5.22. It was possible the acceleration of the vertical axis might have been higher than was reported in this study (as those reported by Bhattacharya et al. 1980), however the data obtained in this study was sufficient to discriminate between running and different walking activities. Frequency analysis was also able to be used to distinguish running from walking as the frequencies of running were between 2.34Hz and 2.93Hz whereas in walking, the frequencies were lower between 1.37Hz and 1.95Hz. The frequency properties of walking up and down steps were not studied due to the small range of data collected.

Veltink et al. (1996) reported success in the detection between ascending or descending stairs and walking, and this was done using a sensor on the thigh. However the authors did not mention whether the algorithm was able to differentiate stairs ascents and descents. In the current study, there was no sensor attached to the leg and hence the feasibility of classifying different walking activities via this method was not examined.

From these results, it is clear that different spinal postures, spinal physiological movements, running and walking activities can be measured and discriminated by analysing their properties using accelerometer and gyroscope to collect data from the lumbar spine. Inertial measurement systems proved to be a valid method for spinal posture and motion measurement.

6.6 Conclusions

The inertial measurement system is a valid tool for use in 3 dimensional spinal posture and motion measurements. Different postures and motions were able to be differentiated by analysing their characteristics using accelerometer and gyroscopic data, though the system was unable to differentiate between level walking and walking up and down steps with only 2 sensors on the lumbar spine. The inertial measurement system used was shown to be feasible in spinal posture and motion measurement with the advantages of being small, having low power consumption and being portable, it provides a wider scope of possible research in everyday life outside of the laboratory environment, possibly over an extended period of time. Before utilising the system in a large scale field study, it was necessary to first examine the feasibility and suitability of inertial measurement system for use of spinal posture and motion measurement in normal daily life over an extended period of time.

Chapter 7. Study to monitor spinal posture and motion of desk workers

7.1 Overview

In previous chapters, it has been shown that an inertial measurement system is a valid tool for 3 dimensional spinal posture and motion measurement. In this chapter, the feasibility of using an inertial measurement system for long term continuous 3 dimensional spinal posture and motion measurement and monitoring outside the laboratory in a normal daily working environment is examined.

There are many occupations which involve working in a sitting posture, these occupations range from administrative desk workers, to assembly line workers, cashiers, call centres operators, and vehicle drivers. These workers may work in a sitting posture for the course of a whole working day. In 2005, 44% of British workers reported that their job involved sitting for at least 4 hours a day (Health and Safety 2008).

Although sitting at work has not proved to be a lone risk factor for the development of low back pain (Hartvigsen et al. 2000), prolonged static sitting has been widely accepted to be associated with low back injuries (as discussed in Section 2.4) by increasing the loading on spinal structures (Callaghan and McGill 2001a; Hedman and Fernie 1997; Kelsey and White 1980; Lotz et al. 1998); increasing stiffness of the lumbar spine (Beach et al. 2005); resulting in deconditioning and fatigue in spinal muscles (O'Sullivan et al. 2006a; Veiersted et al. 1990); and it may also lead to insufficient nutrition to the intervertebral discs (Kelsey 1975a).

In this technologically advanced society, the increasing use of computers in the work place has consequently promoted increasingly sedentary sitting habits. In earlier days, documents were stored in filing cabinets and interaction between workers might require workers to transfer files physically from one place to another by walking. However with the use of computers and internet technologies, documents are mostly stored electronically, interaction and file sending can be done through networks without workers having to leave their desks. Another survey conducted in 2005 reported that 37% of European workers were involved in significant computer use in their jobs and almost 15% of European workers who mainly used computers at work reported having back pain (Parent-Thirion et al. 2007).

To gain insight into sitting patterns in order to subsequently enable development of improved office working regimes, it is necessary to study continuous 3 dimensional spinal postures and motions of computer/desk workers in their normal working environment over an extended period of time. However there have been limited studies carried out in this field, with studies of spinal posture and motion of desk workers having been mostly performed in laboratory settings and/or with predefined conditions (Beach et al. 2005; Vergara and Page 2000a; Vergara and Page 2002), or only involving 1 or 2 planes of measurement (Mork and Westgaard 2009; Vergara and Page 2000a; Vergara and Page 2002). Studies that measure spinal posture and/or motion in a laboratory setting may not be representative of the posture and/or motion of the normal population in the real working environment as participants tend to perform differently in such artificial settings. Predefined conditions and assumptions in a laboratory study may alter participants' usual sitting habits in order to become accustomed to the conditions provided in the laboratory; for instance in the study carried out by Beach et al. (2005) who studied the effects of prolonged sitting over a 2 hour period, the participants in their study were requested to sit in an office chair with the back support removed and engage in reading and writing tasks at a desk. The authors believed that the chair design was not an important limitation in the study based on the observation that individuals tended to lean forwards during reading and writing activities. However, this assumption may not be true in a real life situation. The human body is an intelligent adaptive system, if a back rest is available, a person has a choice of different sitting postures and he/she may adapt into different angles of sitting when the previous posture starts to become uncomfortable due to muscle fatigue. A person may flex forward to read at a desk but if a back rest is available, reading by holding the reading material while resting on the back rest may also be another scenario in normal daily life. Even in writing, if the angle of the back rest is adjusted with the chair close enough to the desk, writing without leaning forward may also be possible. Nonetheless, this experimental configuration was found to be appropriate to achieve the aim set out by Beach et al. (2005) who had shown that prolonged sitting posture increased stiffness in the lumbar spine. The findings of this study may have been applicable for occupational groups that worked in a constrained space to perform the same task throughout the day, such as cashiers.

Short measurement duration may also impair the real picture of normal desk work activities; therefore measurement duration should be taken into consideration in any study design. Although spinal posture and motion seem to be an important measure in desk workers, there have not been many studies (Snuders et al. 1987; Van Riel et al. 1995) carried out in this area from a 3 dimensional perspective. As the spine is a complex 3 dimensional structure, one or 2 planes of measurement may not provide the whole picture of posture and movement. Otun and Anderson (1988) used inclinometers for continuous sagittal spinal movement measurement with a male participant in a car assembly plant. However this study only measured posture and motion in a sagittal plane and the inclinometers were attached to the participants using only double sided tape, which could result in the security of sensor attachment being compromised if there was any friction against clothing, backrest of a seat, or during heavy assembly work, which in turn would affect the quality of results.

Vergara and Page (2000a) measured the sagittal posture of 6 participants during 100 minutes of sitting on 6 different types of chair, ranging from a chair without any adjustable function to a chair with seat height, seat and back rest inclination adjustment and with lumbar support. The authors utilised a rachimeter or a thin steel band of a flexible goniometer to measure lumbar curvature angle and an inclinometer to measure inclination of the pelvis. The method of attachment of such equipment was not discussed in their paper, but was discussed in a later paper by the same authors (Vergara and Page 2002). In the later paper, the description of participants (number of participants, mean and standard deviations of height) and the procedures used were similar to Vergara and Page (2000a), therefore the author of the current thesis has assumed both papers were describing the same study. In an image provided in Vergara and Page (2002) the rachimeter could be seen to be attached to the participant from the top of the thoracic spine to pelvic level, the authors indicated that the rachimeter was attached to the spine in such a way that the lumbar curvature angle was measured between T12 and L5 spinous levels. Inclination of the pelvis was measured at the level of 15mm below L5 spinous process. However as different individuals have a different structural build, by assuming the pelvis is always 15mm below L5 spinous process might lead to errors in lumbar spinal curvature angle when comparing between participants.

Snuders et al. (1987) studied the working postures and movements of a bricklayer, an office clerk, a physiotherapist, a storehouse worker and a delivery man over a period of 8 hours. Snuders et al. (1987) used inclinometers to measure sagittal posture and movement; a strain gauge based sensor that measured the length of skin during lateral posture and movement; and a single turn potentiometer to measure rotational posture and movement. However to have 3 different sensors on the lumbar spine may not be ideal for participants, although the authors claimed that there was no hindrance to the participants in the study, it might be expected to have some effect on natural behaviour of the participants. As discussed in Section 3.2, the reliability and validity of the equipment used in the study by Snuders et al. (1987) are uncertain.

Van Riel and co-workers (1995) performed a study on 3 dimensional posture and motion of the head and trunk using 4 straddle carrier drivers, 5 crane operators and 5 office employees over a 2 hour period using inclinometers and a torsionmeter. Two inclinometers were used to measure spinal movement, one at T2 for lateral movement and another at the level of L2/L3 for sagittal movement; the torsionmeter was attached across T2 and T10 spinous processes to estimate total spinal rotation. This study could only provide data for overall posture or movement of the spine as a whole and the torsionmeter showed a large variation of 9°, which may not be ideal for a study that requires better accuracy. It would not be ideal to have 3 different sensors in order to measure 3 dimensional posture and movement of a single segment, inertial measurement systems can overcome this issue.

As discussed in Section 3.3, Wong and Wong (2008b; 2008c) monitored sagittal and coronal spinal postures of 5 participants in their own homes using an inertial measurement system over a 3 to 4 days (2 hours per day) trial period, by using a feedback system on 2 of the trial days to prompt participants to adopt a posture similar to neutral standing. These authors showed that inertial measurement systems are feasible for use in spinal posture monitoring over long period of time outside the laboratory setting. They also found that the inertial measurement system was a reliable and valid system for spinal posture measurement with the capability of detecting change in static calibration with an RMS error of less than 1°. However in the studies by Wong and Wong (2008b; 2008c), only 2 planes of posture were monitored and the posture angles were normalised when comparing the results between the 3 or 4 day trials, this could lead to misleading results, as standing, sitting or other dynamic activities such as walking and lifting would produce very different spinal angles. If a participant engaged in mainly sitting in day 1 of the trial and mostly standing on day 2, the spinal angles of the 2 trial days would lead to misleading assumption that the feedback system was in fact correcting posture. The authors did not mention if they were monitoring the types of activities engaged by the participants during the trials, although they noted that the participants claimed they sat more during the monitoring period, however this information may not be adequate enough to justify a mean posture being used for comparison if the feedback system is truly effective. A more controlled study with a larger sample size that can analyse different postures separately would provide stronger evidence in the results.

The objectives of this study were to investigate the feasibility of inertial measurement system in long term 3 dimensional spinal posture and motion monitoring and measurement in a normal daily working environment; to examine and compare spinal mobility before and after 3 hours of desk work activities; and to study the relationship between desk work activities and changes in spinal mobility if applicable.

In this present study, 3 dimensional spinal posture and motion of healthy desk workers who had not experienced back pain in the past 12 months were measured and monitored using inertial sensors over a period of 3 hours. The spinal ranges of movement and standing lumbar curvature angles before and after the 3 hour desk work were measured in order to compare any differences in spinal mobility and lumbar posture after a prolonged period of desk working. The procedures and results of the study are described and discussed in the following sections.

7.2 Participants and recruitment

This study was approved by the University of Brighton's Faculty of Health and Social Science Ethics and Governance Committee. A copy of the letter of approval is shown in Appendix Section A1.1b.

Participants were recruited by advertising via a recruitment poster (see Appendix Section A1.2b) through email communication within Eastbourne campus of the University of Brighton. The researcher provided detail information about the nature and procedures of the study, together with a copy of an information sheet sent by email to the interested participants who contacted the researcher by email or phone. A copy of the participant information sheet for this study can be found in Appendix Section A1.3b. Interested participants were free to take as long as they wished to decide if they were interested in participating; and they were encouraged to contact the researcher at any time if they had any questions or concerns regarding the study. An appointment for data collection with interested participants was arranged after they had agreed to participate in the study. Participants were provided with the knowledge that they could withdraw from the study at any time even if an appointment for data collection was made. Participants were encouraged to wear 2 piece clothing (shirt/t-shirt with trousers/skirt/shorts) on the day of data collection to facilitate sensor attachment to the lumbar spine.

The participants were requested to attend to the Human Movement Laboratory at University of Brighton on the day of data collection. Participants were again given a verbal explanation of the procedures of the study and a printed information sheet which they could take with them. Participants were given as much time as needed to decide if they would still like to participate in the study. A consent form (as shown in Appendix Section A1.4b) was provided to obtain participants' signature if they agreed to participate, with the understanding that they could withdraw from the study at any time without penalty or prejudice, or the need to provide any reason for withdrawing. Participants were encouraged to raise any questions or concerns regarding the study at any time.

Sensor attachment to the participants was performed by the researcher either in the Human Movement Laboratory or participants' work place depending on their preference. During the process of locating anatomical landmarks and attachment of sensors, there were certain levels of undress needed to expose the lumbar spine as the sensors were attached to the first lumbar and first sacral spinous processes of participants. These procedures were performed in a private area to ensure privacy.

Participants experienced no pain or discomfort during the course of data collection. There was no known risk associated with the method of data collection or the sensors used in this study. Participants were given the right to request access to their own personal measured information and results on the day of data collection or contact the research team after the day of data collection.

Twenty two healthy participants were recruited for this study, 4 participants were excluded based on the exclusion criteria shown below. With a sample size of 18, power analysis produced a power of 0.878 (effect size = 0.69, $p < 0.05$), which indicated that this sample size was sufficient to reveal any significant differences between ranges of movement before and after 3 hours of desk work data collection. The power analysis was performed based on a paired t-test using the means and standard deviations of ranges of movement measured by the earlier study using an inertial measurement system (Xsens) as reported in Section 6.4. The analysis was performed using the same protocol as described in Section 6.2.

As discussed in Section 2.2, the biochemical and structural changes in the intervertebral discs, vertebral end plates, vertebral bodies and the zygapophyseal joints during aging (Bogduk 2005) can affect the mechanical properties and kinematics of the spine. Therefore, an age group of 20 to 44 years of age (Soanes and Stevenson 2006) was chosen as the focus of the current study was to measure and monitor spinal posture and motion of a group that is more prone to non-specific low back pain. In this study, only participants who worked at a desk for a minimum of 15 hours per week were recruited as desk workers (Dumas et al. 2009). In order to achieve a normalised analysis, participants who had difficulties and limitations in performing daily physical activities, suffered any spinal conditions that could affect normal spinal posture and motion patterns, or diagnosed with health conditions that could limit the activity tolerance were not included in the study.

The inclusion and exclusion criteria for this study are summarised as follows.

Inclusion criteria were:

- 20 to 44 years of age (both genders)
- body mass index (BMI) between 18.5kg/m^2 to 30kg/m^2
- no history of back pain or leg pain that could be related to a spinal problem or requiring medical attention/treatment in the past 12 months.

- working at a desk for more than 15 hours a week (Dumas et al. 2009)

Exclusion criteria were:

- underweight or obese (body mass index, BMI < 18.5kg/m^2 for those who were underweight and BMI > 30kg/m^2 for those who were obese (WHO 2006))
- difficulties and limitations in performing daily physical activity;
- pregnancy;
- any known musculoskeletal disorders;
- any neurological or orthopaedic disorders;
- rheumatoid arthritis;
- joint dislocation;
- serious observable abnormality in spinal posture; and
- injury, surgery, infection, bone fracture, dislocation, or diseases related to the spine; that may affect normal spinal posture and motion patterns
- cancer or other serious conditions;
- asthma;
- coronary heart disease; that may decrease activities tolerance
- leg length discrepancy of more than 20mm as this was found to affect the symmetry of the spinal structures and thus affecting normal spinal posture and movement patterns (Kakushima et al. 2003, Lee and Turner-Smith 2003)
- allergy or hypersensitivity to the adhesive tapes used in this study.

Table 7.2.1 summarises the general information of the 18 participants (4 males and 14 females) in this study. All of the participants were staff and students of the University who worked at a desk for more than 15 hours per week.

Participant	Gender	Occupation	Age (year)	Height (m)	Weight (kg)	BMI (kg/m^2)	Hours of desk work/week
1	F	Research Student	41	1.51	48	21.05	40
3	F	Lecturer	43	1.69	85	29.76	22
4	F	Student	37	1.64	67	24.91	15
5	F	Research Officer	42	1.73	66	22.05	32
7	F	Student	28	1.72	59	19.94	18
8	F	Development Manager	27	1.70	69	23.88	20
9	F	Student	23	1.67	62	22.23	40
10	F	Research Administrative Assistant	35	1.67	63	22.59	26
12	F	Research Administrative Assistant	39	1.78	76	23.99	35
13	M	Research Officer	36	1.72	68	22.99	35
14	M	Research Officer	37	1.86	80	23.12	15
15	F	Research Student	33	1.64	50	18.59	40
16	F	Research Officer	29	1.68	78	27.64	40
17	F	Laboratory Technician	20	1.66	55	19.96	20
19	F	Student	21	1.72	87	29.41	28
20	M	Graphic Designer	44	1.85	90	26.30	28
21	M	Lecturer	44	1.74	65	21.47	28
22	F	Lecturer	40	1.65	74	27.18	40
Minimum			20.00	1.51	48.00	18.59	15.00
Maximum			44.00	1.86	90.00	29.76	40.00
Mean			34.39	1.70	69.00	23.73	29.00
Standard deviation			7.94	0.08	12.15	3.24	9.15

Table 7.2.1: Summary information of all 18 participants who participated in the study of spinal posture and motion measurement of desk workers

7.3 Methods

After participants had agreed to participate and signed a consent form on the day of data collection in the Human Movement Laboratory, measurements of height, weight, lower limb length and shoulder width were taken. The method of measuring lower limb length and shoulder width were the same as described in Section 6.3. The general health of participants was also documented. A copy of the information form on information requested from participants is shown in Appendix Section A1.5.

The landmarks for sensor attachment, which were the L1 and S1 spinous processes, were located and marked by a trained physiotherapist in the Human Movement Laboratory. The methodology in identifying L1 and S1 spinous processes is explained in Section 6.3. After L1 and S1 spinous processes were identified by palpation and marked, ultrasound imaging was used to confirm the locations by scanning the spinous processes from S2 at the level of the PSIS to L1.

Palpation, ultrasound scanning and sensor attachment were performed with participants in an upright standing position.

Participants were then given a choice to have the sensors attached in the Human Movement Laboratory or at their work place. The majority of participants preferred to have the sensors attached at their work place, only 1 participant chose to have the sensors attached in the Human Movement Laboratory. The attachment method used in this study was based on the Configuration 3 as described in Section 5.3. Transparent plastic plates (103x48x1 mm) were attached to the participants' L1 and S1 spinous processes with double sided tape, as the base for sensor attachment. The sensors were attached to a small plastic plate that was treaded with an elastic Velcro strap and attached to the transparent plastic plates with double sided tape. The 2 sensors were attached to participants with most bottom edge of the top sensor aligned with the inferior aspect of L1 spinous process; and the uppermost edge of the bottom sensor aligned with the superior aspect of the S1 spinous process. This was to ensure consistency of lumbar levels for spinal measurement. The elastic straps were fastened around participants' spine to secure the sensor attachment, as shown in Figure 7.3.1 below. Wider straps were used in this study compared to those in Chapter 6 to ensure better security and comfort during the long term (> 3 hours) measurement. Spirit levels were used to ensure sensors were aligned to the horizontal axis (ground) with an estimated accuracy of ±1°. This method of attachment used was found to be the most secure attachment method for the current study as discussed in Section 5.3.

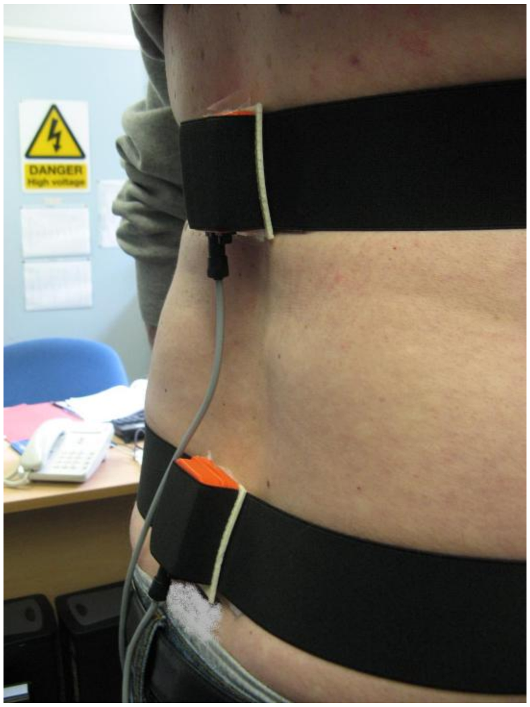


Figure 7.3.1: Attachment of inertial sensors (Xsens) to L1 and S1 spinous processes of participants

Figure 7.3.2: Sensors stayed underneath clothing and data logger was worn over clothing

Two inertial sensors (Xsens) were used in this study. The sensors were set to record data at a rate of 50 samples/second in order to achieve maximum available resolution of the data for the monitoring of small sitting movement in the 3 hours data collection period. After sensor attachment, the sensors stayed underneath the participants' clothing and a data logger was worn around the participants' waist over the clothing as shown in Figure 7.3.2. The cables were folded up carefully (not shown in Figure 7.3.2) and taped together to ensure no obstruction to the participants' posture or movement, and it was ascertained there was no tilting of sensors in the process.

Participants returned to their place of work with the researcher after all the measurements and initial preparations were completed in the Human Movement Laboratory. A laptop was set up in the participants' work place for data logging. The Xsens sensors were set to Bluetooth function for wireless operation. Before the 3 hour desk work data collection, participants were requested to perform 6 physiological movements to maximum range. These movements were flexion, extension, lateral flexion to both left and right sides, and axial rotation to both left and right sides. Two markers were placed on the floor at a distance apart of the participants' shoulder width. Participants were instructed to stand on the markers and performed the 6 physiological movements following the processes described in Section 6.3. Each physiological movement was repeated 3 times and 30 seconds was allowed for data collection for each movement. The maximum value of the 3 trials of each movement was taken for comparison with ranges of movement data taken after 3 hours of desk work in order to study if there is any difference in spinal mobility before and after prolonged desk work activities.

After performing the 6 physiological movements, the alignment of sensors was checked with a spirit level to ensure the sensors were aligned to the horizontal axis. Participants were requested to stay in an upright standing posture for 15 seconds as the standing reference data and then resumed normal desk work activities. Data was then collected over a period of 3 hours. The participants were not restricted to sitting during the 3 hour period and were encouraged to perform any daily activity as usual and instructed that it was not necessary to avoid performing any unusual activity. The researcher kept a log of events during the 3 hour data collection period. The researcher was present for the 3 hour period in order to ensure that data collection was completed without interruption. Every effort was made to ensure participants' working patterns were not disturbed by either the equipment or the presence of the researcher.

After 3 hours of desk work, participants were requested to repeat the 6 physiological movements as previously performed before the sensors were detached. Participants were not required to return to the Human Movement Laboratory after data collection. Sensors were removed from participants at their work place and all equipment returned with the researcher.

Data analysis

All the data analysis in this study was performed using MATLAB and Microsoft Excel, statistical analysis was carried out using SPSS software.

Ranges of movement data from before and after 3 hour desk work activities were computed into 3 dimensional relative angles between L1 and S1 spinous processes by using direction cosine matrices and Euler angles solutions were used to represent the anatomical rotation angles as discussed in Appendix A6.1. Descriptive analysis was performed on all variables, and all variables were analysed using a paired t-test to determine any significant difference between the 2 sets of measurement.

Before analysis of the 3 hour desk work activities' data, the raw data was screened through to separate it into 2 main categories, static posture and movement, as shown in Figure 7.3.3.

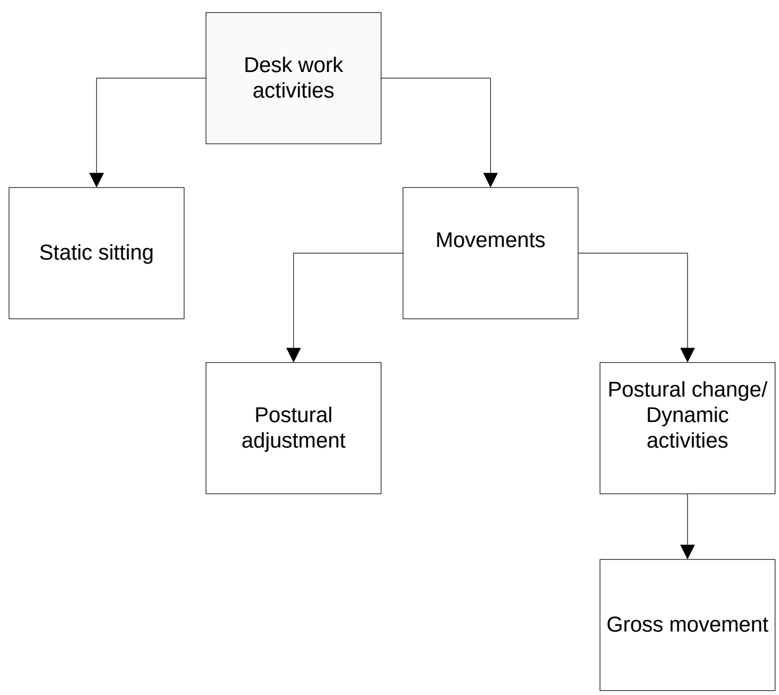


Figure 7.3.3: Main categories during desk work activities

Similar to the terms used by Vergara and Page (2000a; 2002), postural change referred to a change in angle (>2° in the current study) between 2 static sitting postures. Postural adjustment (termed as fidgeting movement in Vergara and Page 2000, 2002) referred to the small movements (<2°) occurred during sitting. Dynamic activities referred to activities involved participants to leave their seats, such as taking a toilet break or making drink. While gross movement was a sub-category of postural change/dynamic activities, it referred to a change in angle of >5° in any of such movements.

The conditions for static posture are as described below and the differentiating algorithm is shown in Figure 7.3.4.

- there was no movement observed in raw gyroscopes data (-0.1 rad/s < gyroscopes < 0.1 rad/s) on any axis;
- or, the standard deviation of 5 consecutive raw accelerometers data (1 second moving window) was less than 0.0085g (0.487°) on any axis;
- and, these static conditions lasted for 1 second or more

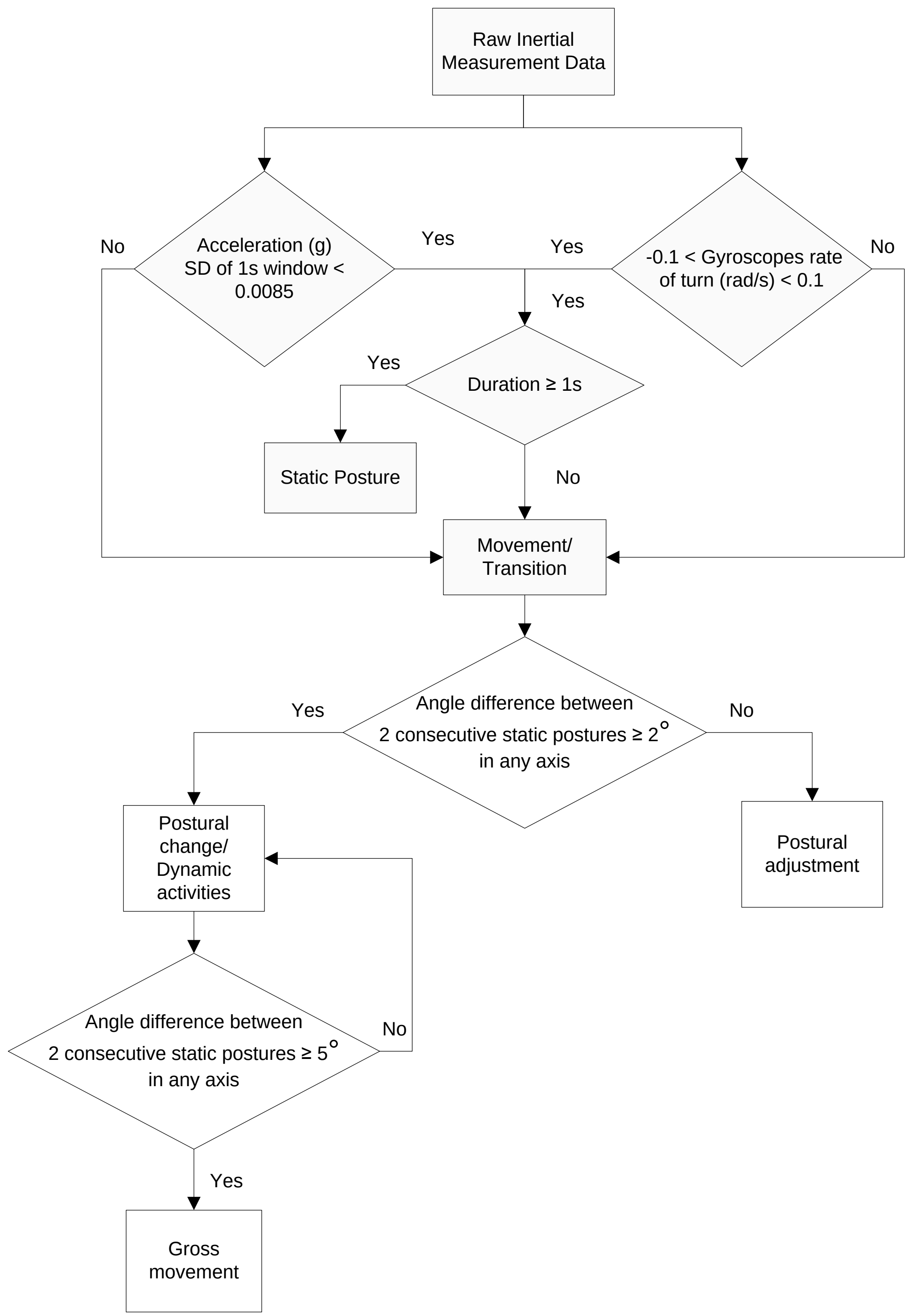


Figure 7.3.4: Flowchart to discriminate static posture and movements from raw inertial measurement data

The standard deviation of the accelerometer signals indicated the variability for the 1 second window of data (Culhane et al. 2004; Lyons et al. 2005), a variability of below 0.5° was treated as a possible static posture and a change of more than 0.5° was defined as movement. The gyroscope signals were also analysed and any values that were between ±0.1rad/s were also treated as possible static postures and those outside this range was defined as movement. The possible static posture data were further analysed, if the period of possible static posture was equal to or longer than 1 second, the data was classified as static posture and if the period of the possible static posture was shorter than 1 second, the data was defined as movement. These conditions were chosen based on 2 early experiments as described below.

The first experiment: was performed by placing 2 Xsens sensors on a table with no movement (static), 30 seconds of data were recorded before moving the sensors slightly (±1°) for 5 seconds to imitate small movements and then setting them to the static position for 30 seconds, and finally moving the sensors with random movements for 5 seconds before ending the experiment by returning the sensors to the static position on the table for 30 seconds;

The second experiment: was carried out with 2 participants of the current study before data collection of the 3 hour desk work period, where the participants were requested to sit still for 30 seconds, followed by engaging in small fidgeting movements for 5 seconds, after the fidgeting movements, the participants continued to sit still for 30 seconds before requested to stand up from the seat and walk around the room for 10 seconds.

The raw accelerometer and gyroscope data from these 2 experiments were analysed to study the characteristics of static posture, small movements and large movements. Based on the results of these experiments, it was found that the above discriminative conditions were suited to differentiate between these activities. Before applying the discriminative algorithm to all the 18 participants, 5 sets of data from 5 participants were used to test out the effectiveness of the algorithm. It was found that this algorithm was able to discriminate between different activities during a desk work period when comparing the output with the observations of the activities of participants noted by the researcher during the data collection period.

For movement data, discriminative analysis continued to separate the movements into 2 main groups, which were the postural change/dynamic activities (when angle difference between 2 consecutive static postures was equal or greater than 2° in any axis) and postural adjustment. Figure 7.3.4 illustrates the discriminative process. Under postural change/dynamic activities, any angle difference between 2 static postures equal or greater than 5° was further classified as gross movement. In general, 5° is favoured and viewed to be more appropriate to represent any clinical significant difference between 2 values. Vergara and Page (2002) used 5° as the condition in classifying a movement as a postural change. However after analysis of all 18 data sets from the current study, it was observed that many of the angle differences between 2 consecutive static sitting postures after a dynamic activity (e.g. taking a toilet break) were between 2° and 5°. If 5° was chosen as the condition for postural change/dynamic activities, there would be many misdetections in the results.

By changing the cut off point for the discrimination between dynamic activities and postural adjustment movements to study the percentage of misdetection on 18 participants for 3 hours of data per participant by comparing the results with recorded observations of activity, it was found that when the cut off point was set at

- 3° misdetection was seen in 9 of the participants, with the error ranging from 12.5% to 100%
- 4° misdetection was found in 12 participants, with the error ranging from 12.5% to 100%
- 5° misdetection was also found in 12 participants with the error percentage ranged from 12.5% to 100%
- 6° misdetection of 12.5% to 100% was observed in 13 of the participants.

Three participants did not engage in any dynamic activities during the 3 hours of data collection and hence no relevant data on error analysis for Participants 9, 17 and 21, as shown in Table 7.3.1. As the cut off point was set to 2°, there was no misdetection observed in any of the participants; while 1° was too small of an angle to be considered as postural change/dynamic activities. Therefore, 2° as the cut off point for discrimination of postural change/dynamic activities and postural adjustment was the optimal threshold for this study. Any angle difference between 2 consecutive static sitting postures was greater than 5° was further classified as gross movement.

	Misdetection (%) when cut off for discrimination between dynamic activities and postural adjustment movements was				
	2°	**3°**	**4°**	**5°**	**6°**
Participant 1	0.0%	33.3%	33.3%	33.3%	33.3%
Participant 3	0.0%	100.0%	100.0%	100.0%	100.0%
Participant 4	0.0%	0.0%	0.0%	0.0%	100.0%
Participant 5	0.0%	12.5%	12.5%	37.5%	50.0%
Participant 7	0.0%	0.0%	0.0%	0.0%	0.0%
Participant 8	0.0%	0.0%	50.0%	50.0%	50.0%
Participant 9	-	-	-	-	-
Participant 10	0.0%	0.0%	0.0%	0.0%	0.0%
Participant 12	0.0%	22.2%	44.4%	44.4%	66.7%
Participant 13	0.0%	0.0%	12.5%	12.5%	12.5%
Participant 14	0.0%	12.5%	12.5%	12.5%	25.0%
Participant 15	0.0%	0.0%	100.0%	100.0%	100.0%
Participant 16	0.0%	50.0%	50.0%	50.0%	50.0%
Participant 17	-	-	-	-	-
Participant 19	0.0%	25.0%	25.0%	25.0%	25.0%
Participant 20	0.0%	16.7%	33.3%	33.3%	83.3%
Participant 21	-	-	-	-	-
Participant 22	0.0%	42.9%	42.9%	85.7%	85.7%

Table 7.3.1: Error analysis on percentage of mis-detection with different cut off points during discrimination between dynamic activities and postural adjustment movements

During the process of analysing the 18 sets of data with the discriminative algorithm, the raw data from both sensors were also plotted into 1 minute window graphs and inspected visually to ensure there was no mis-detection or over-detection with the conditions. Figure 7.3.5 shows an example on how data was inspected with the 1 minute window graph of 1 sensor. The first 3 columns were condition set for raw accelerometer data and following 3 columns were condition set for raw gyroscope data. A graph of 1 minute duration was plotted for visual inspection to match the positive movement flagged by the conditions.

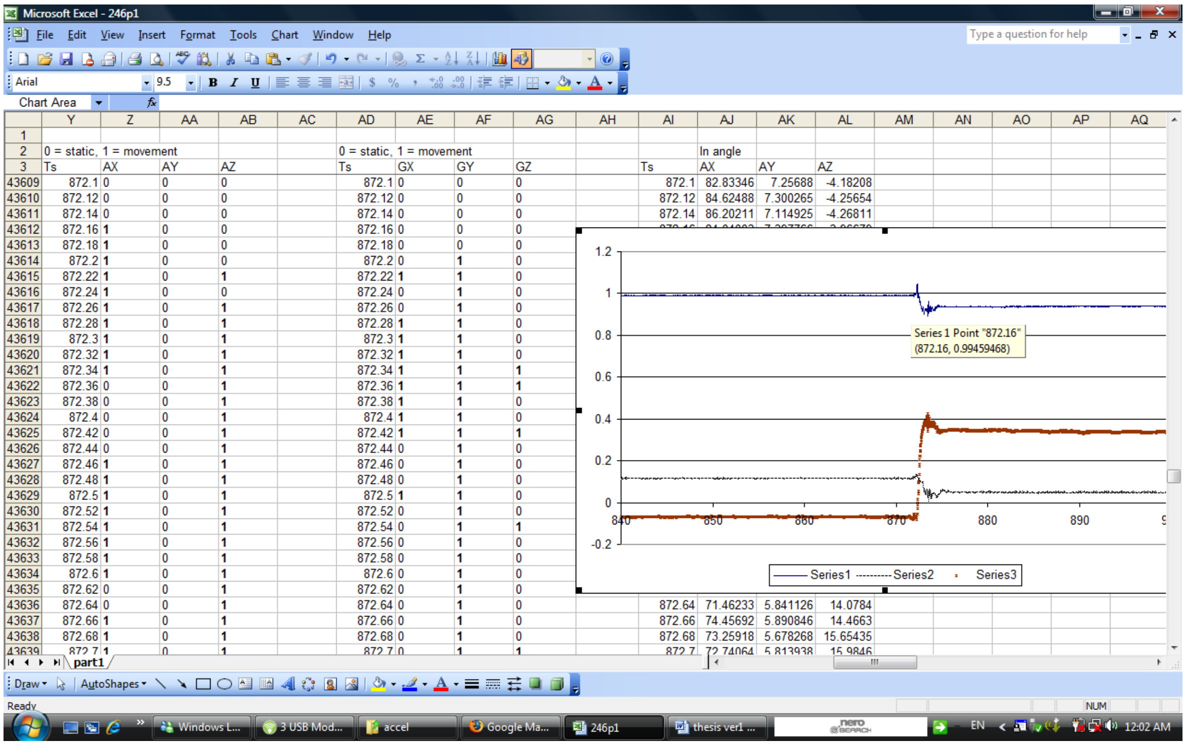


Figure 7.3.5: A typical example of how raw data was segregated into static posture and movement

Once the data was separated into static posture and movement, static posture data between 2 movements was averaged to produce inclination angles that represent the position of the static posture. Inclination angles were calculated based on equations E A6.17 and E A6.18 in Appendix A6.2.

Three dimensional relative orientation angles between L1 and S1 spinous processes were computed with upright standing as the reference point using direction cosine matrices as described in Appendix A6.1. Lumbar curvature and lateral flexion angles during static postures were calculated with the inclination data from the accelerometers.

Lumbar curvature and lateral flexion angles during static postures were calculated using the same principles as the Cobb method that is often used to measure lumbar lordosis on radiographic measurement (Been et al. 2007; Harrison et al. 2001; Lord et al. 1996). As discussed in Section 6.3, the Cobb method was found to be the most suitable method for use in this study. Figure 7.3.6 illustrates how these angles were calculated.

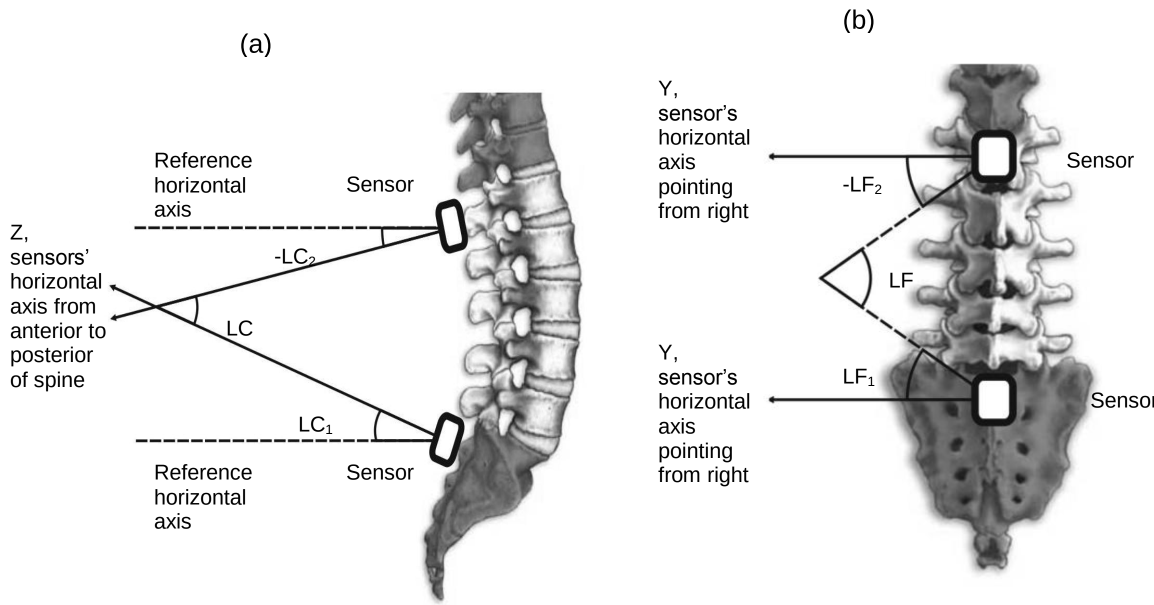


Figure 7.3.6: Graphical illustration of how lumbar curvature (a) and lateral flexion (b) of static posture were calculated with inclination data from accelerometers

In Figure 7.3.6a, the sensors' Z axis was used to determine the inclination of L1 and S1 spinous processes, and the lumbar curvature angle (LC) was calculated based on equation E 6.3.1 in Chapter 6, also shown as equation E 7.3.1 in this chapter. Positive lumbar curvature angle indicates lordosis and negative lumbar curvature angle implies kyphosis of lumbar spine.

$$LC = LC_1 + LC_2 \qquad \text{E 7.3.1}$$

Similarly, lateral flexion between L1 and S1 spinous processes during static posture was calculated using the same principle. Figure 7.3.6b shows when the spine is not tilted to either right or left side, the Y axis of sensors are in parallel with each other; hence the angle is 0°. However, if the spine is tilted to the left, negative lateral flexion angle ($-LF_2$) is produced on L1 and positive lateral flexion angle (LF_1) on S1. Therefore, the lateral flexion angle (LF) can be expressed as

$$LF = LF_1 + LF_2 \qquad \text{E 7.3.2}$$

A positive lateral flexion angle means that the spine is tilted to the left and negative lateral flexion angle implies the spine is tilted to the right. Other than desk work activities, lumbar curvature angle was also calculated during reference upright standing posture before and after 3 hours of desk work to compare if prolonged sitting had any effect on lumbar lordosis in standing.

Frequency and duration for all static postures and movement were also analysed and angles adopted during static sitting posture were studied. All parameters were analysed using descriptive analysis. Lumbar curvature angles before and after 3 hours of desk work during standing was compared using a paired t-test.

Based on the product specification of Xsens, the gyroscopes are capable of measuring pitch and roll to the nearest 0.5° and yaw to nearest 1°. As for accelerometers, the maximum error in inclination measurement was found to be 0.9° in Section 4.3. Therefore the values for angles in Section 7.4 below were all rounded up to 1 decimal place for range of movement data, but for static postures, all angles were rounded up to the nearest number to minimise confusion in reading, as any angle less than 1 degree in this part of study was not significantly influential. All the data in this study was analysed using the values from the sensor output, there was no rounding up of the data during the calculations. The rounding up of angles was only performed at the end of analysis for presentation purposes.

7.4 Results

7.4.1 Physiological movements before and after a 3 hour desk work period

The descriptive data for ranges of movement before (BF) and after (AF) 3 hours of desk work activities are summarised in Table 7.4.1 and Table 7.4.2. The full set of range of movement data for each individual participant is tabulated in Appendix Tables A3.1 to A3.6. Please note that positive values refer to flexion, left lateral flexion and left axial rotation, negative values denote movements in the opposite direction. By comparing the mean values of 2 sets of data, it was observed that flexion and lateral flexion to both sides did not show much difference in angle. However, there was approximately a 4° decrease in angle observed during extension; and 1-2° decrease in axial rotation.

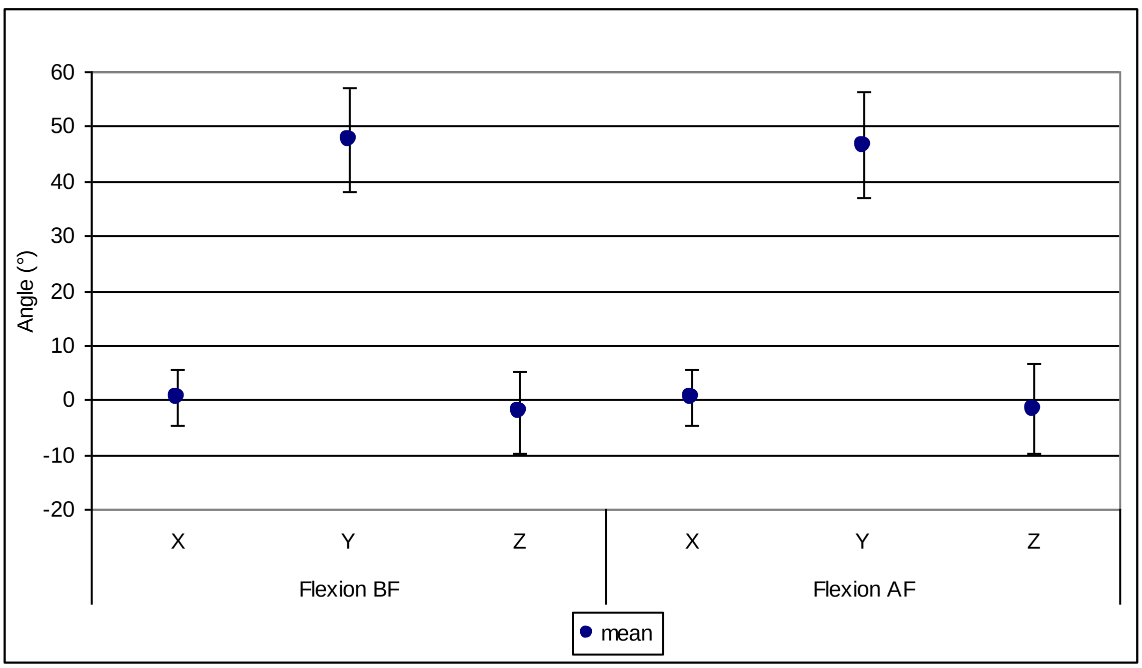
	Ranges of movement (°) before 3 hours of desk work (BF)					
	Flexion	Extension	Right lateral flexion	Left lateral flexion	Right axial rotation	Left axial rotation
Minimum	27.3	-34.9	-27.6	14.9	-16.7	5.3
Maximum	64.8	-13.8	-11.0	33.3	-5.5	17.7
Mean	48.6	-22.9	-20.0	21.0	-10.5	11.1
Standard Deviation	9.3	6.3	4.8	4.3	3.7	3.2

Table 7.4.1: Descriptive data of ranges of movement before (BF) 3 hour desk work

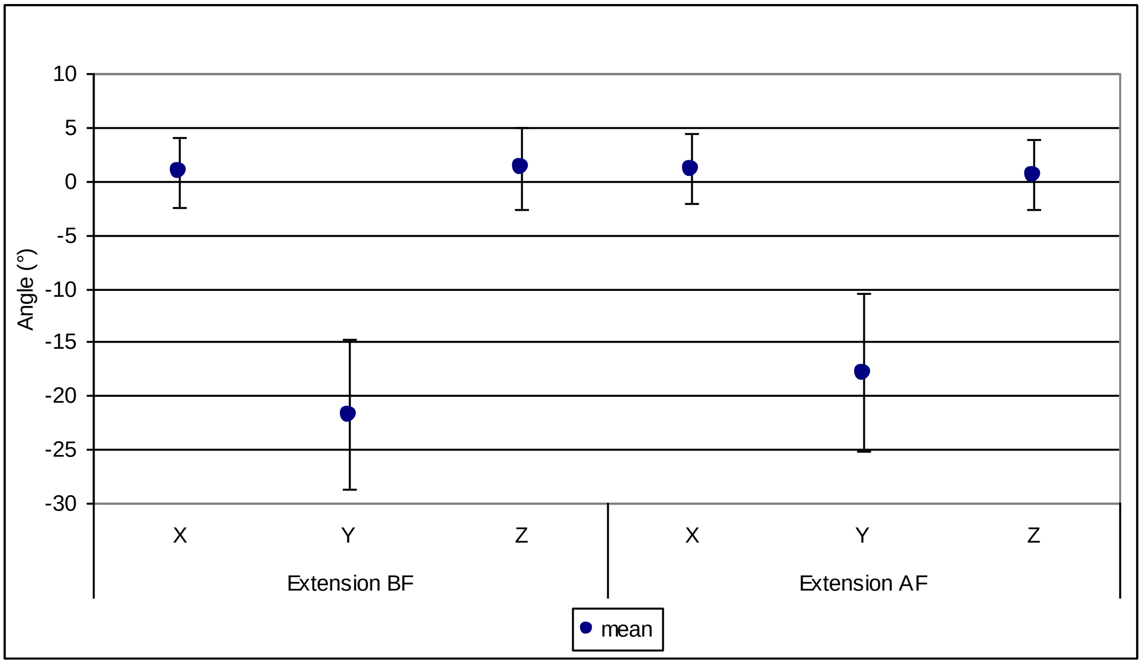
	Ranges of movement (°) after 3 hours of desk work (AF)					
	Flexion	**Extension**	**Right lateral flexion**	**Left lateral flexion**	**Right axial rotation**	**Left axial rotation**
Minimum	30.6	-31.1	-25.8	12.6	-16.9	4.4
Maximum	63.2	-8.7	-12.9	30.7	-2.9	16.5
Mean	48.0	-19.1	-20.2	21.0	-8.7	10.0
Standard Deviation	9.2	6.6	3.9	4.5	3.9	3.1

Table 7.4.2: Descriptive data of ranges of movement after (AF) 3 hour desk work

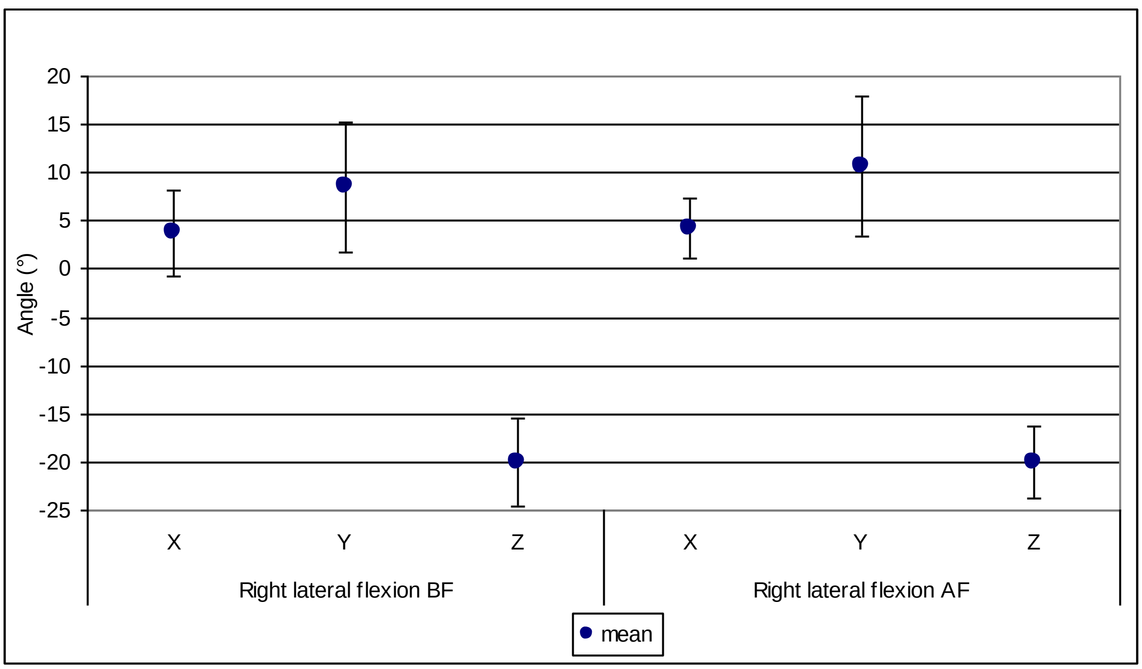
Graphs 7.4.1 to 7.4.6 show the distributions of means and standard deviations of every movement in all 3 axes before and after 3 hours of desk work activities. The X axis is the axis where axial rotation occurred; the Y axis is the axis records flexion/extension movement; and the Z axis denotes lateral flexion movement.



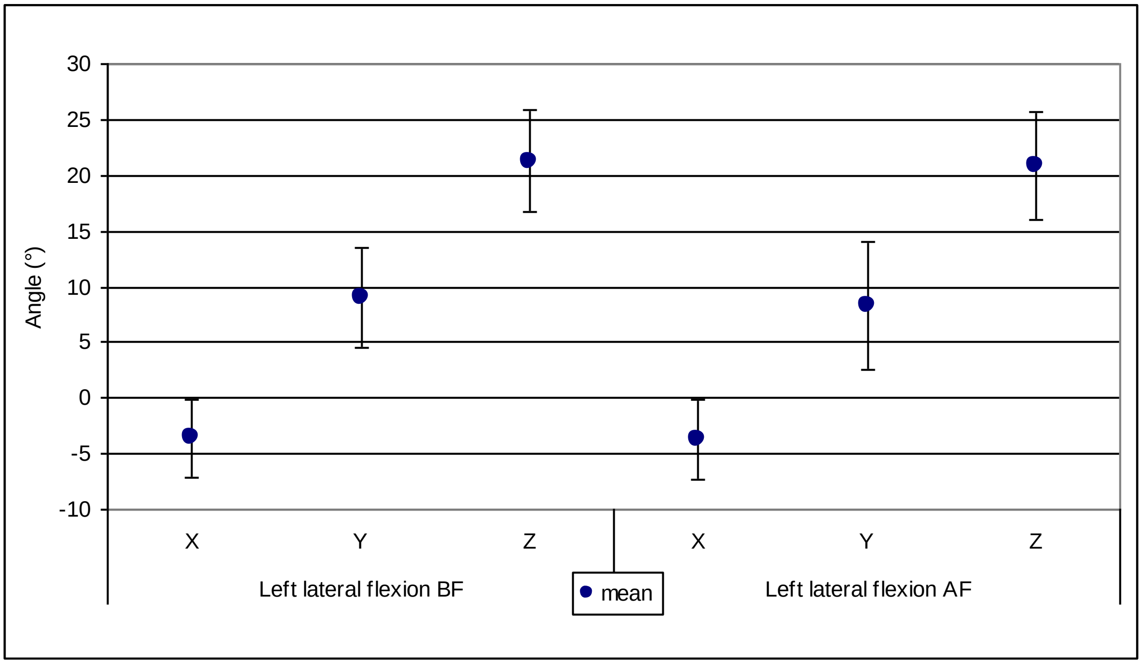
Graph 7.4.1: Distribution of means and standard deviations during flexion before (BF) and after (AF) 3 hours of desk work



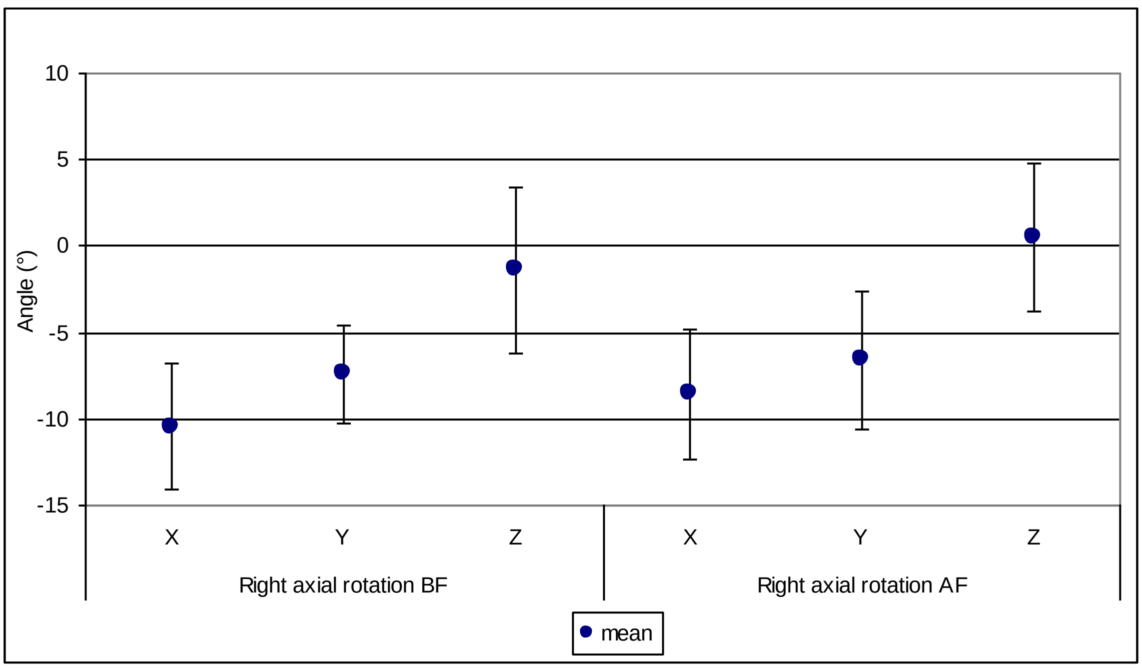
Graph 7.4.2: Distribution of means and standard deviations during extension before (BF) and after (AF) 3 hours of desk work



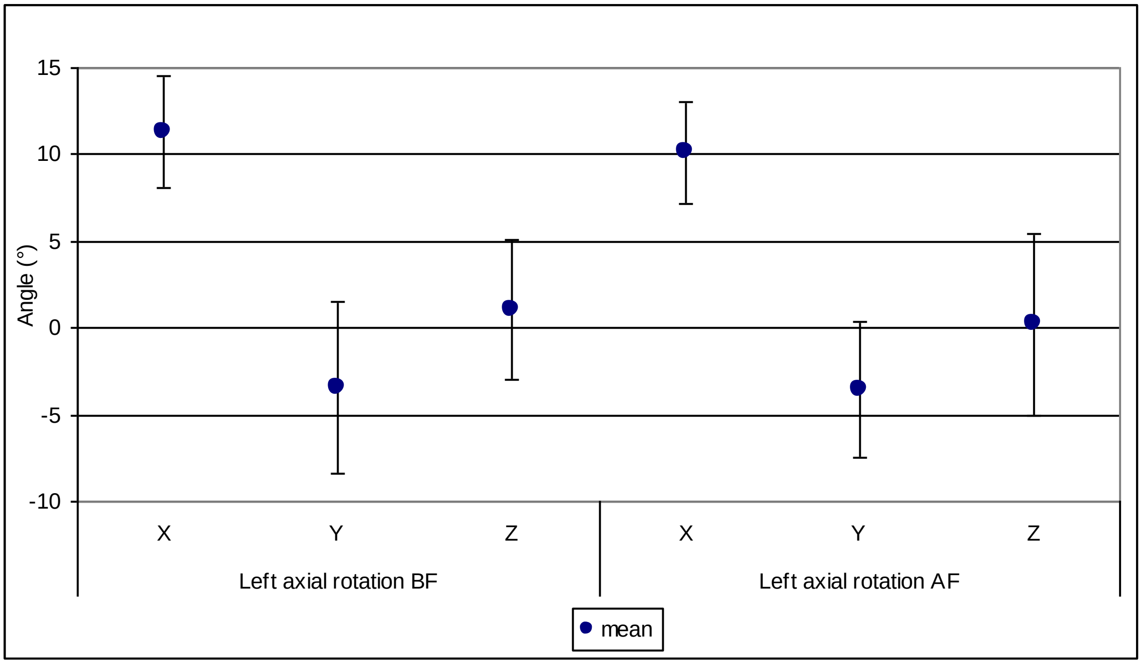
Graph 7.4.3: Distribution of means and standard deviations during right lateral flexion before (BF) and after (AF) 3 hours of desk work



Graph 7.4.4: Distribution of means and standard deviations during left lateral flexion before (BF) and after (AF) 3 hours of desk work



Graph 7.4.5: Distribution of means and standard deviations during right axial rotation before (BF) and after (AF) 3 hours of desk work



Graph 7.4.6: Distribution of means and standard deviations during left axial rotation before (BF) and after (AF) 3 hours of desk work

Although the changes in the range of physiological movements before and after 3 hours of desk work activities were not large (mean difference between 1° to 4°) or perhaps clinically significant, it was important to gain a further understanding of these differences, which could indicate changes in the biomechanical properties of the lumbar spine structures. To further analyse the changes in ranges of movement, Table 7.4.3 below shows the number of participants that showed signs of increased, decreased or no change in the range in each movement before and after 3 hours of desk work. By using the ranges of axial rotation movements as the threshold baseline as these ranges were the smallest (9° to 11°) among all 6 physiological movements, a change of 2° indicated a minimum change of 10% (1° yielded a maximum change of 9%). Therefore, any angle difference between the 2 sets of data that was equal to or greater than 2° was classified as decreased range; any angle difference that was equal to or greater than -2° was identified as an increased range (using the range before 3 hours of desk work as the reference); and any values in between the above conditions was considered as no change in range.

No. of participants	Decreased	Increased	No change
Flexion	6	5	7
Extension	12	0	6
Right lateral flexion	1	3	14
Left lateral flexion	4	3	11
Right axial rotation	9	0	9
Left axial rotation	5	1	12

Table 7.4.3: Summary of number of participants who showed sign in increased, decreased, or no change in range of movement before and after 3 hour desk work

From Table 7.4.3, it can be seen that the majority of participants showed signs of decreased range of movement during extension and axial rotation. There were an almost equal number of participants who showed sign of decreased and increased flexion and left lateral flexion. In lateral flexion, the majority of participants showed no significant change in movement range before and after 3 hours of desk work.

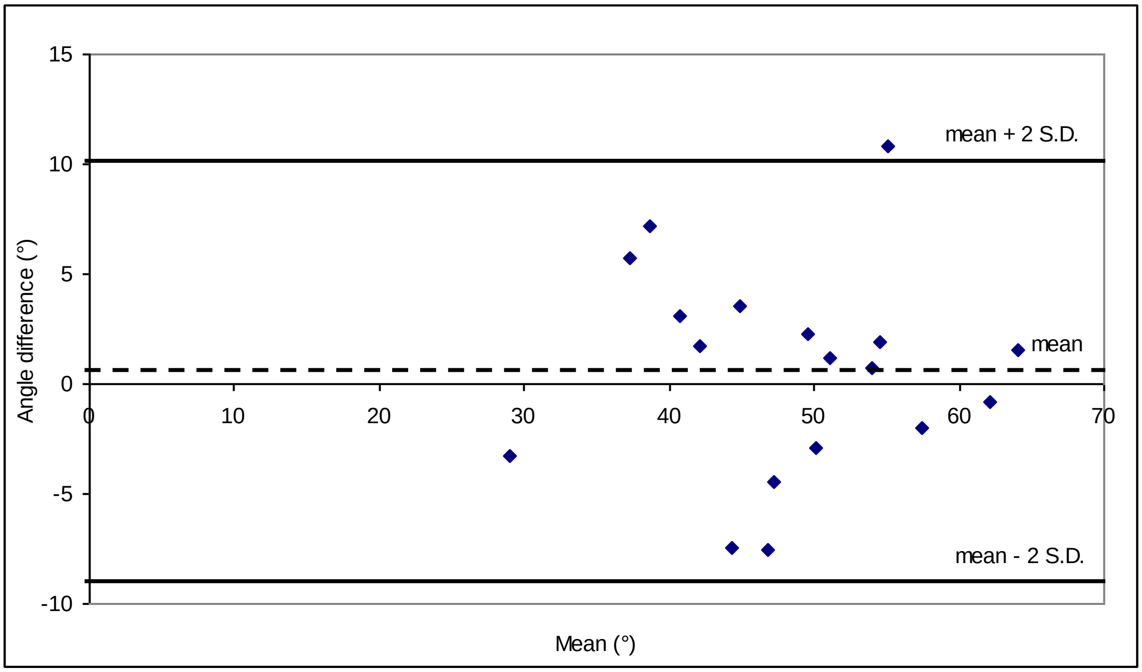
Table 7.4.4 shows the percentage difference in angle between ranges of movement before and after 3 hours of desk work. The table is separated into 3 parts; descriptive analysis was performed separately on data that showed increased, decreased and no change in angle range. For extension and axial rotation, the mean percentages of difference were greater than 20%; whereas the mean angle difference for flexion and lateral flexion were within 17%.

Angle difference (%)

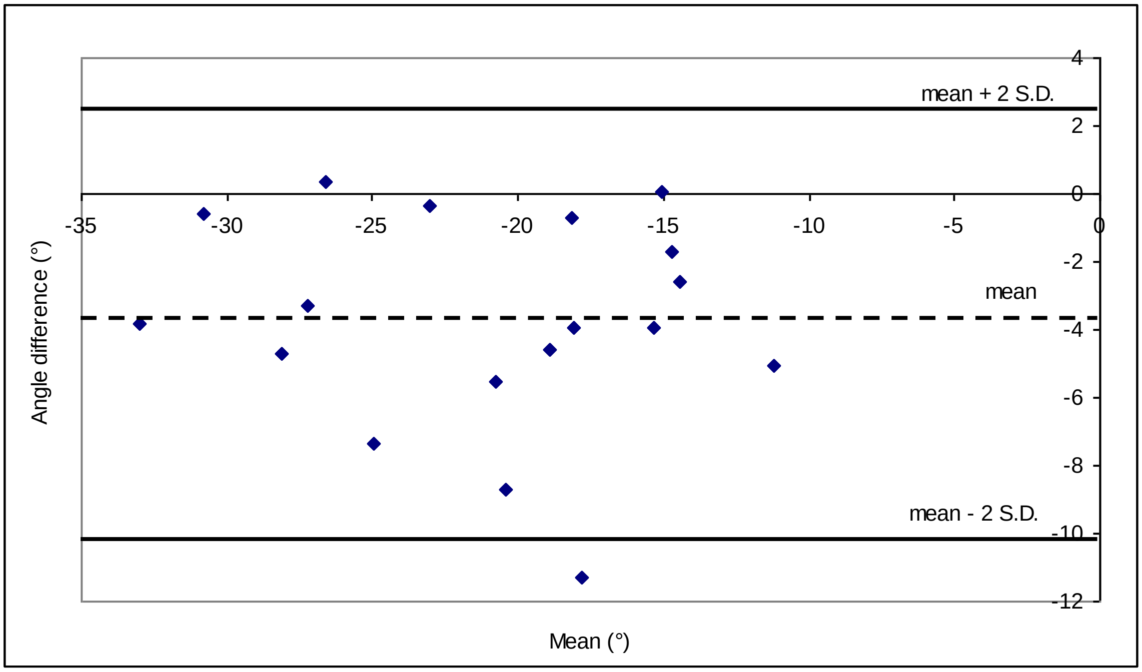
Decreased	Flexion	Extension	Right lateral flexion	Left lateral flexion	Right axial rotation	Left axial rotation
Minimum	4.52	11.12	9.12	7.60	21.77	20.90
Maximum	17.86	48.26	9.12	22.24	47.18	36.10
Mean	11.44	24.00	9.12	14.85	33.02	26.67
Standard Deviation	5.63	11.11	-	5.98	8.87	6.67
Increased	**Flexion**	**Extension**	**Right lateral flexion**	**Left lateral flexion**	**Right axial rotation**	**Left axial rotation**
Minimum	5.96	-	13.91	9.46	-	24.47
Maximum	18.26	-	18.17	14.04	-	24.47
Mean	12.71	-	16.56	12.28	-	24.47
Standard Deviation	5.23	-	2.31	2.47	-	-
No change	**Flexion**	**Extension**	**Right lateral flexion**	**Left lateral flexion**	**Right axial rotation**	**Left axial rotation**
Minimum	1.37	0.27	0.88	0.01	2.58	0.79
Maximum	4.00	11.02	12.51	9.03	18.36	19.21
Mean	2.64	3.32	5.16	3.36	6.51	8.00
Standard Deviation	1.05	3.96	3.50	2.69	5.13	5.29

Table 7.4.4: Descriptive data of angle difference (%) in ranges of movement between before and after 3 hour desk work, separated into decreased range, increased range and no change in range groups

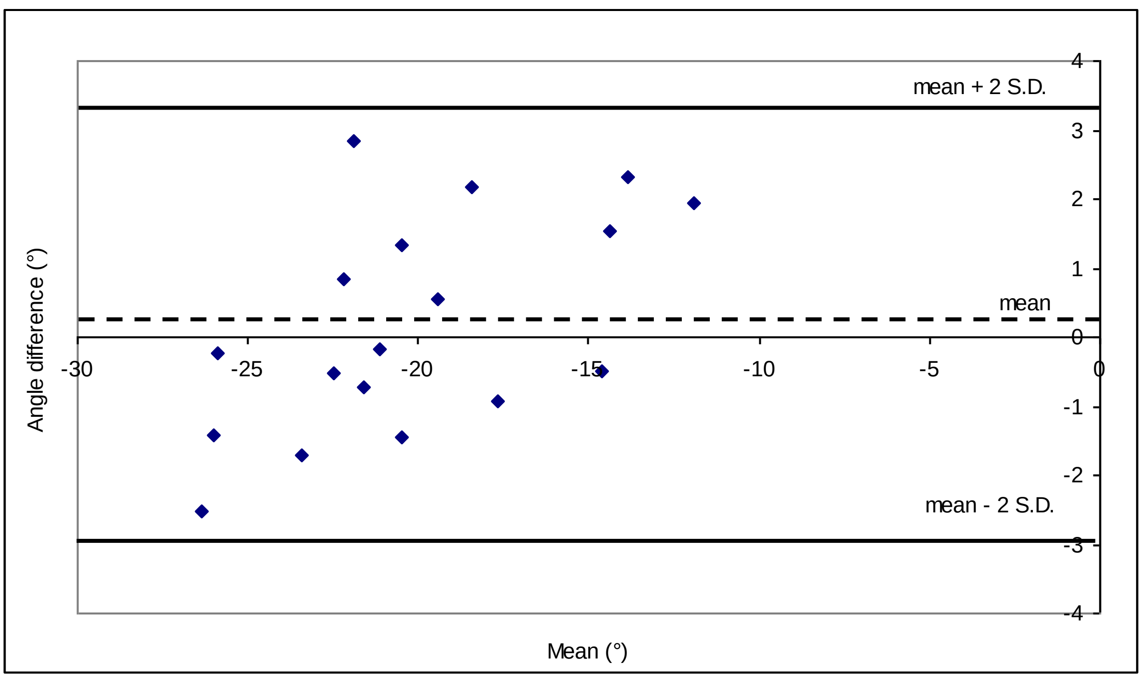
The distributions of angle difference between ranges of movement before and after 3 hours of desk work activities for all 18 participants were plotted to analyse the spread of the differences, as shown in Graphs 7.4.7 to 7.4.12. The x-axis of these graphs shows the mean values of the ranges of movement before and after 3 hours of desk work, and the y-axis shows the angle difference between the 2 sets of data. From these graphs, it can be observed that the mean differences for flexion and lateral flexion were between 0.03° to 0.63°, which indicates that the differences between before and after 3 hours of desk work were small. However for extension (mean difference -3.8°) and axial rotations (mean different 1.1° and -1.8° for left and right respectively), the mean differences were much higher, especially in extension.



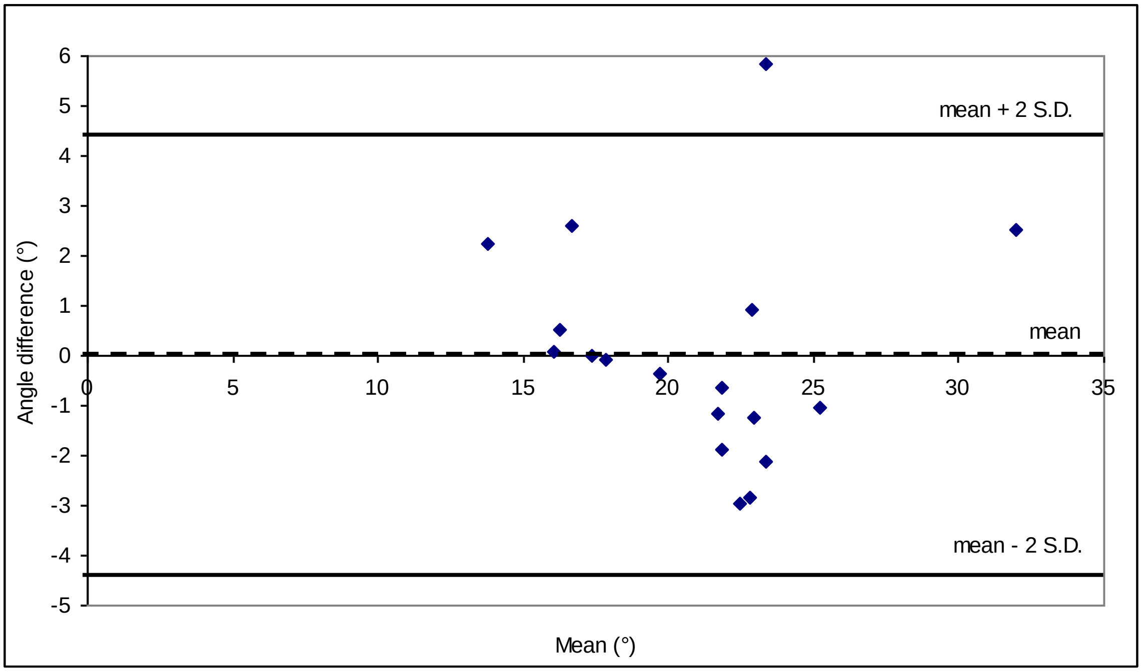
Graph 7.4.7: Distribution of angle differences for all 18 participants in flexion before and after 3 hour desk work, mean difference was 0.63° and standard deviation was 4.78°



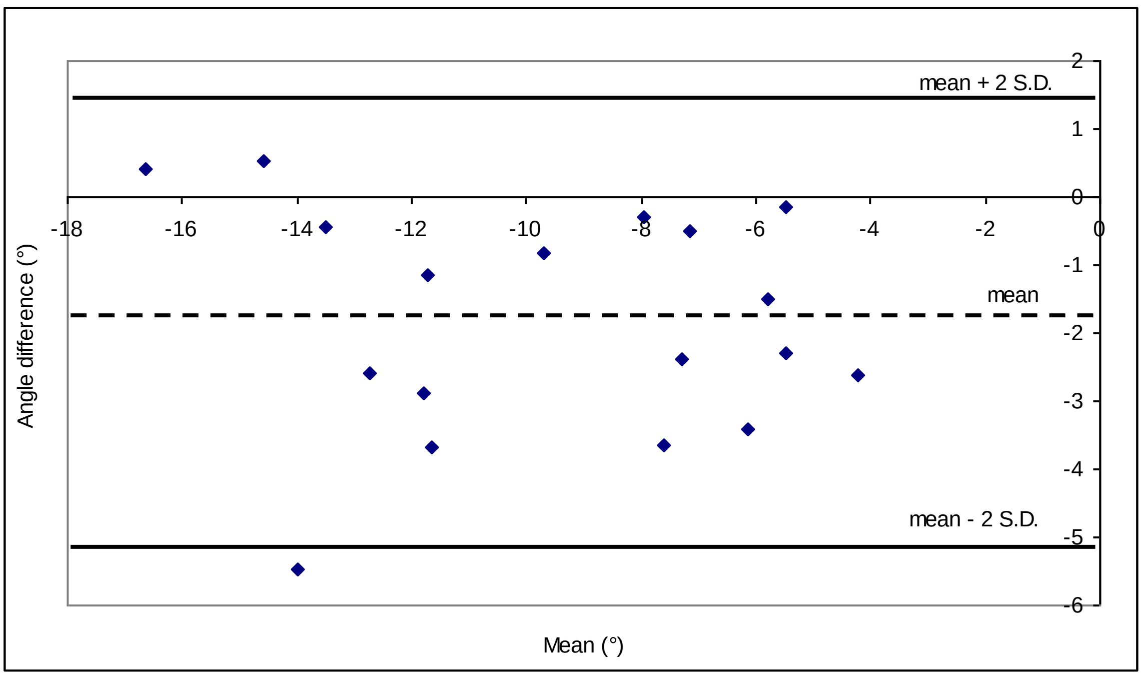
Graph 7.4.8: Distribution of angle differences for all 18 participants in extension before and after 3 hour desk work, mean difference was -3.77° and standard deviation was 3.15°



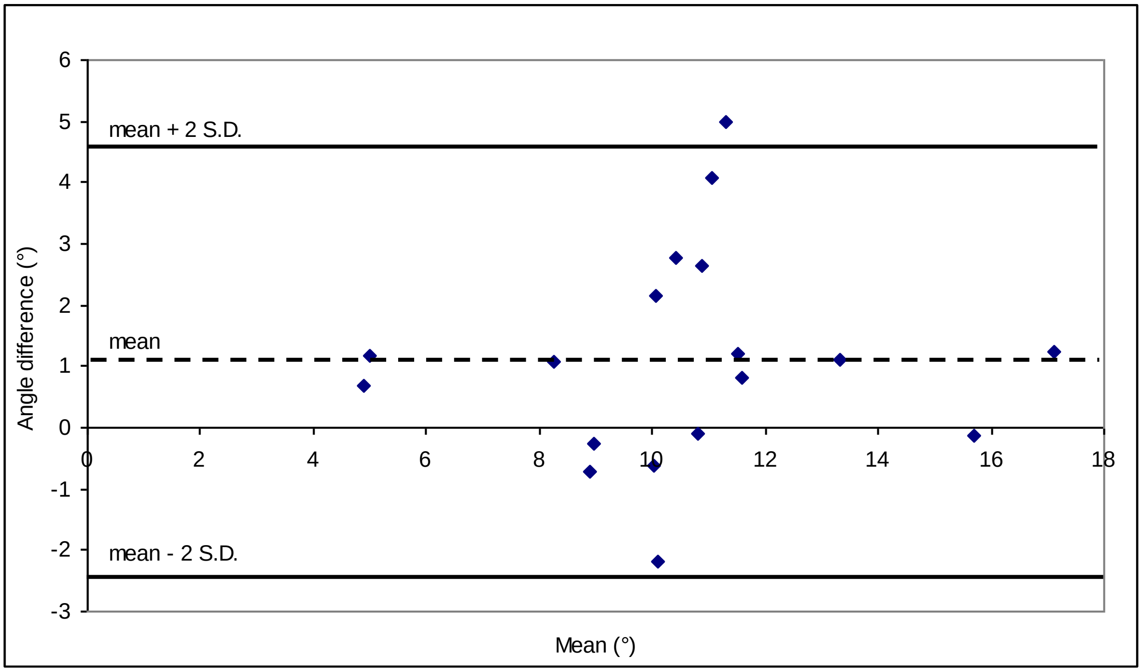
Graph 7.4.9: Distribution of angle differences for all 18 participants in right lateral flexion before and after 3 hour desk work, mean difference was 0.19° and standard deviation was 1.57°



Graph 7.4.10: Distribution of angle differences for all 18 participants in left lateral flexion before and after 3 hour desk work, mean difference was 0.03° and standard deviation was 2.21°



Graph 7.4.11: Distribution of angle differences for all 18 participants in right axial rotation before and after 3 hour desk work, mean difference was -1.83° and standard deviation was 1.65°



Graph 7.4.12: Distribution of angle differences for all 18 participants in left axial rotation before and after 3 hour desk work, mean difference was 1.10° and standard deviation was 1.76°

From the data and the angle difference distribution plots above, the majority of the participants showed a decrease in the ranges of extension and axial rotation movements after 3 hours of desk work activities, the possible relationship between these changes and the activities during the 3 hour desk work period is examined in Section 7.4.4 and the possible causes of reduced ranges of movement are discussed in Section 7.5.1.

It has been shown that there were changes in ranges of movement in the majority of participants however it was necessary to examine if these differences were significant. Therefore, a paired t-test analysis was performed to analyse the level of differences between ranges of movement before and after the 3 hour desk work period. The paired t-test analysis of the 6 physiological movements is shown in Table 7.4.5, flexion ($p = 0.581$) and lateral flexion ($p = 0.622$ and 0.961) did not show any significant differences before and after 3 hours of desk work. However, the differences before 3 hours of desk work activities and after was significant for extension ($p < 0.001$) and right and left axial rotation movements ($p < 0.001$ and 0.016 respectively). This analysis showed good agreement with earlier observations. The validity of the data of the current study and the implications of these significant changes in ranges of movement are further discussed in Section 7.5.1.

	Paired Differences					t	df	Sig. (p)
	Mean	Standard Deviation	Standard Error Mean	95% Confidence Interval of the Difference				
				Upper	Lower			
Flexion	0.635	4.781	1.127	-1.743	3.012	0.563	17	0.581
Extension	-3.772	3.155	0.744	-5.341	-2.203	-5.073	17	<0.001*
Right lateral flexion	0.186	1.567	0.369	-0.594	0.965	0.503	17	0.622
Left lateral flexion	0.026	2.206	0.520	-1.071	1.123	0.050	17	0.961
Right axial rotation	-1.828	1.653	0.390	-2.651	-1.006	-4.692	17	<0.001*
Left axial rotation	1.104	1.759	0.415	0.229	1.978	2.662	17	0.016*

Table 7.4.5: Paired T-test analysis of the 6 physiological movements before and after 3 hours of desk work, * indicates statistical significance

7.4.2 Lumbar curvature angle during standing

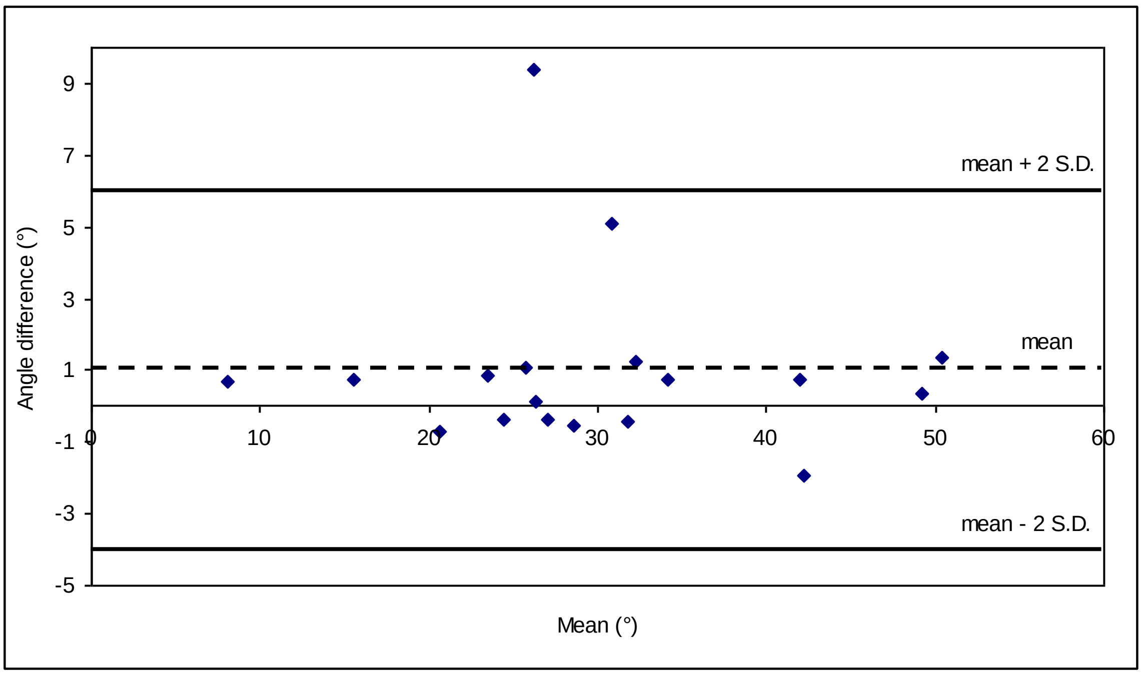
The mean lumbar curvature angle during standing before desk work activities was measured to be 30.4° and after desk work activities was 29.4°. Data from the descriptive analysis is shown in Table 7.4.6. The raw lumbar curvature angles for each participant are shown in Appendix Table A3.7.

	Lumbar curvature (°) before (BF)	Lumbar curvature (°) after (AF)
Minimum	8.4	7.8
Maximum	51.0	49.7
Mean	30.4	29.4
Standard Deviation	10.9	11.0

Table 7.4.6: Descriptive data on lumbar curvature angle during standing before and after 3 hours of desk work

The distribution of standing lumbar curvature angle differences for all 18 participants before and after 3 hours of desk work was plotted as seen in Graph

7.4.13. Most of the angle differences were within ± 2°. Only 2 participants showed a change greater than 2° in lumbar curvature angle (decreased 5° and 9° respectively) after 3 hours of desk work. This showed that 3 hours of desk work activities generally did not change the pattern of upright standing of the participants, the results of the 2 participants who showed a greater decrease in lumbar curvature angle after 3 hours of desk work might be due to muscle fatigue (O'Sullivan et al. 2006a; Veiersted et al. 1990) during this period, this is further discussed in Section 7.5.2.



Graph 7.4.13: Distribution of lumbar curvature angle differences during standing for all 18 participants before and after 3 hour desk work

In order to identify any statistically differences in the lumbar curvature angles before and after 3 hours of desk work activities, a paired t-test was performed and the results showed no significant difference ($p = 0.111$) between standing lumbar curvature angles before and after 3 hours of desk work activities, detailed results are tabulated in Table 7.4.7.

	Paired Differences					t	df	Sig. (p)
	Mean	Standard Deviation	Standard Error Mean	95% Confidence Interval of the Difference				
				Upper	Lower			
Lumbar curvature	0.999	2.523	0.595	-0.255	2.254	1.681	17	0.111

Table 7.4.7: Paired t-test analysis of lumbar curvature angle during standing before and after 3 hours of desk work

7.4.3 Desk work activities

The participants in the study did not use a standardised desk and chair configuration, they returned to their own workplace and data were collected at their own personalised desk and chair set up. Although these parameters were not controlled as in most laboratory experimental set ups, all participants were from the same university and therefore the furniture was mostly standardised though individual adjustment was not. Ergonomic assessments (a copy of guidelines is shown in Appendix A1.7) are undertaken within the university as a routine. A typical work desk and chair used by most participants is shown in Figure 7.4.1 below.

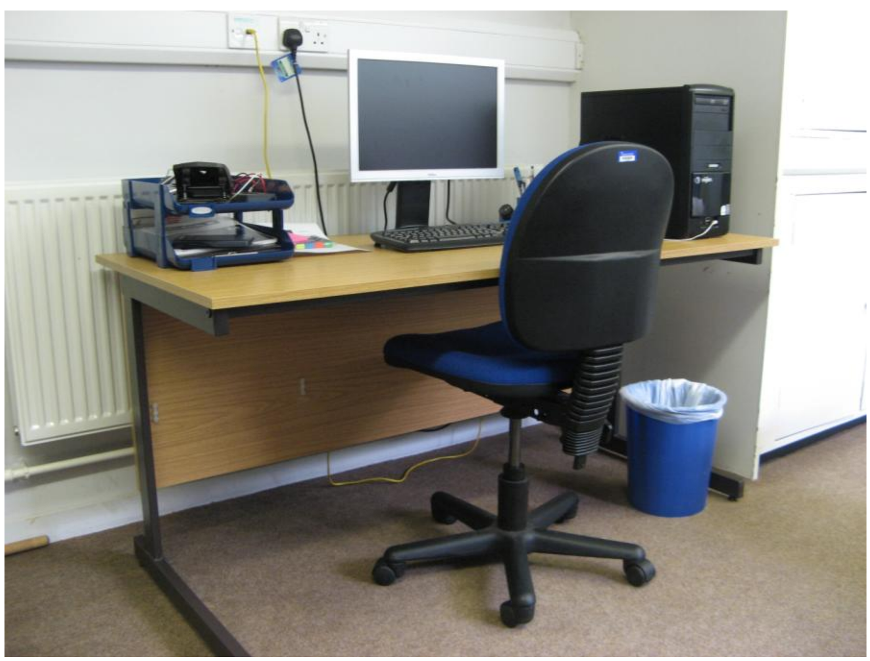


Figure 7.4.1: Typical work desk and chair set up used by most participants in the 3 hour work desk activities study

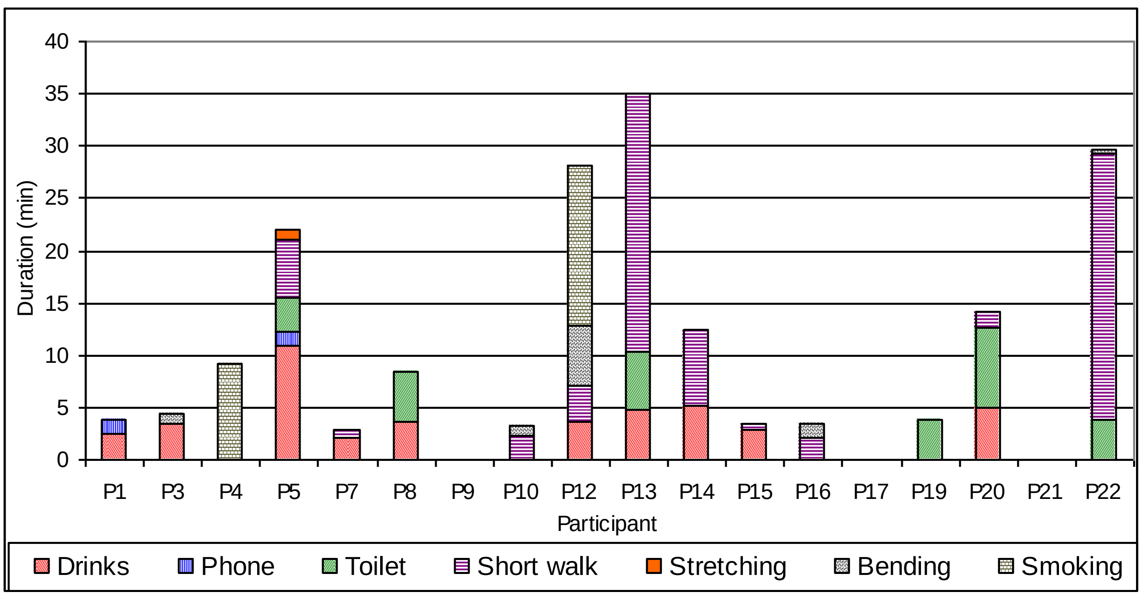
There were only 3 participants who used a different type of work desk as shown in Figure 7.4.2.

Figure 7.4.2: Typical work desk used by 3 participants in the 3 hour work desk activities study

As observed by the researcher, the activities of participants during sitting included computer use, reading, writing, filing, talking to co-workers, using the telephone, and having drinks and light snacks.

Activities duration summary

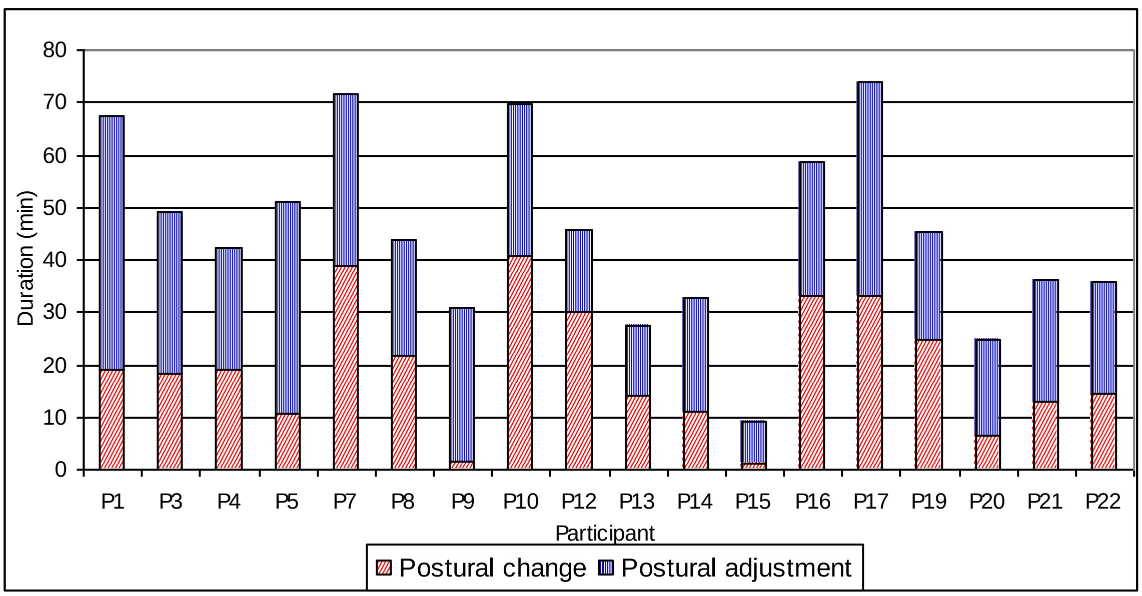
During the 3 hours of desk work, the 3 main activities were static sitting, movement during sitting and dynamic activities. The 7 types of dynamic activities adopted by the participants in this study were making drinks, answering phone calls (not at the participant's desk), taking toilet breaks, having a short walk (to and from the printer or just leisure walking), standing to do some stretching, bending and taking smoking breaks. By studying the data from the sensors (using Figure 7.3.4) and matched with the observation noted by the researcher, Graph 7.4.14 below summarises the time spent on each of these dynamic activities for the 18 participants during the 3 hours of desk work, and provides picture on the activities engaged by the 18 participants. The duration of each dynamic movement included the time from leaving participant's desk, walking to the destination, carrying out the activities (e.g. making drinks) and returning to their seat. The duration of each dynamic activity was a cumulative duration, i.e. it might or might not be accumulated from 1 incident only. The amount of duration spent in dynamic activities varied from participant to participant. The majority of participants spent less than 15 minutes (< 8.3% of 3 hours) on dynamic activities. Three participants did not leave their seats for the whole 3 hour period. There were only 4 participants who spent more than 20 minutes in dynamic activities. The most common dynamic activities during desk work were having a short walk (73.54 minutes total time spent by 10 participants), making drinks (43.99 minutes total time spent by 10 participants) and taking a toilet break (28.90 minutes total time spent by 6 participants).



Graph 7.4.14: Time spent (in minutes) in each activity for all 18 participants during 3 hours of desk work

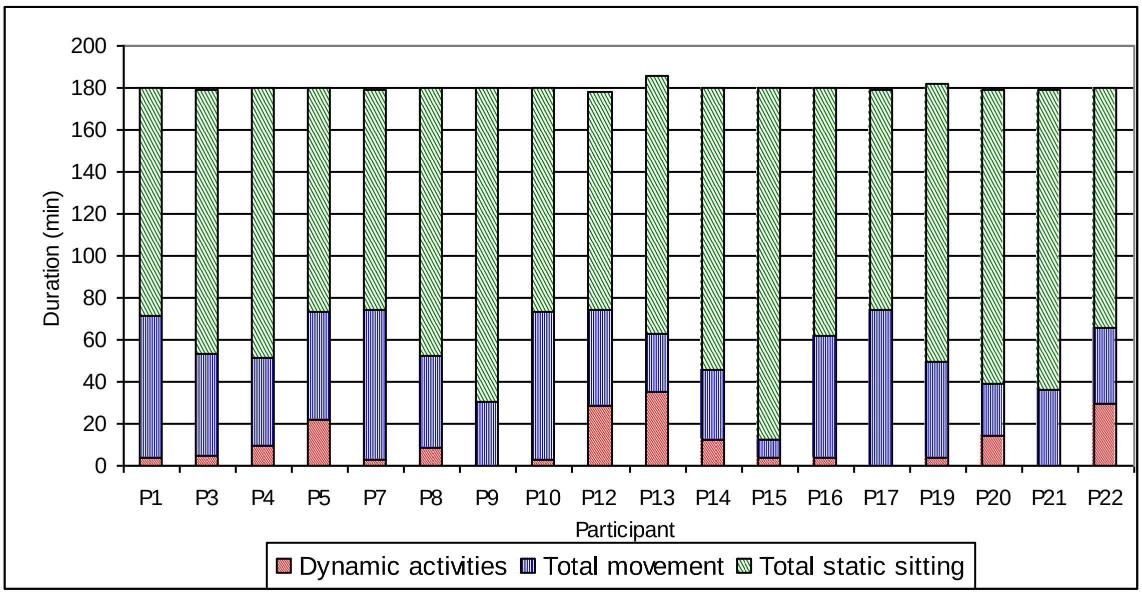
Graph 7.4.15 summarises the total time spent on sitting movements (postural change and postural adjustment) for all participants during the 3 hour desk work period. The amount of time spent on sitting movement also varied between participants. Most of the participants moved on their seat for a total of or less than 50 minutes of the 3 hours (27.8%), with a mean duration of 45.31 minutes across

18 participants. The participants who spent the most time on sitting movements (P1, P7, P10, P16 and P17) spent less than 5 minutes on dynamic activities, which was more than 5 minutes less than the average duration (mean duration for dynamic activities across all 18 participants was 10.24 minutes). However this does not indicate that participants who spent less time on dynamic activities would necessarily spend more time on sitting movements, because the trend was not apparent in other participants. One example was participant 15, who spent only 3.38 minutes on dynamic activities and 9.05 minutes on sitting movements. This participant spent 93.1% of the 3 hours in static sitting. Sixty one percent of participants spent more time on postural adjustment than changing posture; whilst 28% of them spent more time on changing posture; and only 2 participants spent equal amounts of time on postural change and postural adjustment.



Graph 7.4.15: Time spent (in minutes) in postural change and comfort adjustment of all 18 participants during 3 hour desk work

The total duration breakdown for the 3 main desk work activities is shown in Graph 7.4.16. On average, 69.1% of the time was spent on static sitting; 25.2% spent on sitting movements; and 5.7% spent on dynamic activities. Participant 7 spent the least time on static sitting (57.9% of total duration) while Participant 15 spent the longest time on static sitting with this participant spending only 6.9% of the 3 hours on dynamic activities and sitting movement.

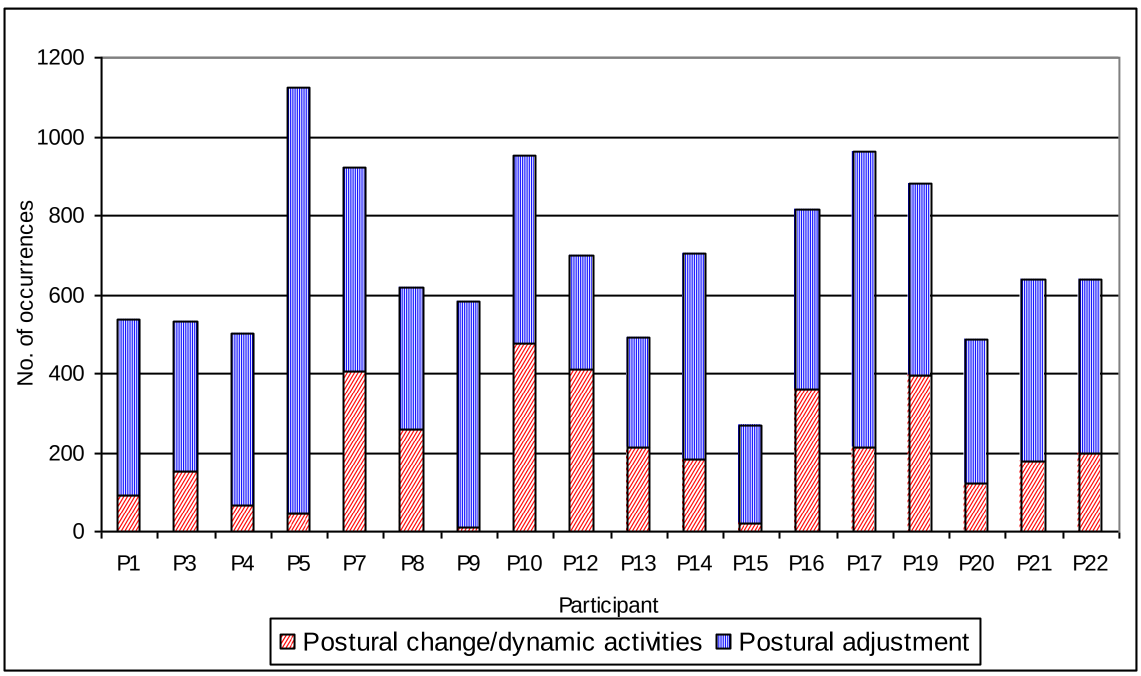


Graph 7.4.16: Total break down of the duration of activities during 3 hour desk work

Tabulated results for Graphs 7.4.14 to 7.4.16 can be found in Appendix Tables A3.8 and A3.9.

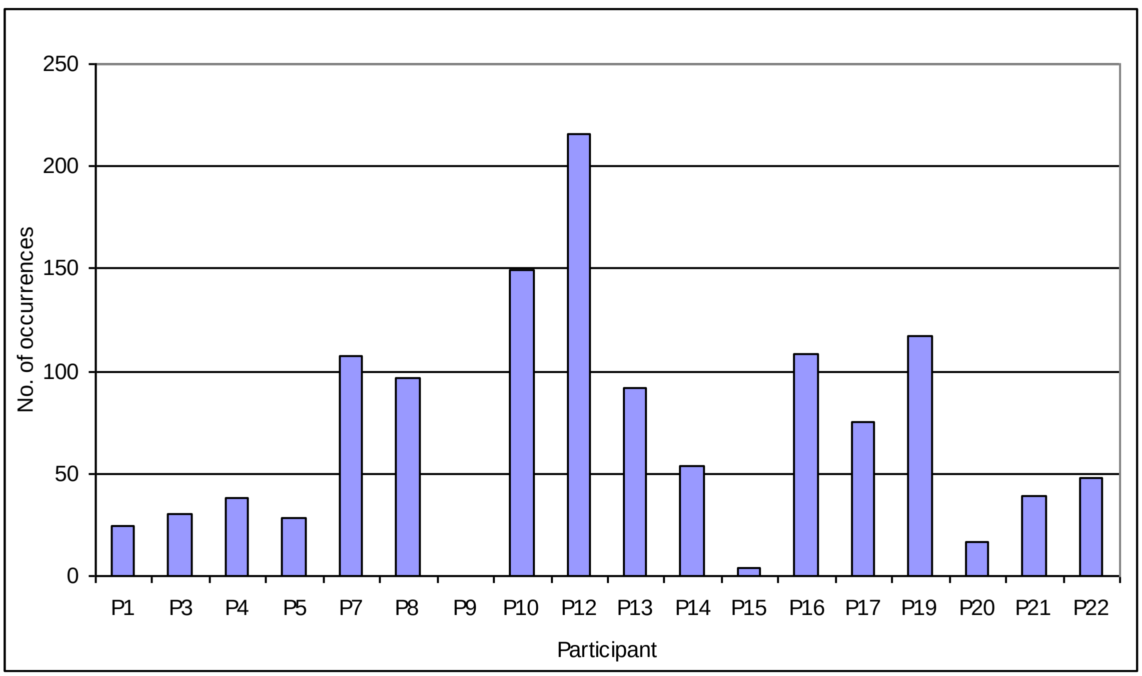
Movement

Graph 7.4.17 below summarises the count of occurrences of postural change/dynamic activities and postural adjustment for all 18 participants during the 3 hours of desk work. Eighty nine percent of participants showed higher counts of postural adjustment than postural change/dynamic activities, the amount of occurrences ranged from 247 to 1078. Participant 10 showed the same amount of occurrences during both movements; while Participant 12 was the only participant who changed posture or performed dynamic activities 122 times more than engaging in postural adjustment movements.



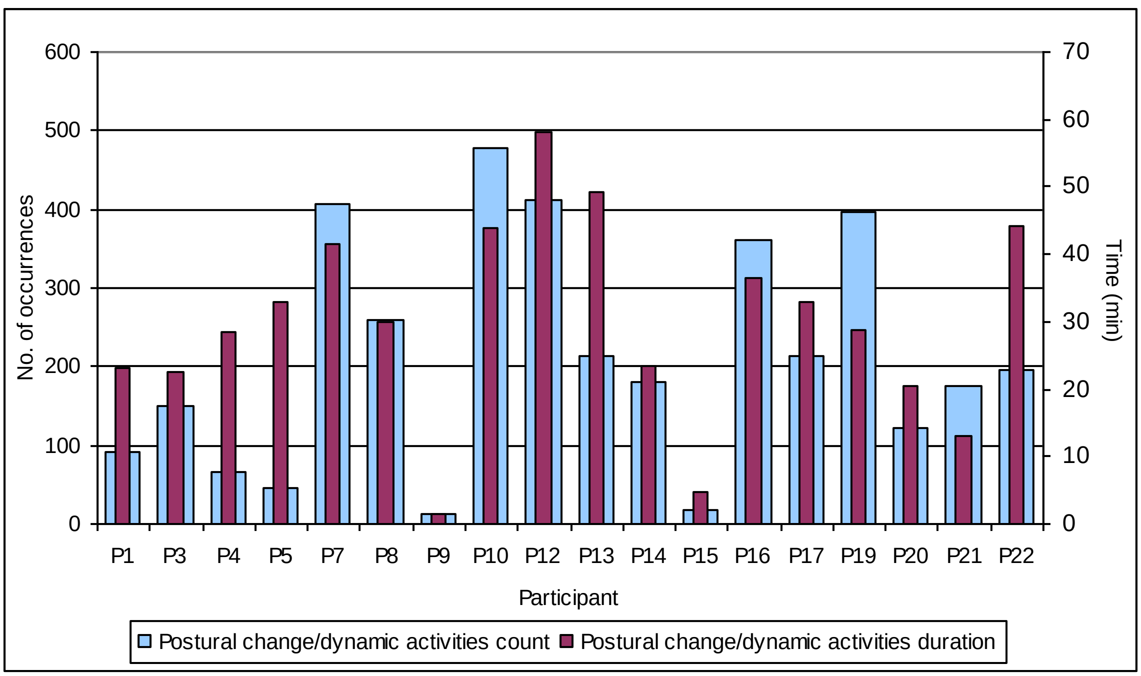
Graph 7.4.17: Summary of the count of postural change/dynamic activities and postural adjustment of the lumbar spine during 3 hours of desk work

When the amount of occurrences of postural change/dynamic activities was further broken down to gross movement, as shown in Graph 7.4.18, it was found that Participant 12 showed the highest occurrence, at 216 counts. Participant 9 did not engage in any gross movements; while Participant 15 only engaged in gross movements 4 times over the course of 3 hours. It was also notable that during the 3 hour desk work period, Participant 9 did not engage in any dynamic activity and had limited occurrences of postural change (12 counts), and consequently it was not surprising that Participant 9 did not engage in any gross movements. Similarly, Participant 15 only engaged in 19 occurrences of postural change/dynamic activities and had a correspondingly low number the occurrences of gross movement (4 counts) when compared to the mean number of occurrences (69 times) across all participants.



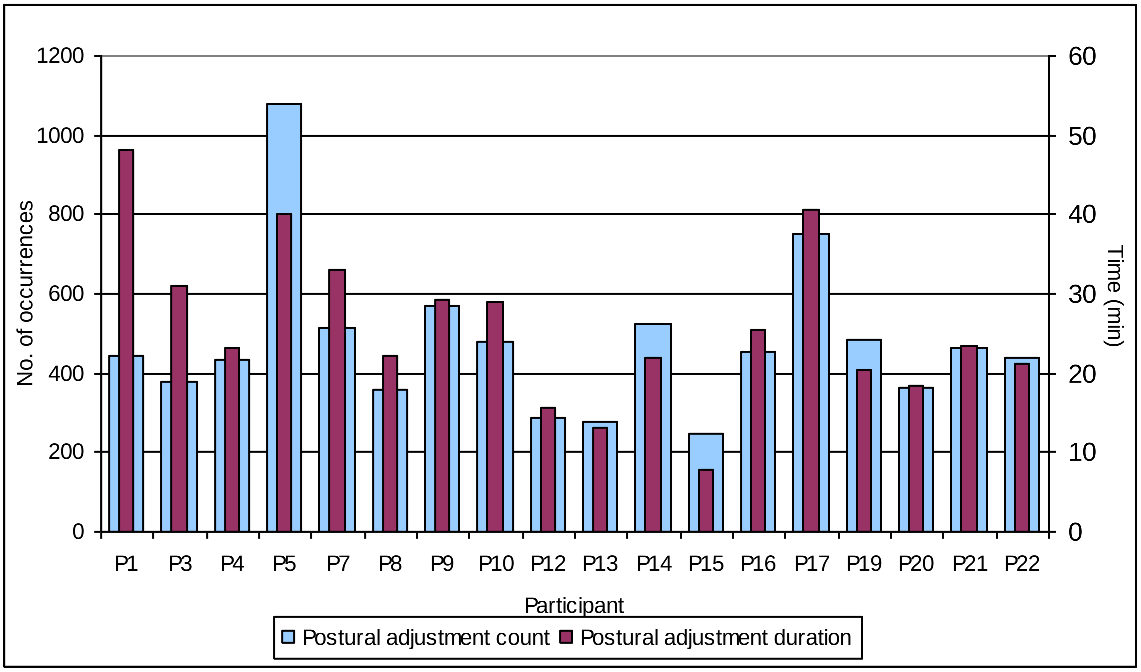
Graph 7.4.18: Number of occurrences of gross movement of the lumbar spine during 3 hours of desk work activities

When comparing the number of occurrences and duration spent in both groups of movement, it could be observed that a long period spent in postural change/dynamic activities did not necessarily show a high occurrence of such movement, as seen in Graph 7.4.19. This observation was not surprising as participants could have spent a longer time on just 1 occasion of dynamic activity (i.e. taking a smoking break), or participants could also have spent a short time walking to and from their printer on a nearby table to collect prints on many occasions. Therefore there was no apparent association between the number of occurrences of postural change/dynamic activities with the time spent on those movements. Participant 13 spent 49.26 minutes in postural change/dynamic activities, however these movements only occurred 214 times; whereas Participant 19 showed 397 counts of such movements that lasted for only 28.78 minutes.



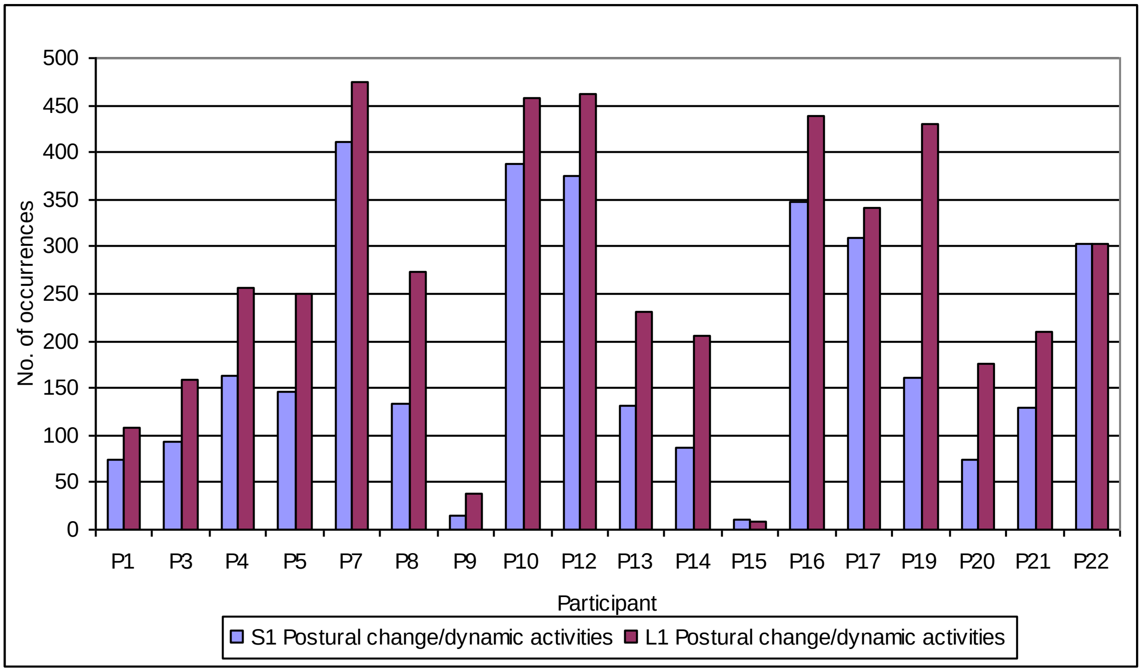
Graph 7.4.19: Duration spent vs. number of occurrences of postural change/dynamic activities of the lumbar spine during 3 hours of desk work

However for postural adjustment movements, a more apparent trend can be observed, as shown in Graph 7.4.20, where a long accumulated time spent on postural adjustment movements mostly indicated a high number of occurrences of such movements.

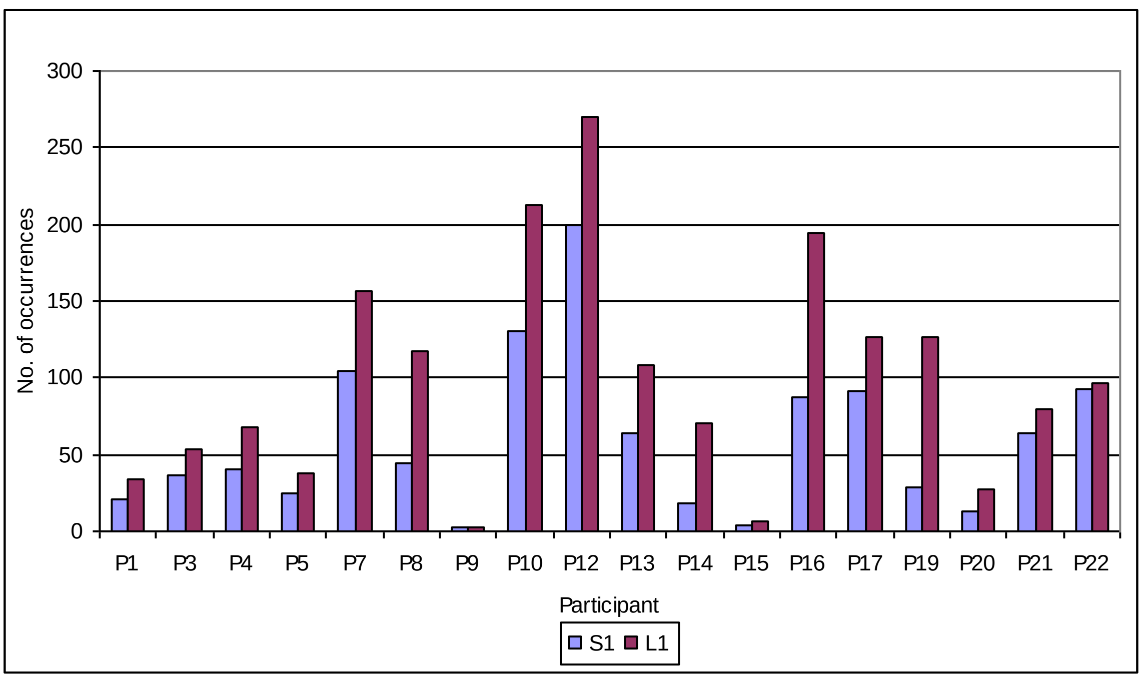


Graph 7.4.20: Duration spent vs. number of occurrences of postural adjustment of the lumbar spine during 3 hours of desk work

To further analyse the movement trends, Graphs 7.4.21 and 7.4.23 were plotted to show the number of occurrences of each movement group on L1 and S1 spinous processes in order to examine the movement trends of the upper lumbar spine and sacrum. For postural change/dynamic activities (Graph 7.4.21), L1 always showed a higher incidence of movement when compared to the sacrum as expected; except Participant 15, where the sacrum moved an extra 3 times more than L1. In gross movement, L1 always moved more when compared to the sacrum, including Participant 15 (as shown in Graph 7.4.22).

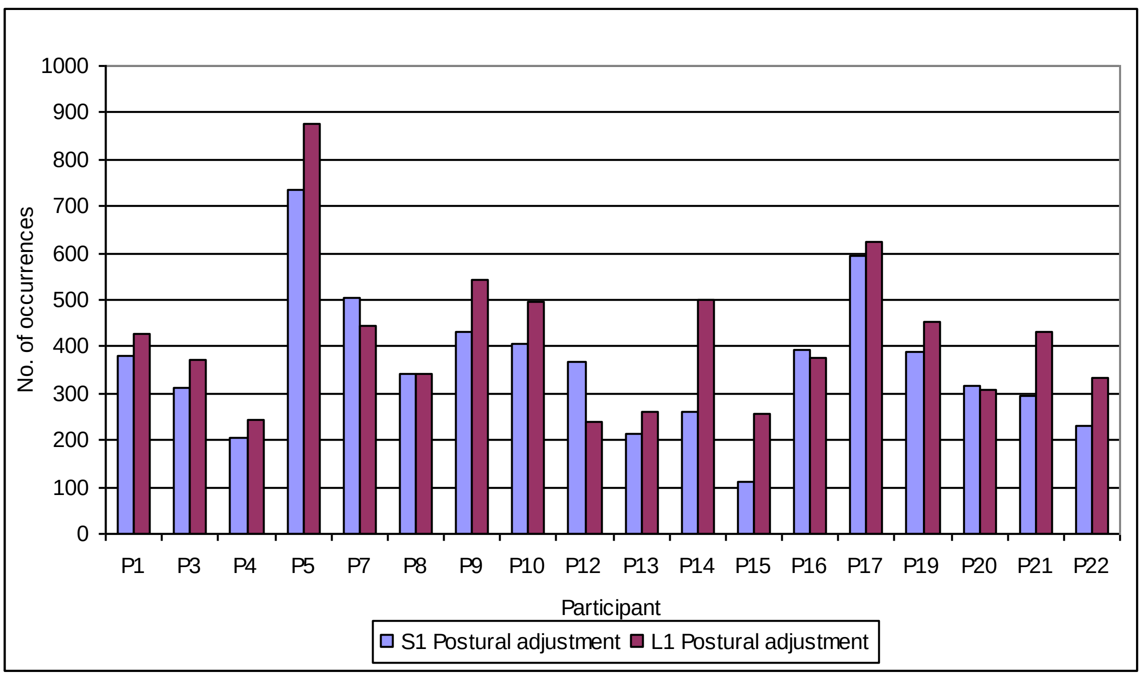


Graph 7.4.21: Comparison of number of occurrences between L1 and S1 spinous processes in postural change/dynamic activities



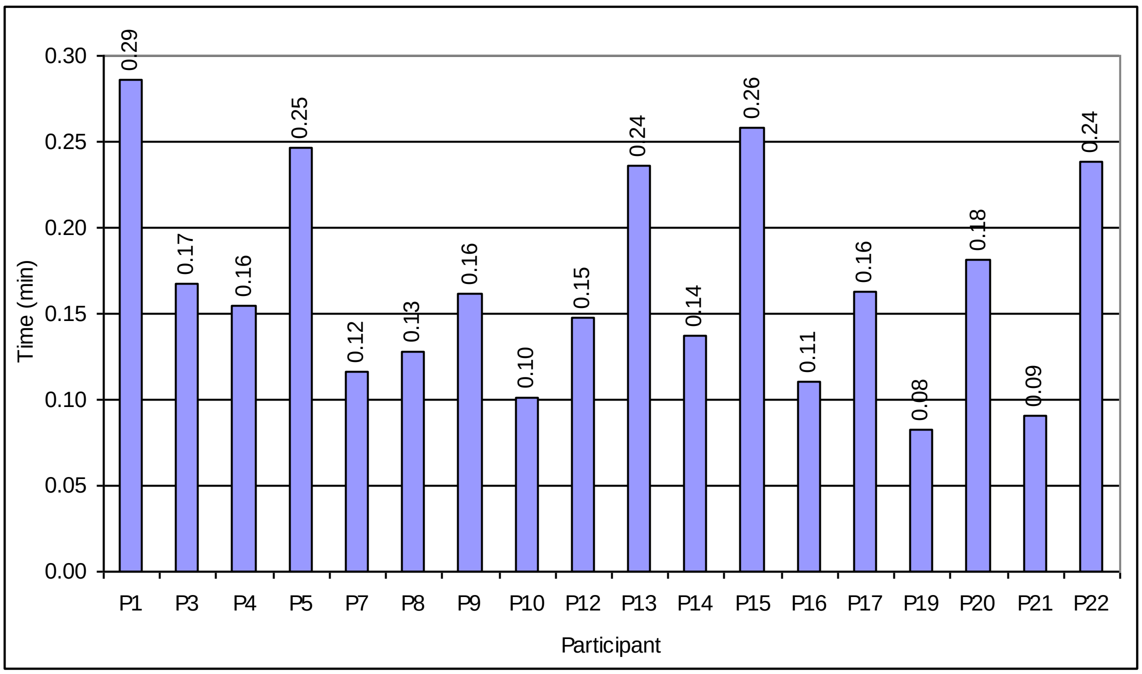
Graph 7.4.22: Comparison of number of occurrences between L1 and S1 spinous processes in gross movement

However, this wasn't the case for Participants 7, 12 and 16 in postural adjustment movement (see Graph 7.4.23). The incidence of postural adjustment was less at L1 than the sacrum in these 3 participants. This could be due to during this postural adjustment movement happened in S1, the movement in L1 at the same time was large enough (>2°) to be classified as postural change/dynamic activities rather than postural adjustment; and hence the count was contributed to postural change/dynamic activities, resulting in less occurrences of L1 movement in this postural adjustment movement. Graphs 7.4.21 to 7.4.23 have shown that on average the amount of movements in the upper body were always higher than the sacrum as of expected. During sitting, the sacrum was supported by the seat and was more stable compared to the upper body, though the upper body could also be supported by the back rest of the seat, however the upper body was more dynamic in sitting in order to be able to perform different tasks during desk working.



Graph 7.4.23: Comparison of number of occurrences between L1 and S1 spinous processes in postural adjustment

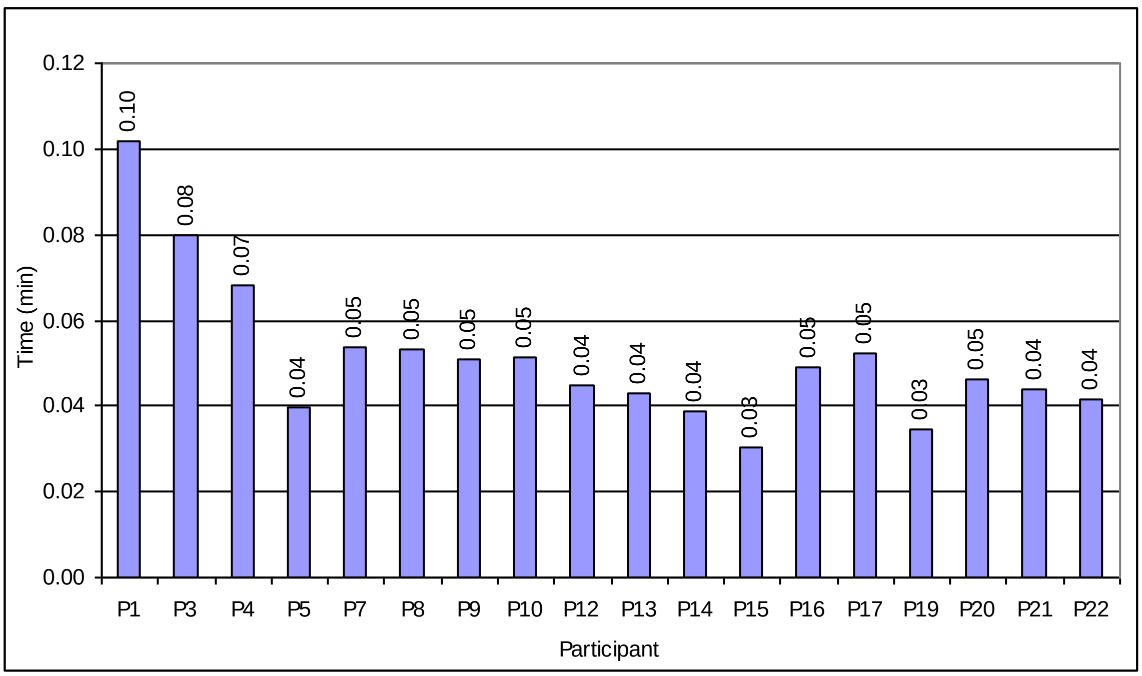
The mean durations spent in postural change/dynamic activities and postural adjustment for each individual participant are shown in Graphs 7.4.24 and 7.4.25 respectively. The mean duration of postural change/dynamic activities ranged from 0.08 to 0.29 minutes. The highest mean duration was seen in Participant 1 and lowest in Participant 19. This indicated that Participant 1 spent an average of 17.1 seconds in changing from 1 posture to another, or performing dynamic activity between 2 static sitting postures; while Participant 19 only took an average of 4.9 seconds in performing those movements.



Graph 7.4.24: Mean (of individual participant) duration of postural change/dynamic activities

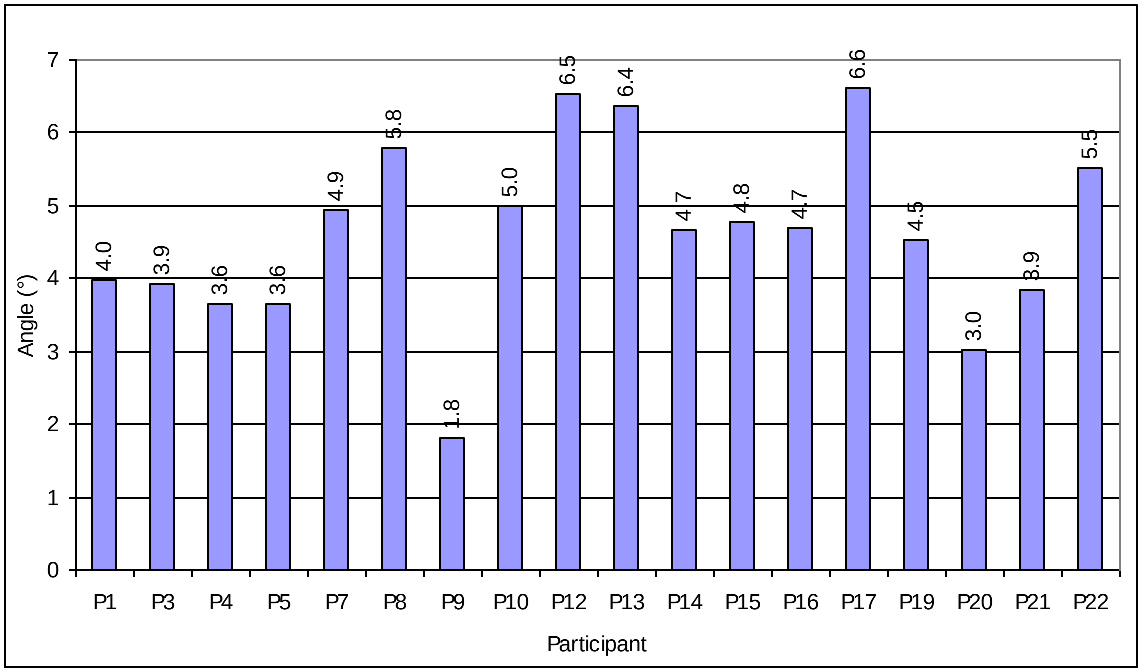
As for postural adjustment movement, the mean duration was much lower than the duration for postural change/dynamic activities, as shown in Graph 7.4.25. The mean duration of postural adjustment ranged from 0.03 to 0.10 minutes, which were again the records of Participant 19 and Participant 1 respectively, Participant 15 also showed a short mean duration in postural adjustment movements. The average time Participant 19 spent on postural adjustment movements was 2.1

seconds; while Participant 1 spent an average of 6.1 seconds on this activity. This showed that Participant 19 moved at a faster pace than Participant 1 in both types of movements, which might indicate that Participant 19 was more active than Participant 1, as this was also shown from the number of occurrences of these movements between these 2 participants (397 vs. 92 occurrences of postural change/dynamic activities and 486 vs. 443 occurrences of postural adjustment movements, for Participant 19 vs. Participant 1). However this parameter (mean duration spent on movement) should not be used to determine the active level of a participant as it also dependent on other parameters such as number of occurrences and total duration spent on such movement.



Graph 7.4.25: Mean (of individual participant) duration of postural adjustment movements

Graph 7.4.26 shows the mean angle change in lumbar curvature for postural change/dynamic activities of every participant. The most common mean angle changes were 5° (seen in 6 participants) and 4° (seen in 5 participants). The mean angle change for postural adjustment was not plotted as the results were all within 0° or 1°, as any angle of less than 1° was considered not significant relevant in this study. This parameter showed the mean amount of movements between 2 static sitting postures during postural change/dynamic activity. This parameter is further studied in Section 7.4.4.



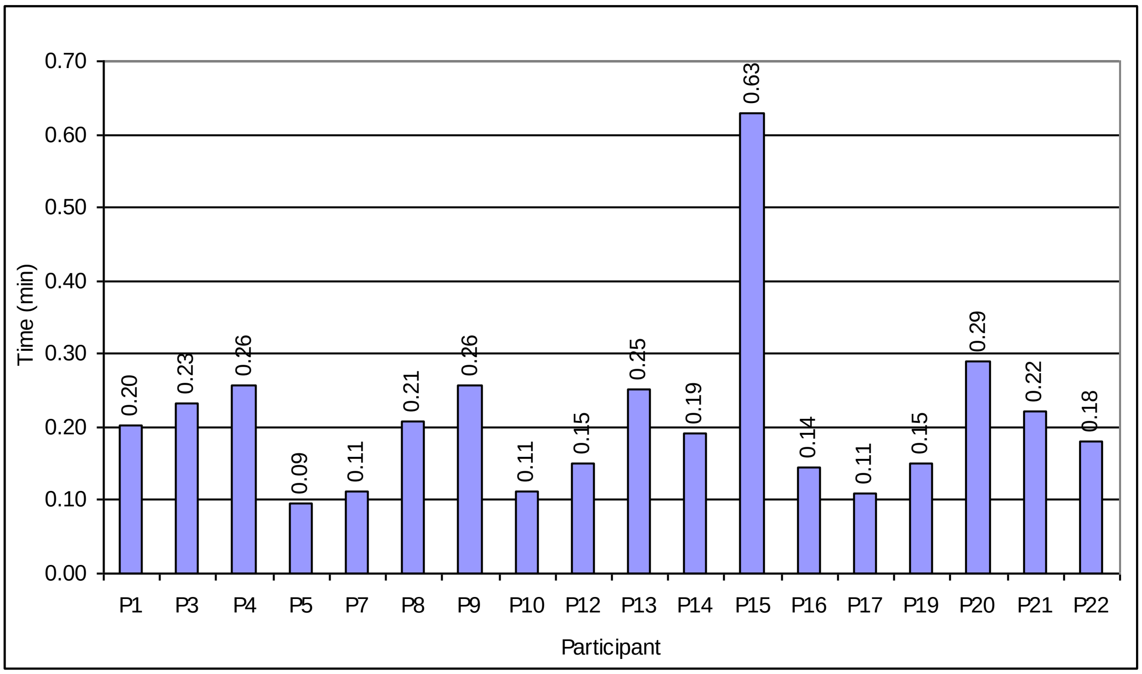
Graph 7.4.26: Mean (of individual participant) angle change in lumbar curvature for postural change/dynamic activities

The tabulated data of Graphs 7.4.17 to 7.4.26 are shown in Appendix Tables 3.10 to 3.14.

Static sitting

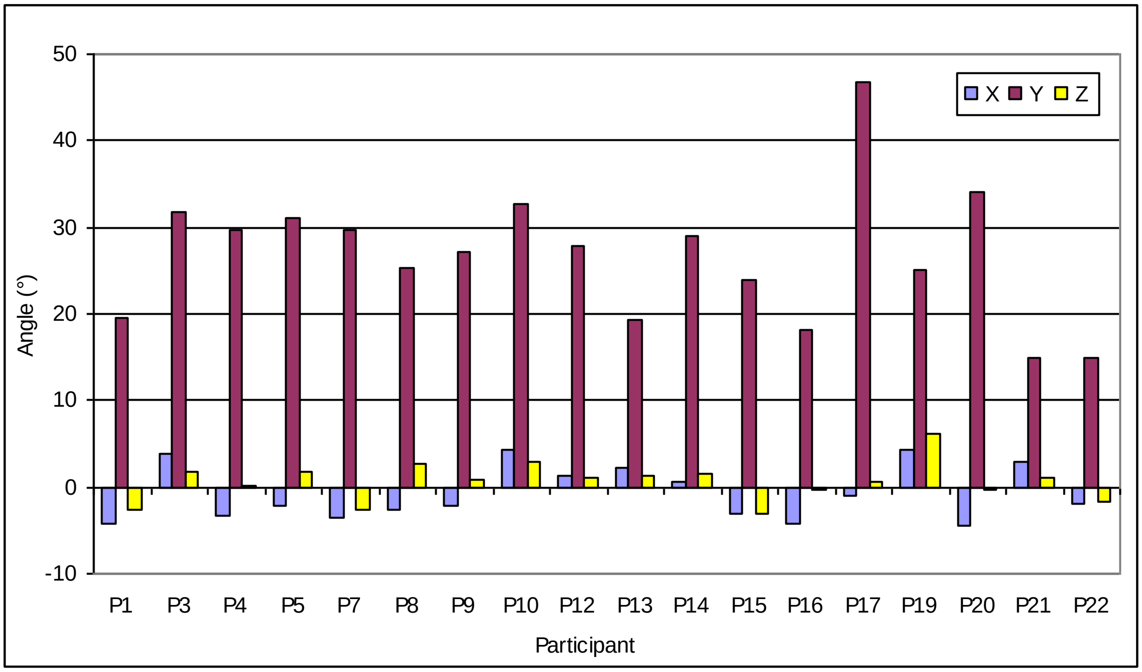
Participants in this study spent more than 58% of their time in static sitting over the 3 hour data collection period. The mean duration spent in static sitting for all 18 participants was plotted in Graph 7.4.27. Participant 15, who spent the least time engaging in movement, had the highest mean duration of 0.63 minutes. Others ranged between 0.09 to 0.29 minutes. This showed that Participant 15 was the most static participant; while Participant 5 was the most active participant who moved to either change posture or to have a postural adjustment every 6 seconds on average.

Though these values of mean static sitting time were very short overall, this was due to the high sensitivity of the discriminative algorithm. In the current algorithm, any possible static sitting posture that was equal or longer than 1 second was considered as static sitting. This resulted in the inclusion of many counts of 1s static sitting data in this parameter leading to a very short mean static sitting duration. Further suggestions to improve the validity of this parameter are discussed in Section 7.5.3.



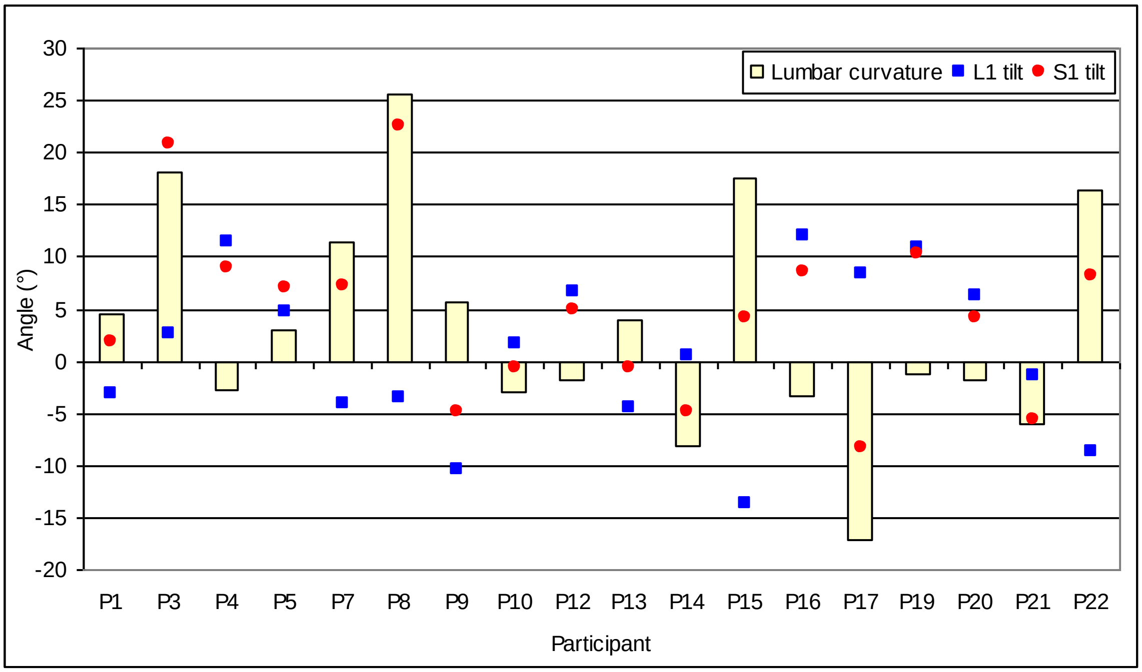
Graph 7.4.27: Mean (of individual participant) duration of static sitting in 3 hours of desk work

Graph 7.4.28 shows the 3 dimensional mean angles adopted during static sitting with reference to upright standing. The X axis refers to axial rotation; the Y axis was the axis for flexion/extension; and the Z axis represents lateral flexion movements. Flexion, left lateral flexion and left axial rotation were presented as positive values and negative values indicated opposite direction of the above mentioned movements. When compared to upright standing (0°), on average the lumbar spine of the participants was in 27° of flexion during sitting. Participant 17 flexed their lumbar spine the most from standing, to a mean of 47°. Participants 21 and 22 flexed their lumbar spine the least during sitting when compared to upright standing, with a mean value of 15°. For axial rotation and lateral flexion, the angle change from standing to sitting was within -4° to 6°.



Graph 7.4.28: Mean (of individual participant) angle adopted on all 3 axes during static sitting with respect to upright standing

The mean lumbar curvature angle during static sitting was also plotted for all participants as shown in Graph 7.4.29. The mean lumbar curvature angle during static sitting varied rather drastically from participant to participant, it ranged from a flexed lumbar spine of 17° to a lordosed lumbar spine of 26°. The results of these angles might be due to the behaviour of participants in sitting, and/or the influence of the initial lumbar curvature of the participants in standing. The relationship between these angles and changes in spinal mobility are further analysed in Section 7.4.4.



Graph 7.4.29: Mean (of individual participant) lumbar curvature angle adopted during static sitting over 3 hours of desk work, where LC = $LC_1 + LC_2$ (E 7.4.1), LC_1 was S1 tilt and LC_2 was –L1 tilt

The tabulated data for Graphs 7.4.28 to 7.4.29 are shown in Appendix Table 3.15.

7.4.4 Relationship between changes in range of physiological movements and 3 hours of desk working activities

Since the changes in physiological movements after 3 hours of desk work were most obvious in extension and axial rotation, in this section, the relationship between changes in these movements and all variables during 3 hours of desk work are explored.

Correlation coefficient (r) analysis was performed between the percentage differences in the 3 physiological movements and all variables reported during desk work activities as discussed in Section 7.4.3. It was found that there was no valid relationship between changes in physiological movements with mean static lateral flexion and rotation angles of the lumbar spine as these angles during static sitting were small (mean and standard deviation of 0.7° ± 2.2° and -0.7° ± 3.1° respectively). There was also no relevant relationship found between changes in physiological movements and the mean static sitting duration, mean movement duration and total static duration for all participants. No correlation was observed between total postural change/activities duration (r < -0.11) and frequency (r < -0.18) with the changes in extension and axial rotation.

Parameters that were found to have a possible relationship with changes in the range of physiological movements after 3 hours of desk work are summarised in Table 7.5.8 below. Any correlation coefficient of ± 0.20 and above was treated as a possible relationship between the 2 variables (Khamis 2008; Mason 2004; Ramrakha 1998; Stewart 2007) and formatted bold in Table 7.4.8.

All the relationships between the monitored parameters during the 3 hours of desk work and changes in physiological movements were classified as weak (correlation coefficient of <0.5). These relationships might not be statistically (p = 0.057 to 0.435) or clinically significant perhaps due to the small changes in physiological movements over the 3 hour period. A longer data collection time and/or a larger sample size is needed to quantify these differences and fully evaluate their significance. However, these relationships even though weak and not fully justified with the current limited data sets, they can provide an insight into which type of variable may be associated with the change in mobility of the lumbar spine.

Correlation Coefficient (p value)	Extension	Axial rotation	
		Right	Left
Standing lumbar curvature angle	**-0.24 (0.333)**	-0.04 (0.872)	**-0.24 (0.347)**
Mean lumbar curvature angle during static sitting	**-0.34 (0.162)**	-0.03 (0.908)	-0.16 (0.527)
Mean changes in lumbar curvature between standing and static sitting	**0.20 (0.435)**	-0.05 (0.852)	-0.12 (0.649)
Total dynamic activities duration	**-0.30 (0.235)**	0.01 (0.981)	0.00 (0.995)
Total postural adjustment duration	-0.07 (0.791)	**0.42 (0.081)**	**0.46 (0.057)**
Total number of occurrences of postural adjustment	0.01 (0.977)	0.02 (0.923)	**0.40 (0.099)**
Total number of occurrences of gross movement	-0.15 (0.549)	**-0.22 (0.386)**	**-0.28 (0.257)**

Table 7.4.8: Correlation coefficients (p value) between changes in 3 different physiological movements (extension, axial rotations) and different variables from 3 hours of desk work activities

In Table 7.4.8, the initial lumbar curvature angle of participants during standing was found to have a -0.24 correlation with extension and left axial rotation. This indicated that larger initial lumbar curvature angle during standing might cause less change in extension and left axial rotation after desk work activities. The mean lumbar curvature angle (correlation coefficient -0.34) adopted during sitting might play a role in changes in extension movements, participants who adopted a sitting posture with a larger lumbar lordosis angle had less changes in extension after 3 hours of desk work when compared to participants who adopted more flexed sitting postures.

The total time spent on performing dynamic activities was also found to may affect changes in extension. The more time spent on dynamic activities (e.g. having a short break from static sitting) might reduce changes in extension range. A similar relationship was found with the occurrences of gross movements with changes in axial rotation. Gross movements (>5°) could prevent the lumbar spine from prolonged static postures. The longer the total duration and the higher number of occurrences of postural adjustment movement during static sitting might cause larger changes in axial rotation movements ($p = 0.057$ to 0.099).

Multiple regression analysis was performed on changes in extension and standing lumbar curvature angle, mean lumbar curvature angle during static sitting, mean changes in lumbar curvature angle between standing and sitting and total dynamic activities duration; between right axial rotation and total postural adjustment duration and total number of occurrences of gross movement; and between left axial rotation and standing lumbar curvature angle, total postural adjustment duration, total number of occurrences of postural adjustment duration and gross movements. Although the results of the analysis did not provide strong significant evidence of a relationship, it showed there were possible weak association between the above mentioned parameters with changes in ranges of movement, with an R^2 of between 0.2 to 0.586, adjusted R^2 values of 9 to 14%, F values of 1.48 to 1.87 and significance values of between 0.19 and 0.26. Detailed tabulated data can be found in Appendix Tables A3.16 to A3.18.

7.4.5 Case Study

In this section, 3 case studies (Participants 8, 13 and 17) are presented to show the activities engaged, activity levels, sitting behaviour and how these parameters might be related to the change in spinal mobility after 3 hours of desk working. Participants 8 and 13 were the only 2 participants who did not experienced any significant changes (<2°) in all the 6 physiological movements. From the data presented in Section 7.5.3, it can be observed that Participant 8 maintained the greatest lumbar lordosed curvature angle during static sitting; while Participant 13 spent the longest duration in dynamic activities. Participant 17 on the other hand maintained the greatest lumbar flexion angle during static sitting and did not engage in any dynamic activity (remained seated throughout the 3 hour period), and this might be the cause of significant changes in spinal mobility after 3 hours of desk work.

Participant 8

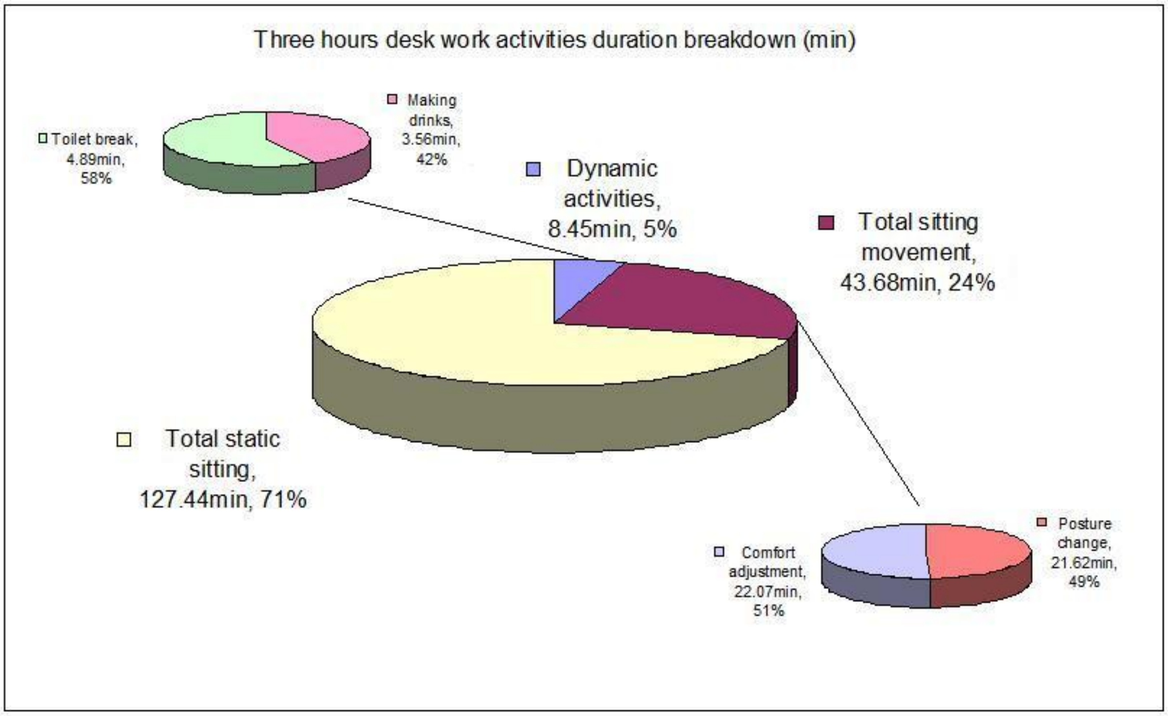
Participant 8 (P8) possessed the highest lumbar lordosis angle (51°) of all the 18 participants; and also maintained the highest mean lumbar curvature angle (26°) during static sitting. Table 7.4.9 below summarises the ranges of all 6 physiological movements for P8 before and after performing 3 hours of desk work activities. It can be seen that P8 showed no significant changes in ranges of movements (<1.2°), except in right lateral flexion (2.1°). However overall, the change in lateral flexion was not significant in this study, and P8 was considered to have no change in ranges of physiological movement after 3 hours of desk work activities.

	Ranges of movement (°) and lumbar curvature angle (°) before and after 3 hour desk work						
P8	**Flexion**	**Extension**	**Right lateral flexion**	**Left lateral flexion**	**Right axial rotation**	**Left axial rotation**	**Lumbar curvature angle (standing)**
Before	61.7	-31.1	-17.4	17.8	-12.3	12.0	51.0
After	62.6	-30.5	-19.5	17.9	-11.1	11.2	49.7

Table 7.4.9: Ranges of 6 physiological movements and lumbar curvature angle during upright standing of Participant 8 before and after 3 hours of desk work activities

Lumbar curvature angles during upright standing before and after 3 hours of desk working are also shown in Table 7.4.9. Participant 8 showed a slight decrease in lumbar curvature angle after 3 hours of desk work, however this change is small (1.3°) and not significant for the overall results of the study.

Graph 7.4.30 shows the breakdown duration for each activity performed by P8 over the 3 hour desk work period. For 71% of the 3 hour period, P8 was in a static sitting posture, 24% of time was spent on sitting movements and the remaining 5% of the time was spent on performing dynamic activities, i.e. making drinks and taking a toilet break. Out of the 43.68 minutes of sitting movements, 49% was spent in postural change and 51% was spent in postural adjustment.



Graph 7.4.30: Breakdown of duration spent in each activity during 3 hours of desk work of Participant 8

Participant 8 engaged in postural change/dynamic activities 259 times and had 258 episodes of postural adjustment movements for the lumbar spine. Out of the 259 postural change/dynamic activities, 97 occurrences were gross movements of >5°. These values are shown in Table 7.4.10.

Participant 8	**Posturalchange/dynamic activities**	**Postural adjustment**	**Gross movements**
No. of occurrences	259	358	97
Mean duration (min)	0.13	0.05	0.17
Total duration spent (min)	30.06	22.07	16.89

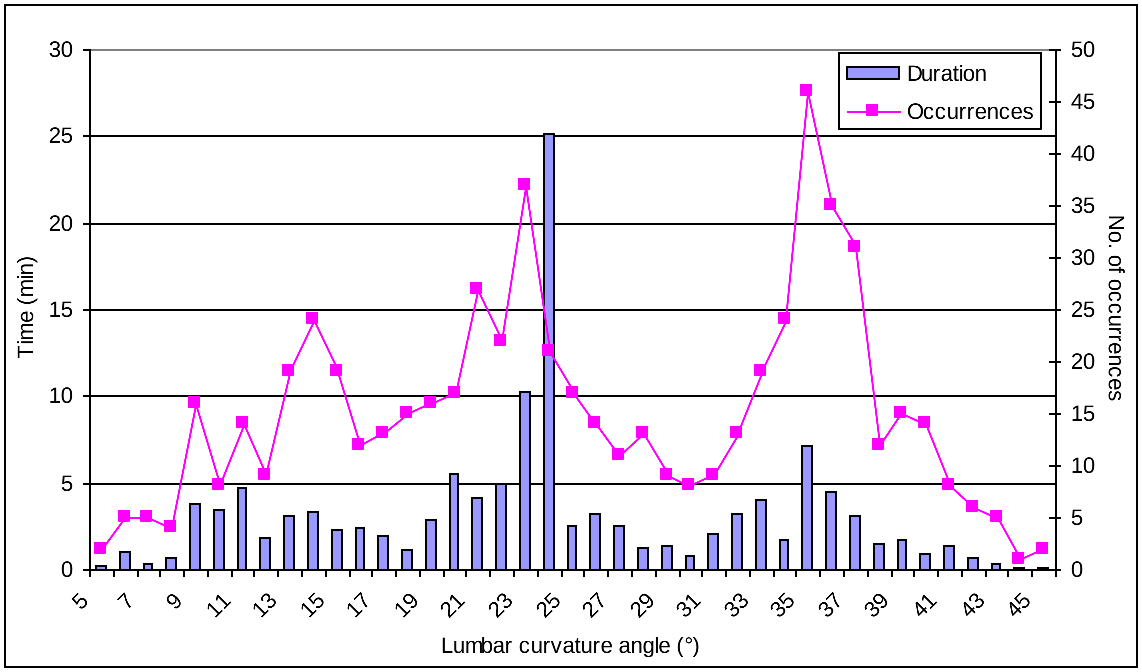
Table 7.4.10: Summary of number of occurrences, mean duration and total duration spent in each movement group of the lumbar spine of Participant 8

During static sitting, P8 on average sat with the lumbar spine in 3° of right rotation, 3° of left lateral flexion and 25° of flexion with respect to upright standing. However since P8 had a standing lumbar lordotic curvature of 51°, the lumbar lordotic curvature angle during static sitting was maintained at a mean of 26°. Table 7.4.11 shows the descriptive data for these static sitting angles for P8. The most common angle adopted by P8 during static sitting was 3° right rotation (110 occurrences), 35° in a lumbar lordotic curvature (occurred 46 times) and 2° lateral flexion to the left side (144 occurrences).

	Mean angle adopted during static sitting with respect to upright standing (°)			
Participant 8	**Axial rotation, X**	**Flexion/Extension, Y**	**Lateral flexion, Z**	**Lumbar curvature (°)**
Minimum	-9	9	-2	5
Maximum	9	49	9	45
Mean	-3	25	3	26
Standard Deviation	4	10	2	10
Mode (count)	-3 (110)	20 (46)	2 (144)	35 (46)

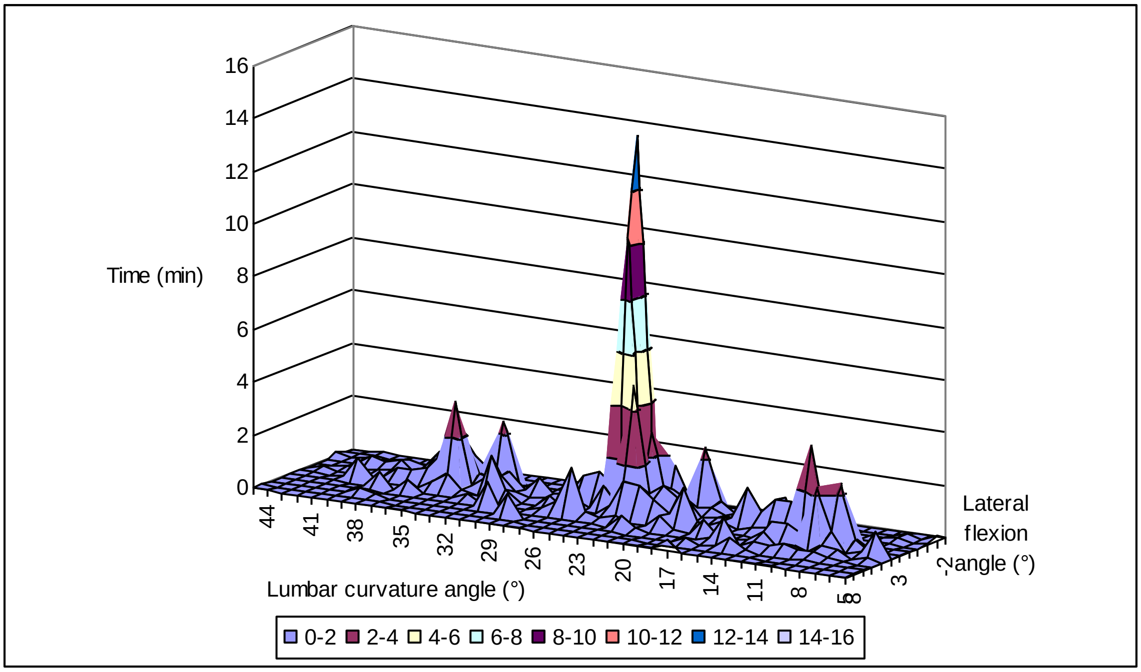
Table 7.4.11: Summary of angle adopted during static sitting of Participant 8

Graph 7.4.31 shows the breakdown of the time spent in each lumbar curvature angle for P8 during static sitting. The number of occurrences for each lumbar curvature angle was also plotted on the same graph as the pink line plot. The graph shows that P8 did not engage in any kyphotic lumbar postures over the 3 hour period. The lowest lumbar lordotic curvature angle adopted by P8 was 5° for a period of 0.25 minutes and this angle only appeared twice over the 3 hour period. Participant 8 spent the longest time in maintaining a lumbar lordotic curvature of 24° (25.12 minutes). The number of occurrences of this angle was only 21 times, which indicated that P8 stayed in this posture for a longer period before engaging in any movement.

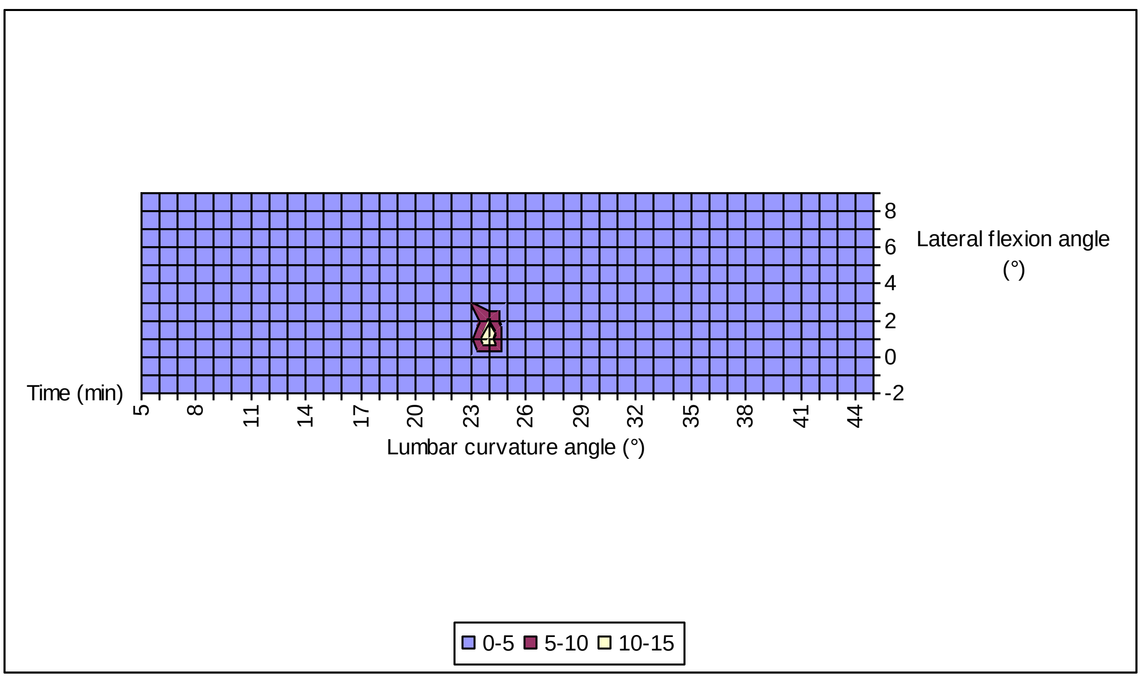


Graph 7.4.31: Breakdown of duration spent and number of occurrences of each lumbar curvature angle during static sitting of Participant 8

A 3 dimensional surface map was plotted with the duration spent against lateral flexion and lumbar curvature angles during static sitting, as shown in Graphs 7.4.32 and 7.4.33 (view from above). The longest duration was spent in 24° of lumbar lordotic curvature angle and 1° to 2° of lateral flexion. The most common/concentrated ranges of static angles for P8 during static sitting were between 0° to 3° of lateral flexion and 23° to 25° of lumbar lordotic curvature, as can be seen in Graph 7.4.33.

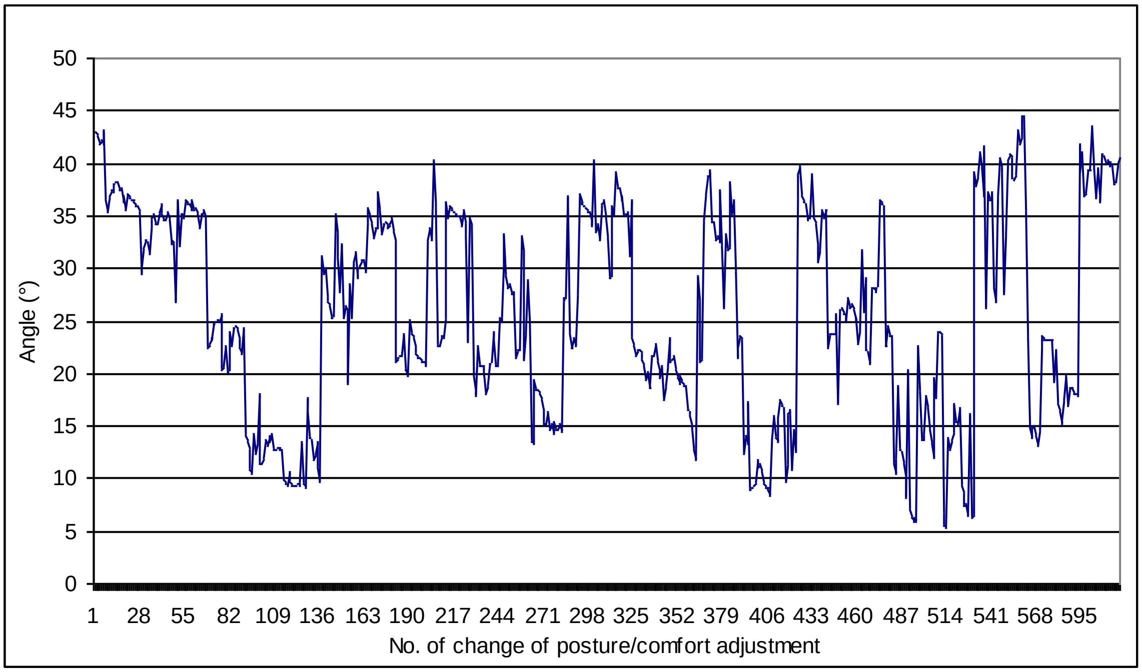


Graph 7.4.32: Surface map of duration spent in lateral flexion and lumbar curvature angle during static sitting for Participant 8 – 3D view



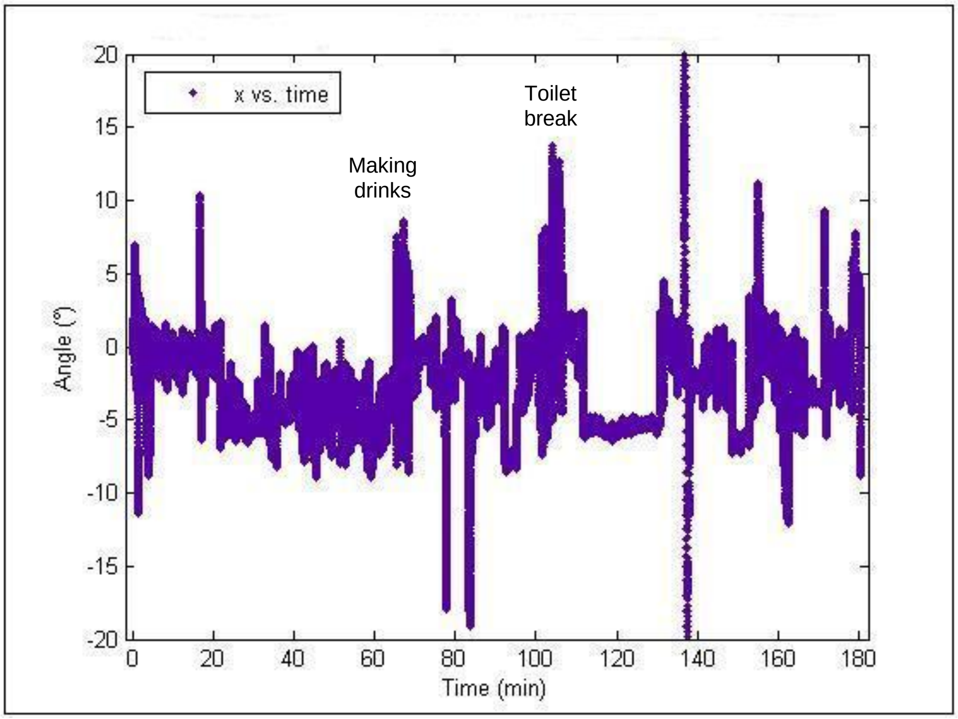
Graph 7.4.33: Surface map of duration spent in lateral flexion and lumbar curvature angle during static sitting for Participant 8 – view from above

Graph 7.4.34 shows how the lumbar curvature angle of P8 during static sitting changed with the change of posture/dynamic activities or postural adjustment over the 3 hour desk work period.

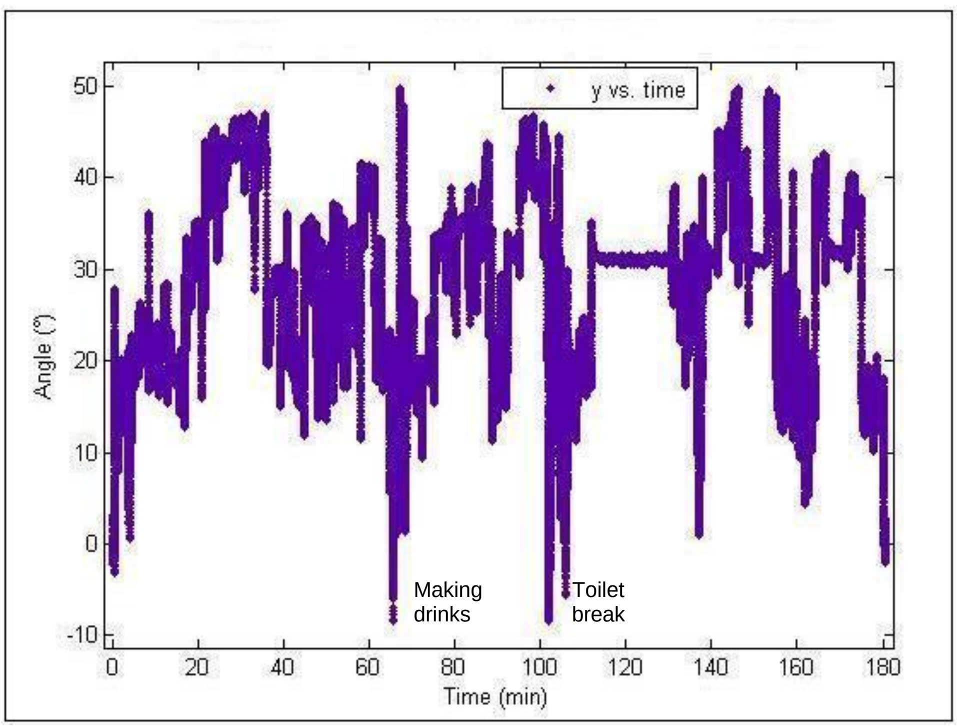


Graph 7.4.34: Changes in lumbar curvature angles during static sitting with the change of posture/comfort adjustment of Participant 8 over a period of 3 hours

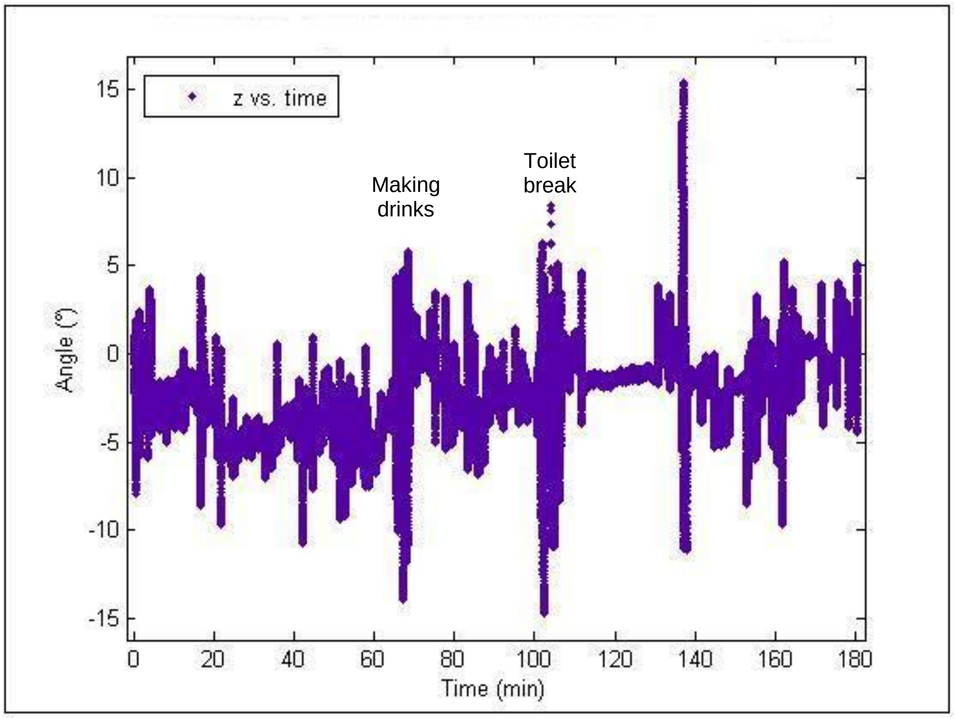
Graphs 7.4.35 to 7.4.37 show the angles of axial rotation, flexion/extension and lateral flexion of the lumbar spine with respect to upright standing over the whole 3 hour desk working activities period (inclusive of angles during movements) for P8.



Graph 7.4.35: Axial rotation angle of Participant 8 over 3 hours of desk work activities (inclusive of movement angles)



Graph 7.4.36: Flexion/extension angle of Participant 8 with respect to upright standing over 3 hours of desk work activities (inclusive of movement angles)



Graph 7.4.37: Lateral flexion angle of Participant 8 over 3 hours of desk work activities (inclusive of movement angles)

Based on the possible relationships observed between the changes in ranges of physiological movements after 3 hours of desk work and the 7 variables discussed in Section 7.4.4, Participant 8 did not show any significant changes in any of the 6 ranges of physiological movements after 3 hours of desk work which might be due to a high initial lumbar lordotic curvature angle during standing; a highly lordosed lumbar curvature maintained during static sitting; moderate dynamic activities between static sitting; longer time spent on postural change/dynamic activities than postural adjustment movements; and a high occurrence of gross movements.

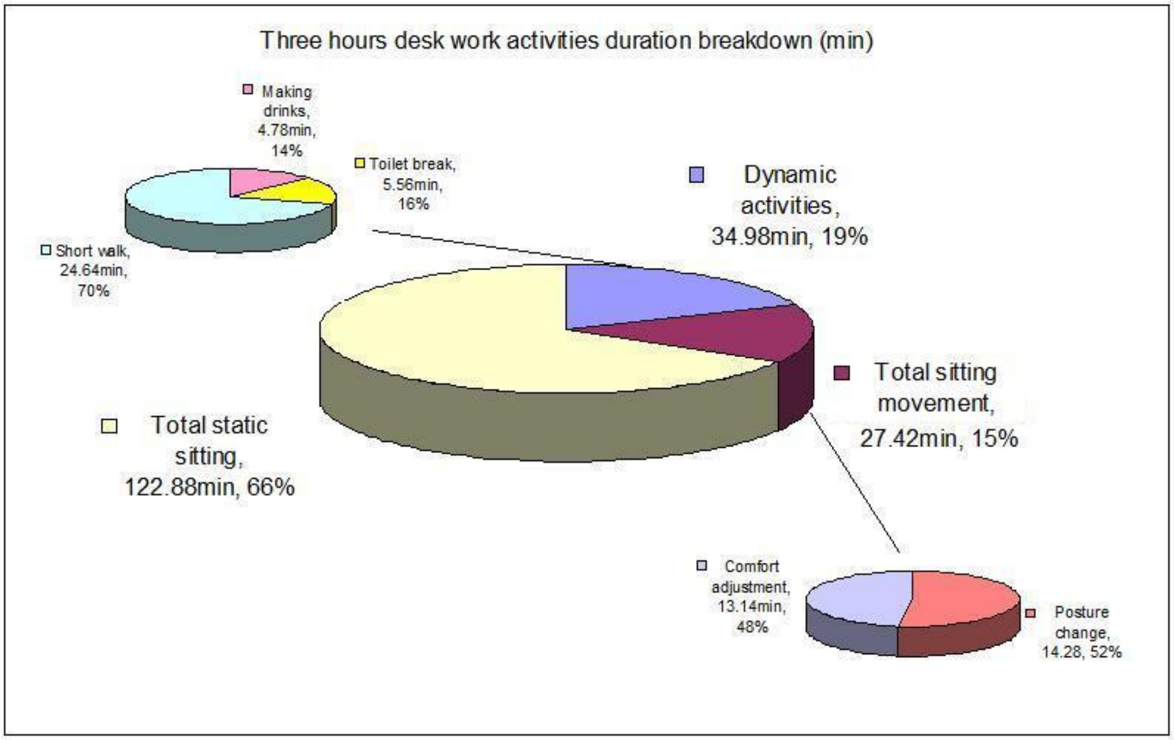
Participant 13

The lumbar lordotic curvature angle of Participant 13 (P13) during upright standing was within a common range among 1/3 of the 18 participants, at 24°. Table 7.4.12 below shows the ranges of the 6 physiological movements of P13 before and after 3 hours of desk work activities, there were no significant changes (< 2°) in the ranges of all 6 movements observed. There was also no significant change in lumbar curvature angle during upright standing before and after the 3 hour period.

	Ranges of movement (°) and lumbar curvature angle before and after 3 hour desk work						
P13	**Flexion**	**Extension**	**Right lateral flexion**	**Left lateral flexion**	**Right axial rotation**	**Left axial rotation**	**Lumbar curvature angle (standing)**
Before	51.7	-23.2	-24.3	20.9	-6.5	8.8	24.0
After	50.5	-22.9	-22.6	22.8	-5.0	9.1	23.1

Table 7.4.12: Ranges of 6 physiological movements and lumbar curvature angle during upright standing of Participant 13 before and after 3 hours of desk work activities

Looking at the breakdown of the duration spent on each desk work activity in Graph 7.4.38, P13 spent 2/3 of the 3 hours in static sitting, 19% of the times in performing dynamic activities and for the remaining 15% of the time P13 was engaging in sitting movements. Out of the 18 participants, P13 spent the longest duration in performing dynamic activities that included taking a short walk for a total of 24.64 minutes, having a toilet break for 5.56 minutes and making drinks for a total of 4.78 minutes. During sitting movements, P13 spent 52% of the time changing posture, and the rest of the 13.14 minutes engaging in postural adjustment movement.



Graph 7.4.38: Breakdown of duration spent in each activity during 3 hours of desk work of Participant 13

By analysing sitting movements further, P13 engaged in postural change/dynamic activities 214 times in the 3 hour period; and had 358 episodes of postural adjustment movements. Ninety two occurrences out of the 214 posture/change/dynamic activities were gross movements. From Table 7.4.13, P13 spent more than 3 times the overall movement duration in postural change/dynamic activities, while 41.41 minutes of it were spent engaging in gross movements.

Participant 13	Postural change/dynamic activities	Postural adjustment	Gross movements
No. of occurrences	214	358	92
Mean duration (min)	0.24	0.04	0.45
Total duration spent (min)	49.26	13.14	41.41

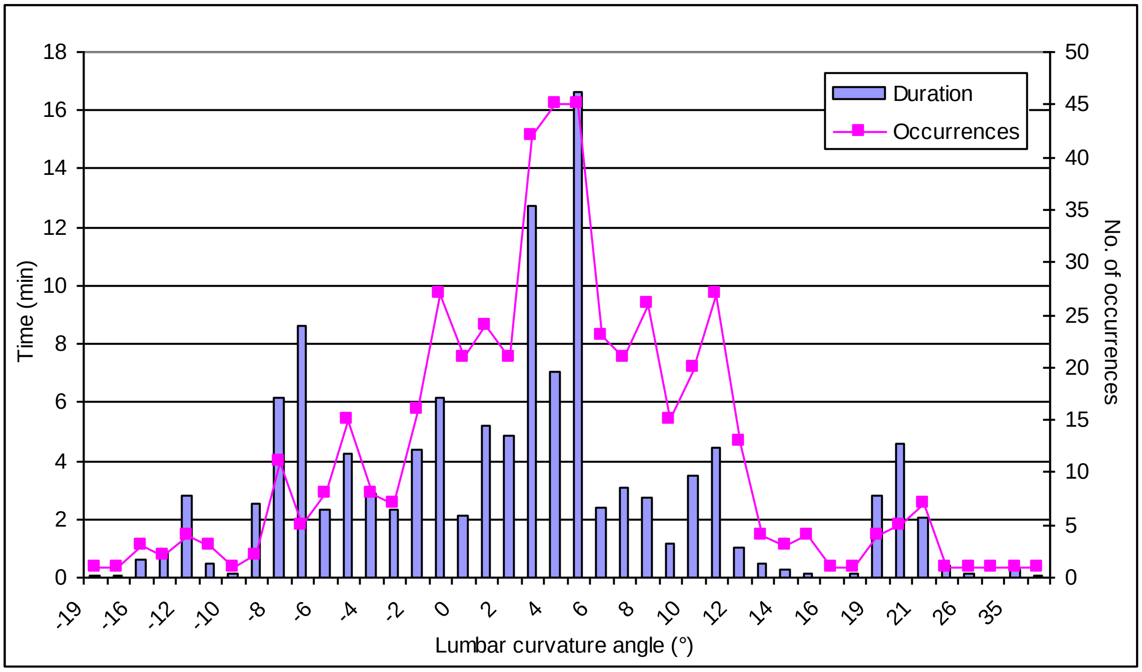
Table 7.4.13: Summary of number of occurrences, mean duration and total duration spent in each movement group on the overall lumbar spine, L1 and S1 spinous processes of Participant 13

Table 7.4.14 summarises the descriptive data of spinal angles adopted by P13 during static sitting. On average by taking standing as the reference point, P13 was found sitting with the lumbar spine 2° rotated to the left; 19° flexed and 2° laterally flexed to the left side. The mean lumbar curvature angle during static sitting for P13 was found to be 4°, i.e. 4° of lordosis in the lumbar spine. From Table 7.4.14, the most common static seated posture for P13 was 5° left rotated (occurred 73 times); 5° in a lordotic lumbar curvature (45 occurrences); and 1° left lateral flexed (60 occurrences).

	Mean angle adopted during static sitting with respect to upright standing (°)			
Participant 13	**Axial rotation, X**	**Flexion/Extension, Y**	**Lateral flexion, Z**	**Lumbar curvature**
Minimum	-12	-13	-8	-19
Maximum	13	43	9	36
Mean	2	19	2	4
Standard Deviation	5	7	3	7
Mode (count)	5 (73)	18 (51)	1 (60)	5 (45)

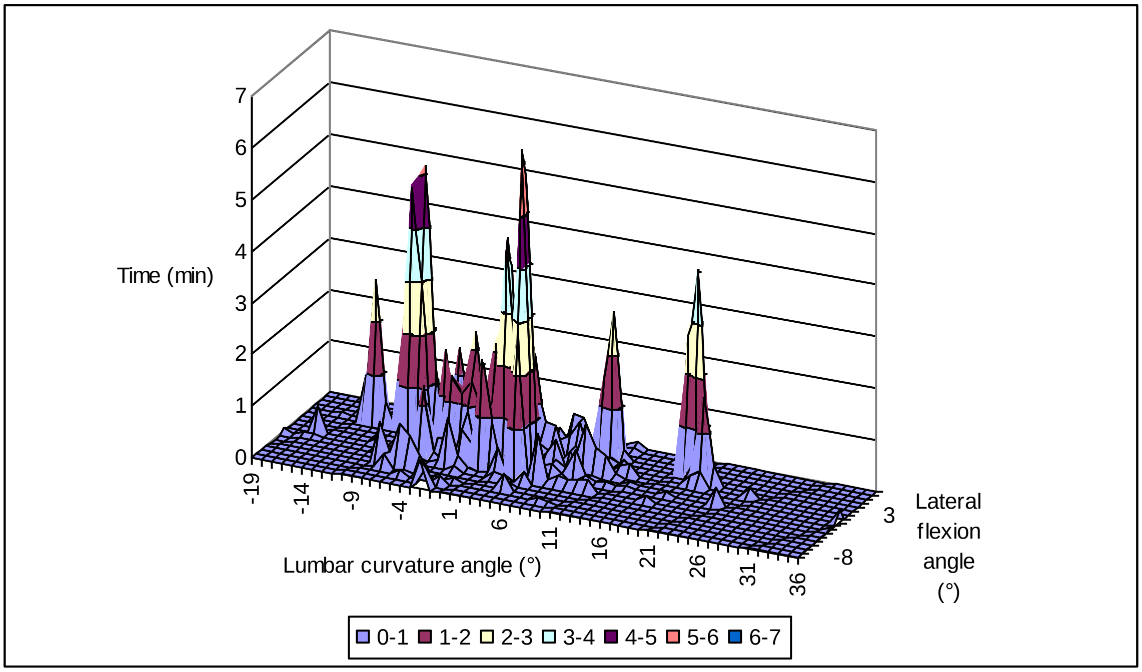
Table 7.4.14: Summary of angle adopted during static sitting of Participant 13

Graph 7.4.39 shows the breakdown of time spent in each lumbar curvature angle by P13 during static sitting, the number of occurrences of each lumbar curvature angle was also plotted on the same graph (pink line plot). The longest duration spent in a single lumbar curvature angle was 16.62 minutes, when P13 was seated with a 5° lumbar lordotic curvature angle. The number of occurrences of this angle was also the highest (45 times). From Graph 7.4.39, it can be observed that P13 engaged in a large range of lumbar curvatures in the 3 hour period, from a lordosed lumbar spine of 36° to a flexed lumbar spine of -19°. This may indicate P13 was an active desk worker who did not stay in a single static position for a long duration.

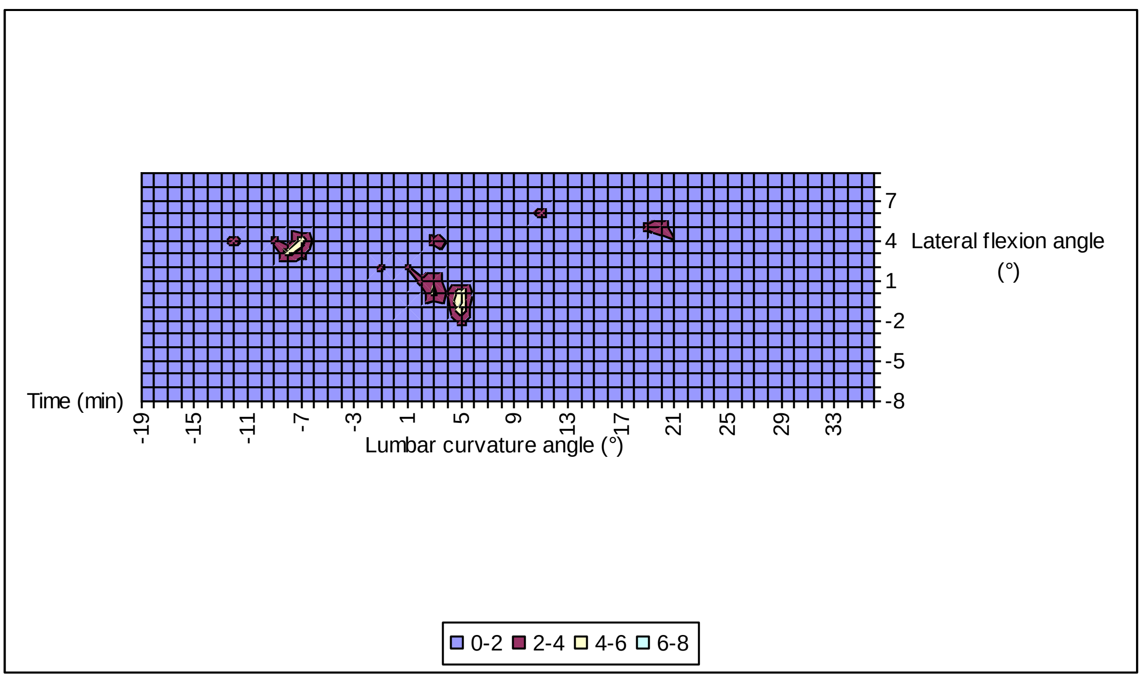


Graph 7.4.39: Breakdown of duration spent and number of occurrences of each lumbar curvature angle during static sitting of Participant 13

Graphs 7.4.40 and 7.4.41 show a 3 dimensional surface for time spent in each lateral flexion and lumbar curvature angles during static sitting. Graph 7.4.41 shows the top view of Graph 7.4.40. From these plots, P13 was found to spend the most time in adopting postures in the ranges of -2° to 1° of lateral flexion angle with 2° to 6° of lumbar lordotic curvature angle; and 2° to 4° of a lateral flexion angle with -9° to -6° of flexed lumbar curvature angle.

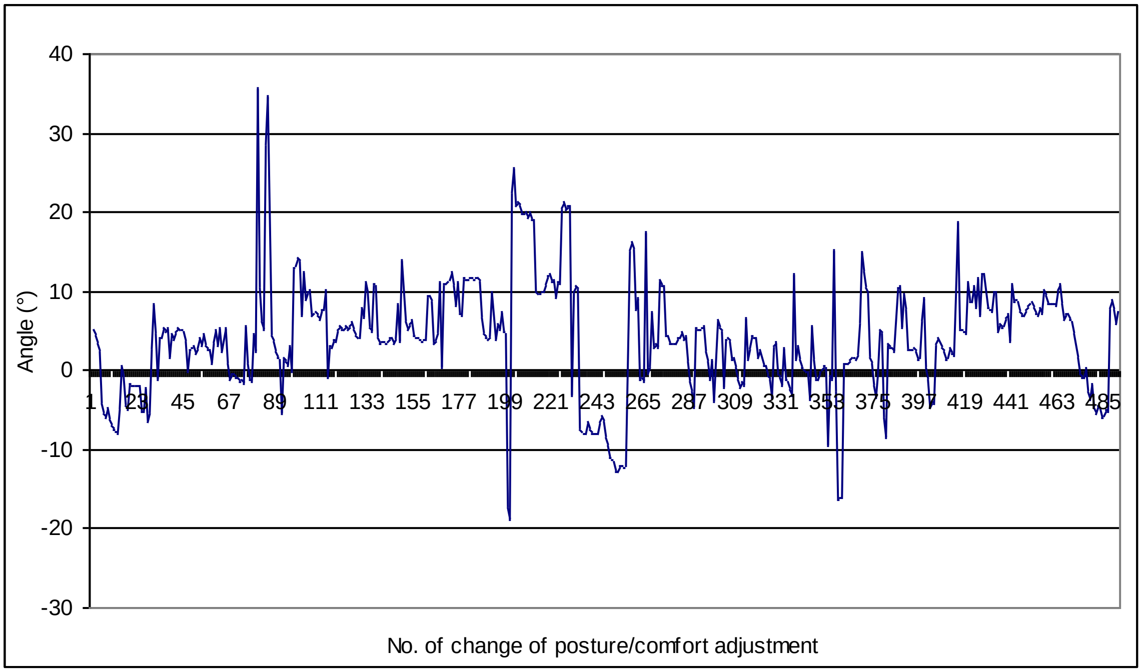


Graph 7.4.40: Surface map of duration spent in each lateral flexion and lumbar curvature angle during static sitting of Participant 13 – 3D view



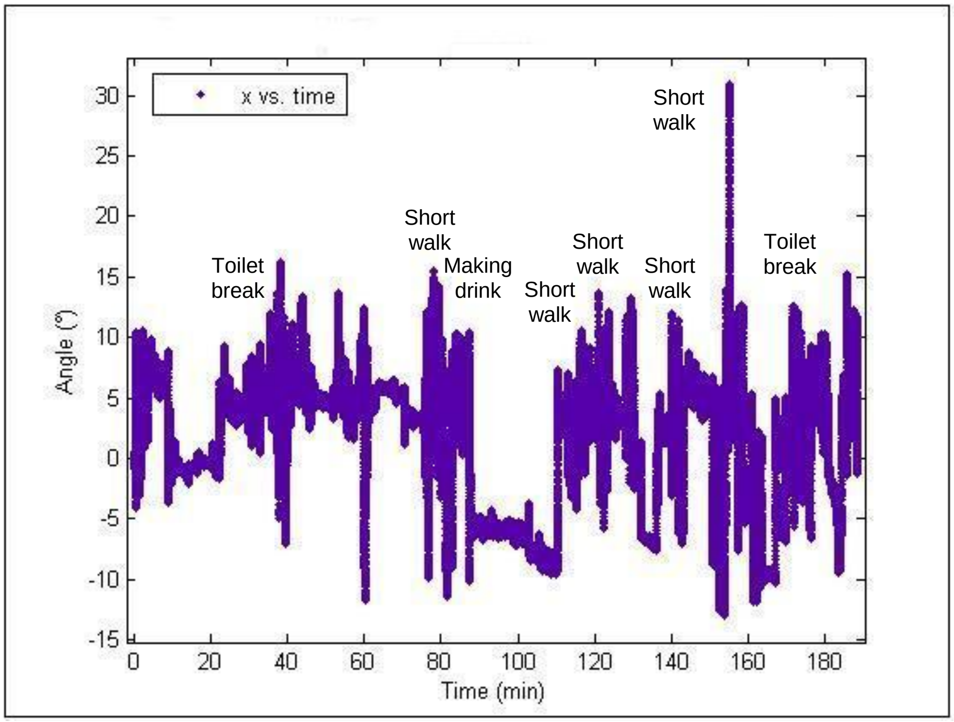
Graph 7.4.41: Surface map of duration spent in each lateral flexion and lumbar curvature angle during static sitting of Participant 13 – view from above

The change in lumbar curvature angle with the change in movement over the 3 hour period of desk work activities of P13 is shown in Graph 7.4.42 below.

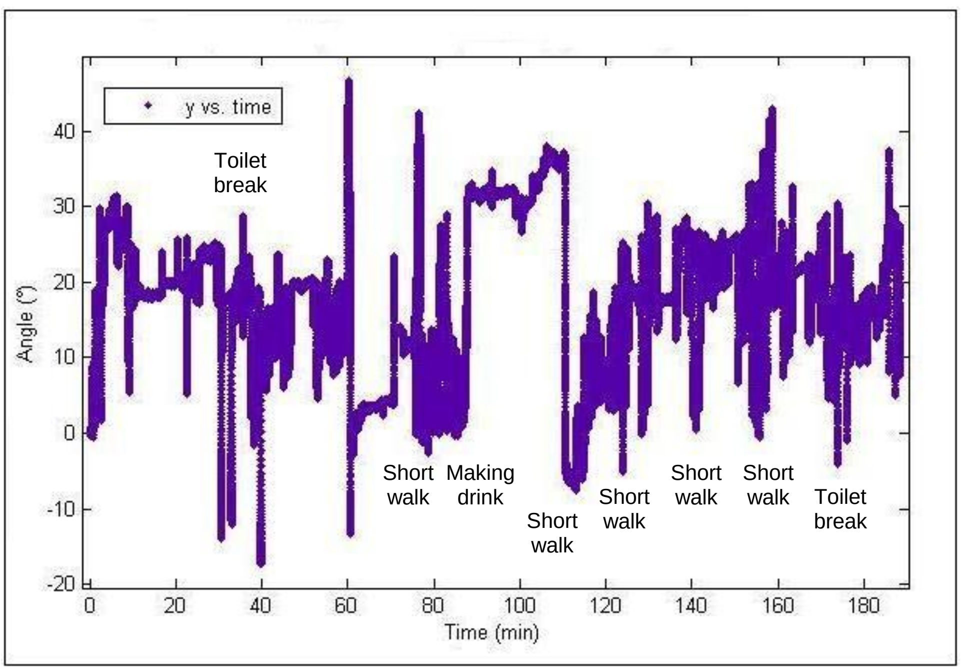


Graph 7.4.42: Changes in lumbar curvature angles during static sitting with the change of posture/comfort adjustment of Participant 13 over a period of 3 hours

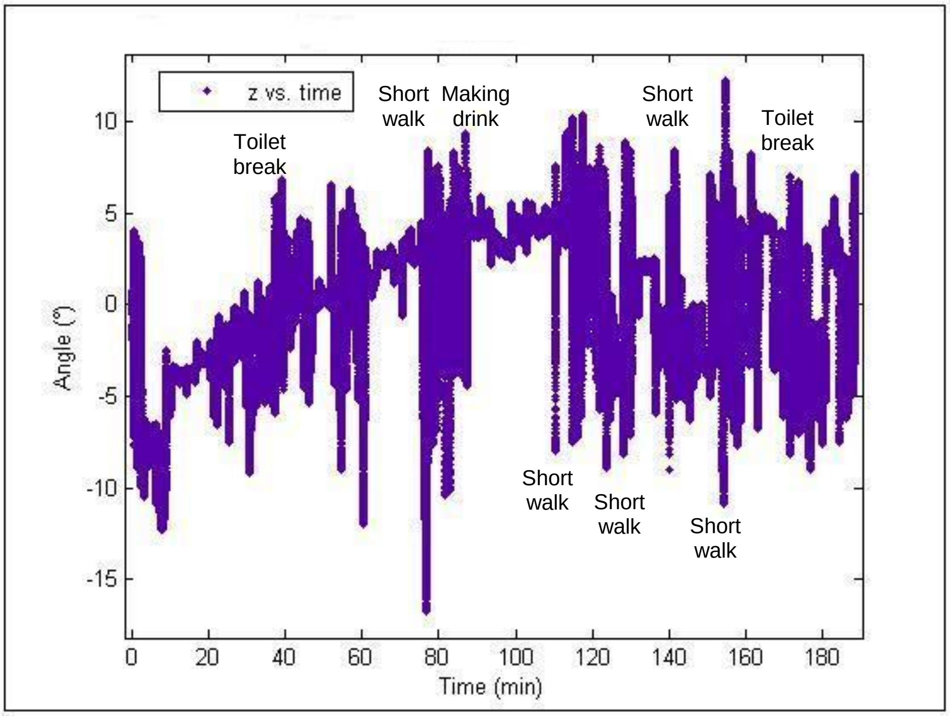
Graphs 7.4.43 to 7.4.45 present the 3 dimensional lumbar spinal angles of P13 over the 3 hour desk work activities (inclusive angles during movement). These angles were calculated by taking upright standing as the reference/neutral point.



Graph 7.4.43: Axial rotation angle of Participant 13 over 3 hours of desk work activities (inclusive of movement angles)



Graph 7.4.44: Flexion/extension angle of Participant 13 with respect to upright standing over 3 hours of desk work activities (inclusive of movement angles)



Graph 7.4.45: Lateral flexion angle of Participant 13 over 3 hours of desk work activities (inclusive of movement angles)

Over the 3 hour period of desk work activities, even though P13 had a slightly lower than average lumbar curvature angle during standing, P13 maintained his lumbar spine at a mean lordotic posture of 4° during static sitting, i.e. a mean of 19° flexed from reference standing. Participant 13 spent the most time engaging in dynamic activities, which could provide periodic rest for the lumbar spine from prolonged static posture. Although the number of occurrences of postural adjustment movement was higher than postural change/dynamic activities, the time spent in performing postural adjustment movements was much less when compared to postural change/dynamic activities. Participant 13 also engaged in a considerable amount of gross movement over the 3 hour data collection period.

There was no significant change in physiological movements before and after the 3 hour data collection period for P13 probably due to the postural behaviour of P13 in the 3 hours of desk work activities as discussed above.

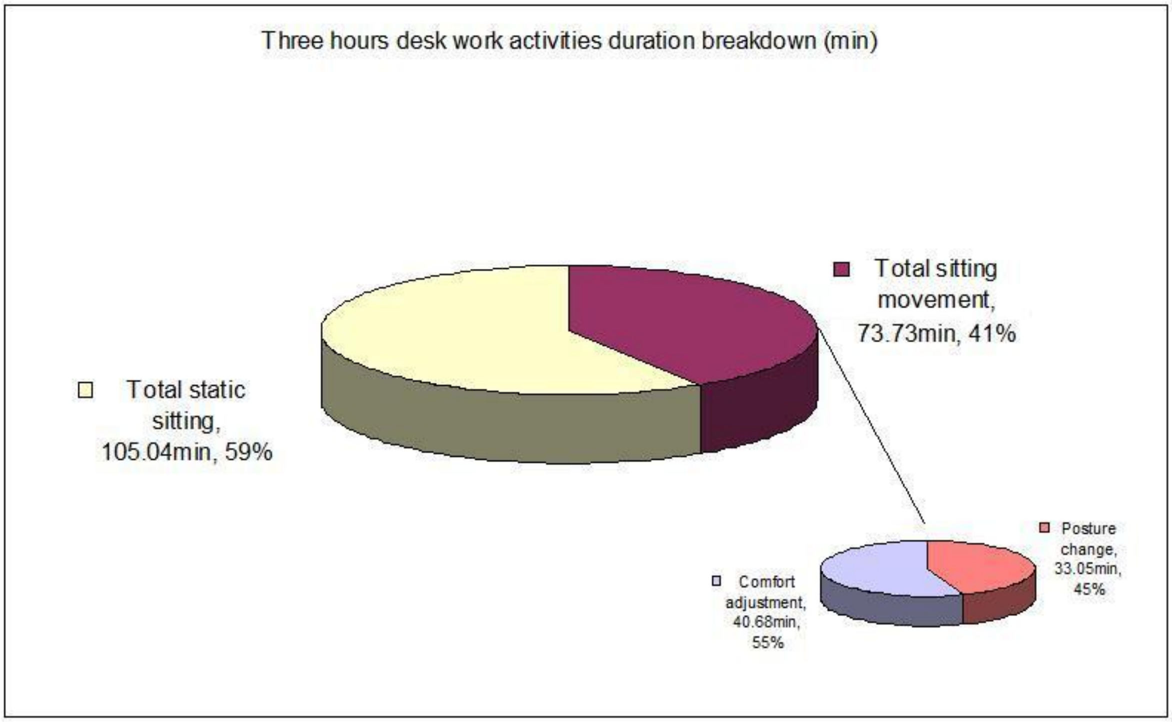
Participant 17

Participant 17 (P17) had an initial lumbar lordotic curvature angle of 28.3° in standing, but adopted the most flexed sitting posture amongst all the 18 participants. Table 7.4.15 summarises the ranges of all 6 physiological movement and lumbar lordotic curvature angles during upright standing before and after 3 hours of desk work. Participant 17 experienced a 2° increase in flexion and a decrease range in all other movements after 3 hours of desk work. The biggest change was seen in extension, with a magnitude of 7.4° (25.7%). Changes in axial rotation movements were also high, decreased for approximately 22%. Lumbar curvature angles of P17 before and after 3 hours of desk work did not show any significant difference.

	Ranges of movement (°) and lumbar curvature angle before and after 3 hour desk work						
P17	**Flexion**	**Extension**	**Right lateral flexion**	**Left lateral flexion**	**Right axial rotation**	**Left axial rotation**	**Lumbar curvature angle (standing)**
Before	56.4	-28.6	-26.7	26.3	-13.2	12.2	28.3
After	58.4	-21.2	-25.3	20.4	-10.4	9.6	28.9

Table 7.4.15: Ranges of 6 physiological movements and lumbar curvature angle during upright standing of Participant 17 before and after 3 hours of desk work activities

A breakdown of duration spent on the 3 main activities during the 3 hour period of desk work of Participant 17 can be seen in Graph 7.4.46. Participant 17 even though did not engage in any dynamic activity over the 3 hour period, P17 spent 41% of the 3 hours on sitting movements. Fifty nine percent of the data collection period for P17 was spent in static sitting. Out of the 73.73 minutes of sitting movements, P17 spent 55% of it in performing postural adjustment movement, whilst only 45% was spent on postural change.



Graph 7.4.46: Breakdown of duration spent in each activity during 3 hours of desk work of Participant 17

The number of occurrences of postural adjustment movement of P17 was more than 3 times higher than the occurrence of postural change. Information on movements engaged in by P17 is tabulated in Table 7.4.16.

Participant 17	Postural change/dynamic activities	Postural adjustment	Gross movements
No. of occurrences	214	750	75
Mean duration (min)	0.16	0.05	0.25
Total duration spent (min)	33.05	40.68	18.65

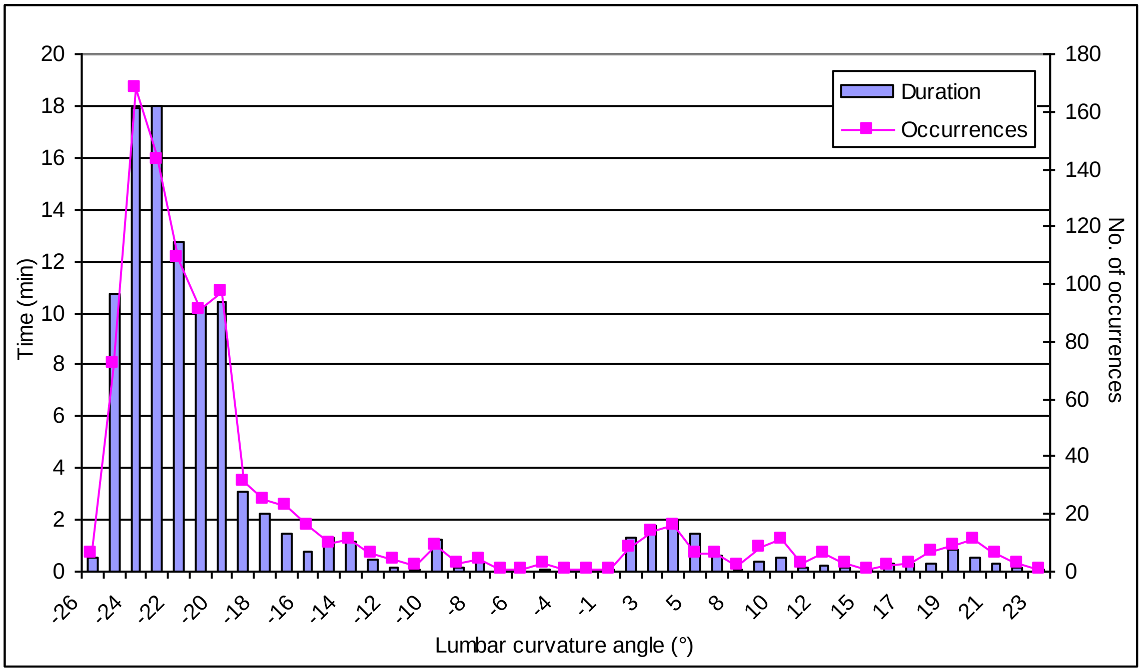
Table 7.4.16: Summary of number of occurrences, mean duration and total duration spent in each movement group on overall lumbar spine, L1 and S1 spinous processes of Participant 17

Table 7.4.17 shows the descriptive data for the 3 dimensional angles of the lumbar spine for P17 during static sitting, with upright standing as the reference/neutral point. On average, P17 was seated with 1° of right rotation, 47° of flexion and 1° of left lateral flexion from standing. The lumbar spine of P17 was on average in a 17° kyphotic posture during static sitting, and exhibited the highest mean seated kyphosed posture amongst all the 18 participants in this study. The most common seated posture of P17 was with the lumbar spine rotated 4° to the right (122 occurrences), 2° laterally flexed to the left and a flexed lumbar curvature of -24° (168 occurrences).

	Mean angle adopted during static sitting with respect to upright standing (°)			
Participant 17	**Axial rotation, X**	**Flexion/Extension, Y**	**Lateral flexion, Z**	**Lumbar curvature**
Minimum	-10	7	-10	-26
Maximum	11	57	7	23
Mean	-1	47	1	-17
Standard Deviation	4	12	3	12
Mode (count)	-4 (122)	54 (132)	2 (14)	-24 (168)

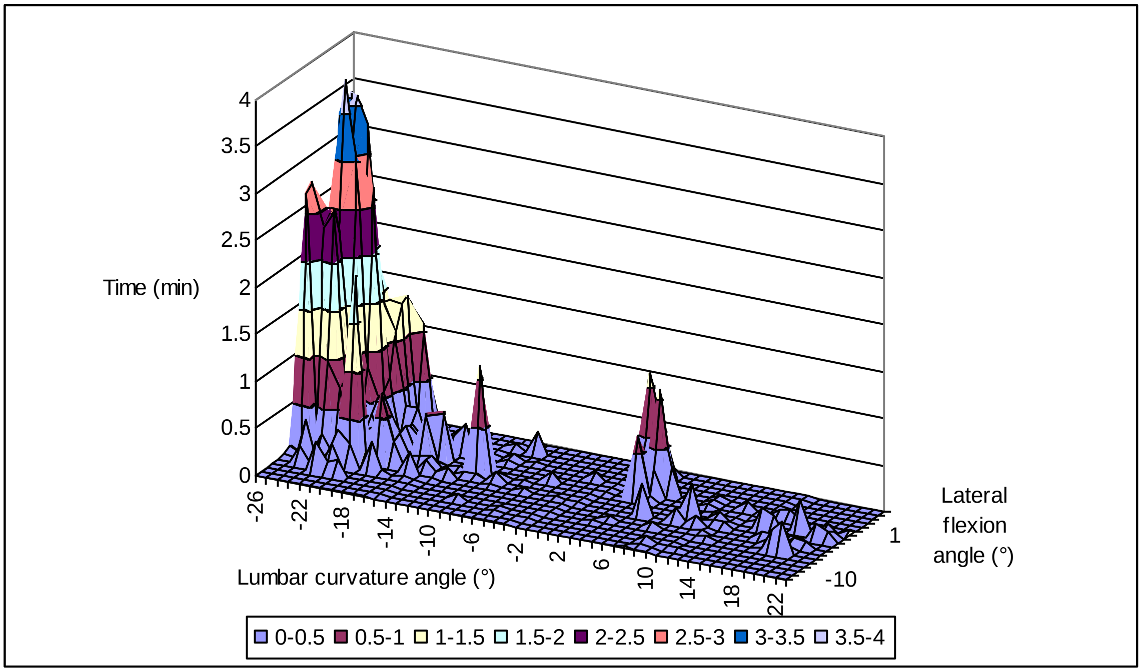
Table 7.4.17: Summary of angle adopted during static sitting of Participant 17

The breakdown of the time spent in each lumbar curvature angle adopted by P17 during static sitting is shown in Graph 7.4.47. It can be seen that P17 engaged in a range of -26° to 23° lumbar curvature angles in static sitting during the 3 hours of desk work activities, with the most time spent between 20° to 25° of a kyphotic lumbar posture. The number of occurrence of each lumbar curvature angle was also plotted in Graph 7.4.47 as the pink line plot. The highest occurrences were found to be between lumbar curvature angles of -20° to 25°.

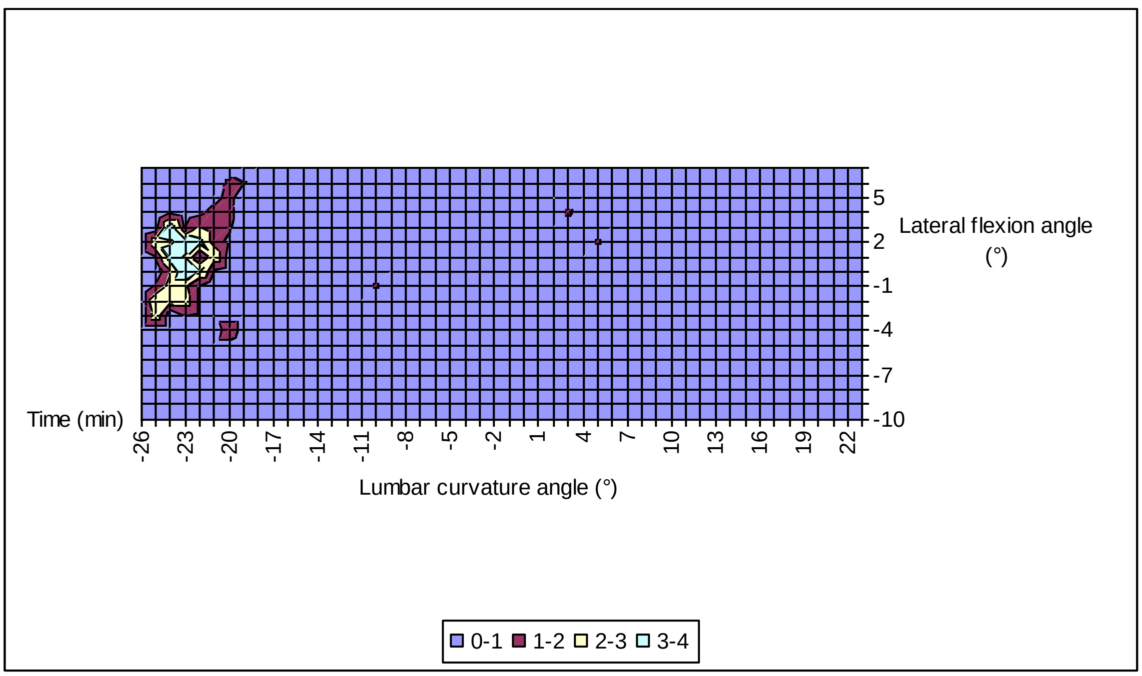


Graph 7.4.47: Breakdown of duration spent and number of occurrences of each lumbar curvature angle during static sitting of Participant 17

Graphs 7.4.48 and 7.4.49 show the 3 dimensional surface plots of time spent in each lateral flexion position and lumbar curvature angles during static sitting, with Graph 7.4.49 showing the top view of Graph 7.4.48. The most time spent by P17 in static sitting was in a range of lateral flexion angles of -4° to 4°, and lumbar curvature angles of between -20° to -26°. Participant 17 barely spent longer than 1 minute in lordosed sitting posture.

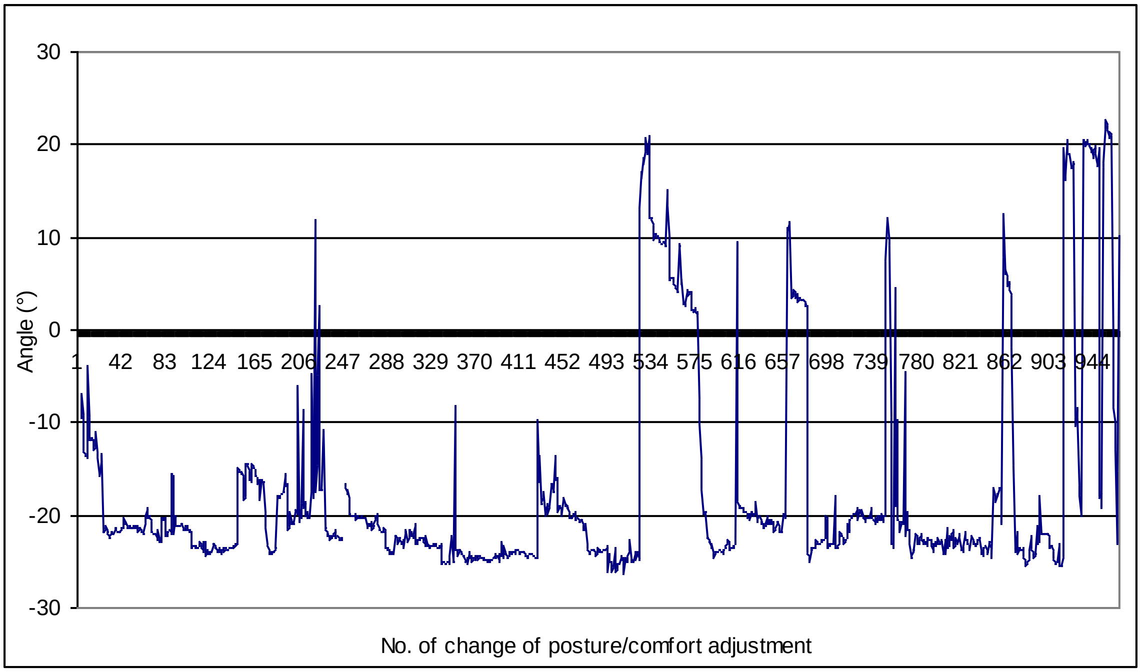


Graph 7.4.48: Surface map of time spent in each lateral flexion and lumbar curvature angle during static sitting for Participant 17 – 3D view



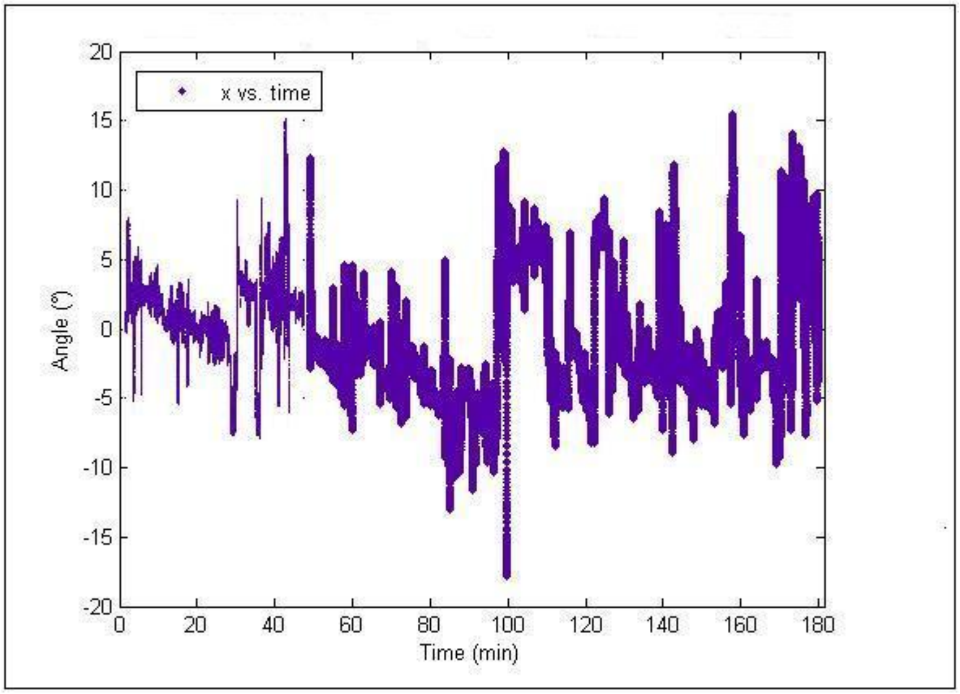
Graph 7.4.49: Surface map of time spent in each lateral flexion and lumbar curvature angle during static sitting for Participant 17 – view from above

The changes in lumbar curvature angles in static sitting with the change of movements over the 3 hour desk work period are shown in Graph 7.4.50.

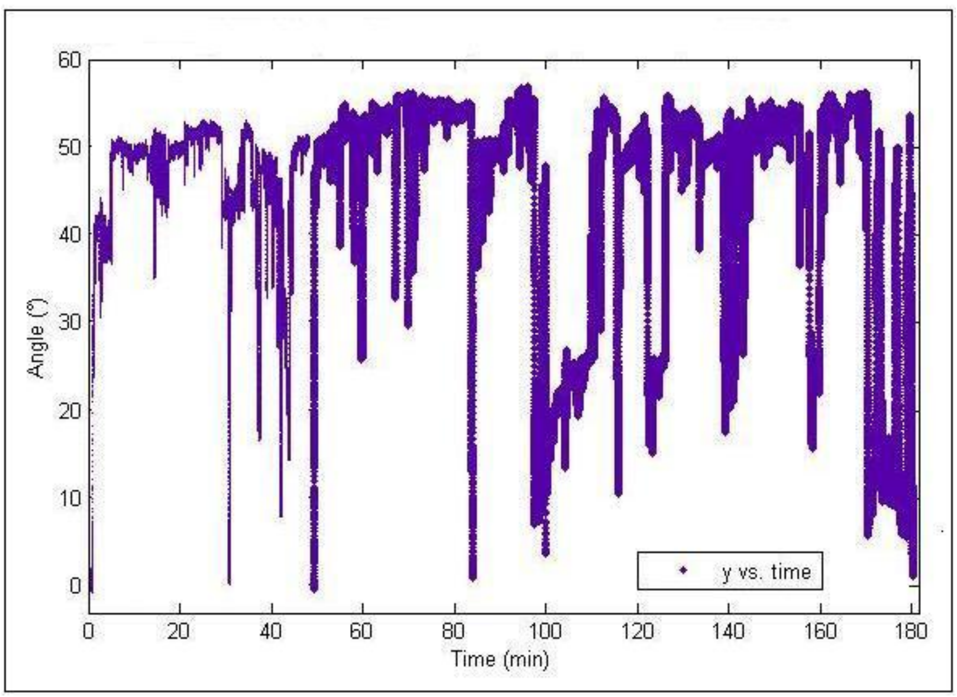


Graph 7.4.50: Changes in lumbar curvature angles during static sitting with the change of posture/comfort adjustment for Participant 17 over a period of 3 hours

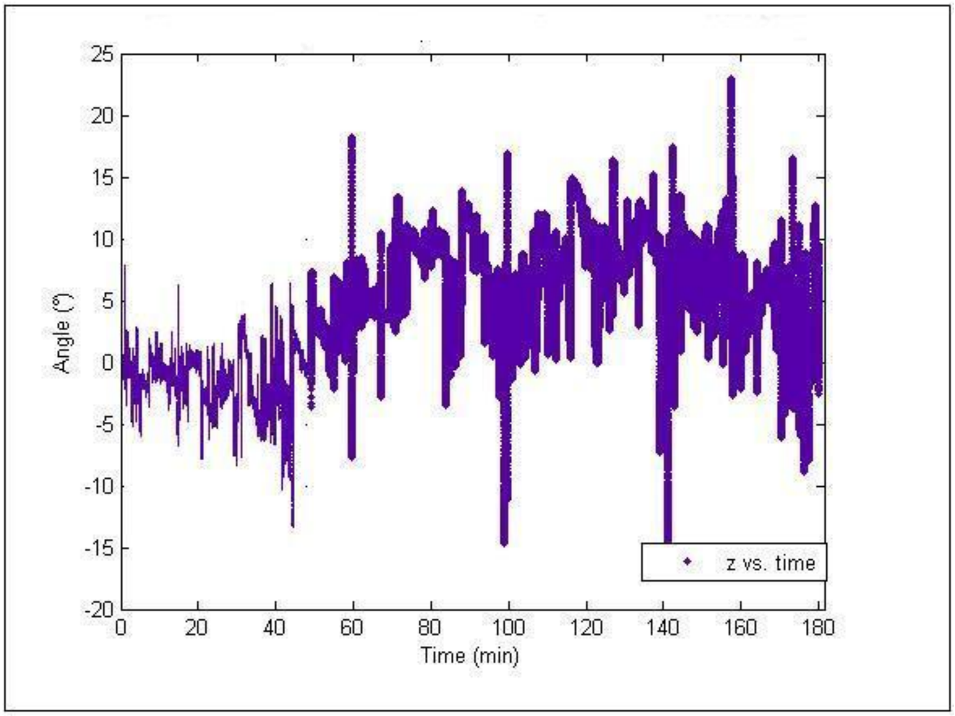
Graphs 7.4.51 to 7.4.53 show the 3 dimensional lumbar spinal angles (inclusive of angles during movements) for P17 over the 3 hour desk work activity period. The angles were calculated by taking upright standing as the reference/neutral posture.



Graph 7.4.51: Axial rotation angles of Participant 17 with respect to upright standing during 3 hours of desk work activities (inclusive of movement angles)



Graph 7.4.52: Flexion/extension angles of Participant 17 during 3 hours of desk work activities (inclusive of movement angles)



Graph 7.4.53: Lateral flexion angles of Participant 17 during 3 hours of desk work activities (inclusive of movement angles)

Participant 17 experienced decreased ranges (>2°) in all 6 physiological movements after 3 hours of desk work. These changes in range could be due to the postural behaviour of P17 over the 3 hour data collection period. Even though P17 had an initial lumbar curvature of 28° in standing, P17 sat with an average flexed lumbar curvature of 17° (a mean of 47° flexed from standing) during static sitting. Participant 17 also did not engage in any dynamic activities during the 3 hour period, but spent 40.68 minutes on postural adjustment movements, which occurred more than 3 times of postural change movements. The flexed posture and lacked of activity in the 3 hours of desk work might have loaded the lumbar spine of P17 with static stress thus resulting a decrease in mobility.

7.5 Discussion

7.5.1 Physiological movements before and after a 3 hour desk work period

In the current study, a comprehensive analysis of 3 dimensional spinal posture and motion of 18 desk workers in a normal daily working environment was undertaken.

From the results of this study, inertial measurement systems have been shown to be feasible for use in long term 3 dimensional spinal posture and motion measurement outside the laboratory. Although the same set up and methods were used in measuring the ranges of 6 physiological movements in the current study and in the previous study as reported in Chapter 6, the ranges of the 6 physiological movements measured in this current study were slightly lower as shown in Table 7.5.1. The ranges of physiological movements of Chapter 6 were from results measured by inertial measurement systems; and the ranges of physiological movements for the current study that are compiled in Table 7.5.1 were data taken before 3 hours of desk work.

	Ranges of physiological movements (°)					
	Flexion	**Extension**	**Right lateral bend**	**Left lateral bend**	**Right axial rotation**	**Left axial rotation**
Current study Inertial measurement system	48.6	22.9	20.0	21.0	10.5	11.1
Chapter 6 Inertial measurement system	56.6	26.2	27.3	26.6	14.2	16.1
Pearcy et al. (1985) Biplanar radiography	51.0	16.0	18.0	17.0	5.0	4.0
Hindle et al. (1990) electromagnetic tracking system	69.4	24.6	28.3	28.3	14.7	14.7
Russell et al. (1993) electromagnetic tracking system	70.8	25.0	27.1	27.1	15.3	15.3
Peach et al. (1998) electromagnetic tracking system	71.6	-	29.7	30.8	16.6	15.6
Van Herp et al. (2000) electromagnetic tracking system	56.9	28.2	25.5	25.9	15.7	14.0
Lee and Wong (2002) electromagnetic tracking system	58.1	15.6	21.3	19.9	7.6	9.8
Lee et al. (2003) Gyroscopic system	48.6	18.7	16.3	16.3	8.9	8.4

Table 7.5.1: Comparison of ranges of physiological movements in the current study with studies reported by other authors

The lower ranges of physiological movements reported in the current study compared to those reported in Chapter 6 are probably due to the differences in participants in terms of gender, age, body structures, occupations and lifestyles, as discussed in Section 2.3 in Chapter 2. Participants in the current study had a mean age of 34.39 ± 7.94 years, while participants in Chapter 6 on average were about 6 years younger, with a mean age of 28.23 ± 7.42 years. There were 78% female participants in the current study while the study reported in Chapter 6 had a better balance between the 2 genders, with 54% female and 46% male participants. In Chapter 6, 73% of participants were students, but in current study, 78% of participants were staff of the university. These 2 different groups of participants might have different lifestyles that could cause differences in their ranges of movements. It could also be due to the sample size of both studies, as they were not large enough to produce a direct comparable data set. In both studies (current and Chapter 6), measurements were not taken at the same time of the day for all the participants. However ranges of movements were compared between participants who had their data taken in the morning and those who had their data taken in the afternoon, no correlation was found in ranges of movement between these 2 groups, therefore this factor was not taken into account in the comparison of these studies. Despite the observed lower ranges in the current study, when compared to the ranges of movement reported by other authors as shown in Table 7.5.1, the current study had the most comparable results to those reported by Lee et al. (2003). This study also had a close range of flexion agreement with studies by Pearcy (1985); extension data was just slightly lower than those reported by Hindle et al. (1990) and Russell et al. (1993); and had similar range of lateral flexion with ranges reported by Pearcy (1985) and Lee and Wong (2002). This suggests that ranges of physiological movement measured in the current study were valid when compared to the ranges of movement reported in the literature.

From the results of Section 7.4.1, there were no differences in ranges of flexion and lateral flexion movements before and after 3 hours of desk work activities. However there were significant decreases in ranges of extension and axial rotation movements observed after 3 hours of desk work. As discussed in Section 2.3, Dvorak et al. (1992), Ensink et al. (1996) and Russell et al. (1992) all agreed that the ranges of movement were highest in the afternoon due to loss of intervertebral disc height, and suggested that measurement of ranges of movement should be performed in the afternoon or evening to reduce variability. However none of the 3 studies mentioned if participants' activity was monitored during the data collection period, as the rate of disc height reduction depends on the compressive load acting on the intervertebral disc as described in Section 2.4. In the current study, the time of day of data collection did not seem to be a significant factor in the magnitude or change of mobility after 3 hours of desk work as the participants were mostly sedentary during the 3 hour data collection period and their activities were being monitored throughout the study in order to relate any changes in spinal mobility with the activities performed during this period. The time for data collection for 11 participants was started between 1:30 to 2:00pm, and between 9:30 to 10:30am for the remaining 7 participants. Participants who had their data collected in the morning did not necessary show bigger changes in mobility than participants who had their data taken in the afternoon, and vice versa. Due to the small sample of male participants in the study, it was not possible to analyse if either gender group had greater changes in mobility after the 3 hour period. There was also no correlation (< 0.20) found between age or body mass index of the participants and the magnitude of change of mobility.

The changes in ranges of extension and axial rotation after 3 hours of desk work could be due to creep loading on the intervertebral discs. As discussed in Section 2.5, extension and axial rotation movements are mostly resisted by the zygapophyseal joints. Creep loading causes fluid to be expelled from the intervertebral discs, thus causing the gaps between the posterior elements of the vertebral bodies to narrow and come closer to each other. As the gaps between posterior elements are narrower, loading on the zygapophyseal joints increases and this leads to higher bending stiffness in the zygapophyseal joints (Russell et al. 1992), hence strongly resisting any extension and axial rotation movements. The range of extension could also be further reduced by the impaction of inferior articular processes with the laminae of the vertebrae below due to reduced distance between vertebral bodies (Adams et al. 2002; Bogduk 2005).

However the results of the current study are not supported by other reports on mobility differences with diurnal changes in the literature. By using inclinometers, Ensink et al. (1996) reported flexion increased significantly, by 11.1° from morning to the evening and although not significant, extension movement increased by 2.9° towards the evening. However a study carried out by Ensink et al. (1996) measured patients with chronic low back pain and only healthy participants with no back pain participated in current study; this difference may have contributed to the discrepancies in results. It was also unclear on the activity levels of the participants over the day in Ensink et al.'s (1996) study, therefore it was hard to justify if these results applied to other studies. Adams et al. (1987) reported a 5° increase in flexion over a day for 21 patients using inclinometers. However the findings of current study did not show any significant change in flexion (mean difference of 0.6°) after 3 hours of desk work. Due to the different measurement methods used, hours of monitoring, activity levels between data collection, type of participants and other factors that could affect different ranges of movement as discussed in Section 2.3, these variants could contribute to the difference between the current study and studies carried out by both Ensink et al. (1996) and Adams et al. (1987).

Russell et al. (1992) measured changes in mobility over a 24 hour period of 10 participants using electromagnetic tracking systems. Overall, Russell et al. (1992) reported a significant increase in flexion, lateral flexion and axial rotation in the afternoon when compared to measurements taken between 2:00 and 7:30am. Russell et al. (1992) explained that as the intervertebral discs lose their resistance to bending after creep loading, under this condition, the zygapophyseal joints and spinous processes work to balance the increased bending by resisting the movement and therefore they did not observe any significant changes in extension in their study. However as the intervertebral discs lose their height during creep loading, the gaps between zygapophyseal joints and between inferior articular processes and the lamina of the vertebrae below are being brought much closer to each other, even if the intervertebral discs may allow more bending after creep loading, quicker impactions between inferior articular processes and lamina and resistance in zygapophyseal joints would have shadowed this effect and provided a reduced range of extension.

From the current study, the changes in ranges of movement were probably due to loss in intervertebral disc height over the 3 hour desk working period. These changes might also be due to fatigue after prolonged sitting posture. Either would indicate a change in the biomechanical properties of the lumbar structures after 3 hours of desk work activities. As the activities of the participants were being monitored in the current study, these changes were studied with relation to all the parameters obtained during desk work activities and are further discussed in Section 7.5.4.

7.5.2 Lumbar curvature angle during standing

The standing lumbar curvature angles before and after 3 hours of desk work activities were measured and compared in the current study and no significant differences between the 2 sets of data was found. This showed that the 3 hour desk work activity did not change the standing posture of participants. Bullock-Saxton (1993) carried out a study to measure the repeatability of lumbar curvature angle in order to examine sagittal postural alignment using inclinometers. The author performed the measurement 3 times in the same day at 3 minute intervals, the procedure was repeated on 3 separate days at 4 day intervals and on a further 2 occasions after 16 and 24 months. The author found that the lumbar curvature angle was consistent and repeatable in standing for at least 2 years for normal participants. Bullock-Saxton (1993) suggested that a person's perception of a comfortable erect posture was sufficiently strong and consistent, therefore they were able to assume a similar posture repeatedly. The current study supports the findings of Bullock-Saxton (1993) in which there were no significant changes in lumbar curvature angle even after 3 hours of desk work activity, as the participants' awareness or proprioception of an upright posture did not change over time or was affected by different activities (Bullock-Saxton 1993).

When comparing the standing lumbar curvature angles measured in the current study with those in the previous study as reported in Chapter 6 and the literature as in Table 6.5.3, the current study produced an average standing lumbar curvature angle that was in close agreement with other studies which have utilised skin surface measurements (Chapter 6; Dolan et al. 1998; Ng et al. 2001; Ng et al. 2002; Mannion et al. 2004; Mannion et al. Unpublished data), but much less when compared to measurements taken using radiographic methods (Lord et al. 1997; Harrison et al. 2001; Vialle et al. 2005; Damasceno et al. 2006; Been et al. 2007). Table 6.5.3 has been re-summarised into Table 7.5.2 for easy reference.

As discussed in Section 6.5, it is impossible to directly compare lumbar curvature angles measured using skin surface techniques with radiographic data due to difference in methodologies, types of participant, age range, spinal segment levels of measurement, and the types of analysis method used. Skin surface measurements are prone to errors due to skin movement, sensor alignment and identification of anatomical landmarks; however these factors were dealt with extra care in the current study. Radiographic methods on the other hand could be subjected to errors due to variabilities with intraobserver, interobserver, analysis techniques, the standing position of the participants and the quality of radiographs.

	Lumbar curvature angle (°)	Measurement Method	Measurement Segment	Participants	No. of Sample	Gender (No)	Age range or mean (years)
Current Study	30.4 ± 10.9	Inertial measurement systems	L1-S1 spinous processes	Healthy	18	M4, F14	20 - 44
Chapter 6	33.3 ± 4.8	Inertial measurement systems	L1-S1 spinous processes	Healthy	26	M12, F14	21 - 43
Lord et al. (1997)	49.0 ± 15.0	Radiography	Superior endplates of L1-S1	Patients	109	M70, F39	21 - 83
Dolan et al. (1988)	31.2	Inclinometers	L1-L5 spinous processes	Healthy	11	M8, F3	25 - 59
Harrison et al. (2001)	58.6 ± 16.4	Radiography	Inferior endplate of T12 - superior endplate of S1	Patients	30	-	-
Ng et al. (2001)	24 ± 8.0	Inclinometers	T12/L1-L1/S1	Healthy	35	M35	29.9
Ng et al. (2002)	25.0 ± 8.0	Inclinometers	T12/L1-L1/S1	Healthy	15	M15	20 - 37
Mannion et al. (2004)	31.7 ± 7.3	Accelerometers (Spinal Mouse)	T12-S1 spinous processes	Healthy	20	M9, F11	41.8
Mannion et al. (unpublished data)	30.0	Electromagnetic tracking systems	L1-S1 spinous processes	Healthy	103	M64, F39	19 - 59
Vialle et al. (2005)	60.2 ± 10.3	Radiography	Superior endplates of L1-S1	Healthy	300	M190, F110	20 - 70
Damasceno et al. (2006)	60.9 ± 10.7	Radiography	Superior endplates of L1-S1	Healthy	350	M143, F207	18 - 50
Been et al. (2007)	51.0 ± 11.0	Radiography	Superior endplates of L1-S1	Patients	106	M56, F50	20 - 50

Table 7.5.2: Comparison of lumbar curvature angles from the current study with lumbar curvature angles reported in Chapter 6 and the literature

Measurements that were taken using electromagnetic tracking systems and accelerometers (including Chapter 6 and the current study) showed slightly higher lumbar curvature angles compared to the angles reported by Ng et al. (2001; 2002), this could be due to the different equipment used, and the difference in spinal segmental levels measured. Also Ng et al. (2001; 2002) only recruited male participants to their studies, which may further contribute to the difference in reported lumbar curvature angles. Therefore, it can be concluded that the method in measuring lumbar curvature angles and the results produced in the current study are valid.

7.5.3 Desk work activities

Overall, the desk workers in the current study exhibited very different postures and activity levels from one another. However, the majority of participants in the study were rather sedentary during the 3 hour period, with only 22% (4 participants) of them engaging in dynamic activities for more than 8% (15 minutes) of the 3 hour period; the most common dynamic activities among participants were taking a short walk and making drinks. All 18 participants spent at least 1.74 hours in a static sitting position, the most sedentary participant in the study spent 2.79 hours in static sitting. The time for sitting postural change movements ranged from 1.24 to 40.64 minutes, while 7.80 to 48.09 minutes were spent in postural adjustment movements in sitting.

During working in a sitting posture, participants often fidgeted or made small lumbar adjustments, on an average of every 23 seconds. The participant who had the largest number of postural adjustment movements adjusted the lumbar spine every 10 seconds on average. However during data collection with this participant, the researcher had observed that this participant spent most of the desk working time doing fast typing on a hard keyboard and noticed frequent upper body movements due to the movements of the hands. This could explain the frequent small adjustment movements observed in the results. Though these results revealed that even in static sitting with no large angle change involved, body adjustment occurred frequently. However due to the threshold of the current discriminative algorithm that included all movement signals lower than 2° as postural adjustment movements, these postural adjustment movements might involve movements due to participants' activities and working tasks such as laughing and fast typing, as well as pure adjustment for comfort. Further improvement in the discriminatory sensitivity of the algorithm will be needed in order to benefit future studies.

The number of postural change/dynamic activities occurred less frequently than postural adjustment movements, with an average occurrence every 51 seconds, with the least active participant changing posture or involved in dynamic activities with a mean of every 15 minutes and the most active participant changed posture or involved themselves in dynamic activities every 23 seconds. Fifty percent of participants were involved in less than 50 counts of gross changes in posture, while the other half of the participants engaged overall in 113 gross movements over the 3 hours of desk work, which translated to a gross movement every 1.6 minutes.

Vergara and Page (2000a) although using 6 very different types of chair in their study, only reported the results as 1 mean value for all 6 chairs. It was reported that the occurrences of macro movement (postural change of 5° and above) ranged from every 4 minutes to every 9 minutes in 4 different sitting groups. The 4 sitting groups were defined as time recorded when the participants sat away from backrest with less than 50% use of backrest; records where a backrest was used to support the whole back for about 80% of the time; records where a backrest was used to support the low back for about 80% of the time; and periods recorded when back rest was used to support the dorsal area for 50% of the time and participants adopted a slumped posture. The same participant might be involved in all the 4 groups of posture during the 6 different data collections with 6 types of chair. Due to the possible misleading comparison between the current study and the paper by Vergara and Page in 2000(a), the analysis of the current study was compared with the later paper by the same author in 2002 where the mean values were reported.

	Mean occcurrence (seconds)		Lumbar lordosis (°)	Posterior pelvic tilt (°)	
	Gross movement	Postural adjustment	Sitting	Mean	Range
Current study	156 (2.6min)	22.6	3.4	0.7	-3 to 4
Vergara and Page (2002)	342 (5.7min)	5.2	12.5	22.8	6.1 to 51.1

Table 7.5.3: Comparison between data reported by the current study and Vergara and Page (2002)

Comparing the current study with the work of Vergara and Page (2002) as shown in Table 7.5.3, Vergara and Page (2002) reported that the mean occurrence of macro movement (similar to gross movement of the current study) was at every 5.7 minutes, while the current study observed a much more frequent mean gross movement (>5°), at every 2.6 minutes. However these authors reported more frequent postural adjustment movement than the current study, at an average of every 5.2 seconds. These differences could be due to different participants recruited, and the different measurement equipment and discriminative algorithms being used. Vergara and Page (2002) discriminated between the 2 different movements by means of digital signal filters, but the current study discriminated types of movement by the use of conditions set on accelerometer and gyroscope data. Differences in working tasks and chairs used in both studies may have contributed further to the differences in both studies. Participants in the study carried out Vergara and Page (2002) were writing and reading for the whole data collection period without any dynamic activity and in a laboratory setting. However in the current study, measurements were taken in real life working conditions with multiple tasks and activities. Therefore it is not surprising that the frequency of gross movement in the current study was higher than those reported by Vergara and Page (2002). Gross movements in the current study might indicate dynamic movements, or posture changes during changes of the tasks performed. While participants in the study by Vergara and Page (2002) were seated for the whole

100 minutes with monotonous tasks, discomfort levels might rise thus producing fidgeting movements more frequently and any macro movement was in fact an effect of discomfort, as claimed by the authors (Vergara and Page 2002). Also, it was hard to conclude if these movements reported in the paper presented by Vergara and Page (2002) were due to discomfort with certain chair designs since the results provided were mean postures or movements for all 6 different types of chair.

In the current study, it was observed that the upper lumbar segment moved more frequently than the sacrum as expected, as the pelvis of participants were seated and supported by the chair while the upper body was more mobile during working tasks although it was also possible for participants to be supported by the back rest of a chair.

On average, participants spent 13 seconds in each static sitting period, with the most active participant seated in a static posture that lasted an average of 6 seconds and the most static participant seated for an average of 38 seconds before the next movement occurred. These values showed a very short mean static sitting time which concealed the true condition of this parameter. This arose due to the time threshold chosen for static sitting posture in the discriminative algorithm. In the current algorithm, as long as the possible static sitting posture lasted equal or longer than 1 second, this entry was considered as static sitting, this condition had included many counts of 1 second static sitting postures, and therefore averaging the total sitting posture duration with these 1 second sitting posture counts reduced the mean static sitting period. The current discriminative algorithm seemed to be too sensitive in discriminating between static sitting posture and sitting movement. It would be necessary to fine tune the time threshold for static sitting posture, further study would be needed to test out the level of threshold that works best for this parameter.

When compared to standing, in static sitting the lumbar spine flexed to 27° on average. The mean lateral flexion and axial rotation movements of the spine during static sitting were minimal when compared to standing. The most common lateral flexion movement was frequently coupled with flexion and rotation of the spine, during bending to the side drawer/floor to retrieve documents or objects, as shown in Figure 7.5.1.

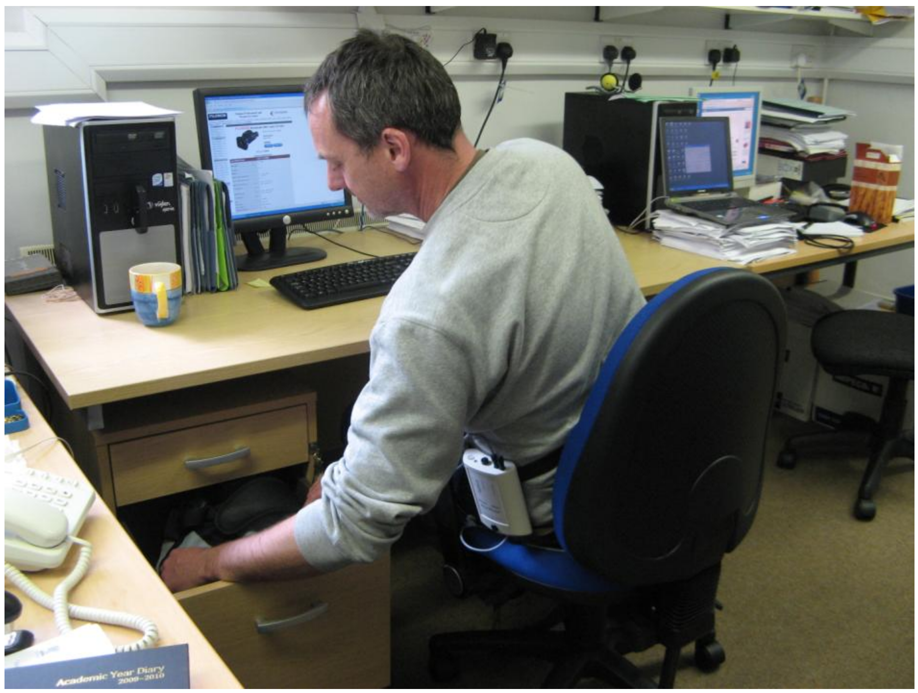


Figure 7.5.1: Illustration of the most common lateral movement of desk workers, i.e. bending to side drawer/floor to retrieve documents/objects

Due to the very different standing lumbar curvature angles of every participant, different sitting habits and tasks performed, the static sitting lumbar curvature angles varied significantly between participants. The participant who sat with the most lordotic posture maintained a mean lordotic lumbar curvature angle of 26°, while the participant who sat with the most slumped posture maintained an average of 17° of flexion of the lumbar spine, the difference between the 2 mean sitting postures of both participants was as high as 43°. When compared to the findings reported by Vergara and Page (2002), the mean sitting lumbar lordosis reported was more than 3 times higher than found in the current study (12.5° vs. 3.4°). The current study also observed a lower average posterior pelvic tilt (0.7°) during static sitting, ranging from 3° anterior to 4° posterior tilt when compared to Vergara and Page (2002), where the mean posterior pelvic tilt was reported as 22.8° (ranging from 6.1° to 51.1°), as shown in Table 7.5.3. Vergara and Page (2002) found a slight association (exact value was not provided) between lordotic lumbar posture with posterior pelvic tilt. A similar small association was also observed in the current study between the 2 parameters overall, however this relationship between the 2 parameters may not be real as this very much depends on the posture and type of chair an individual uses.

A field study carried out by Mork and Westgaard (2009) on sagittal back posture and low back muscle activity measurement of 21 female computer workers throughout a working day observed that computer workers adopted a moderately slumped posture (approximately 15° relative to unsupported upright sitting) when seated, and reported evidence of exacerbation of low back pain during seated work. The participants recruited for their study were call centre operators, help desk workers and secretaries, out of the 21 participants, 8 of them experienced low back pain. In the study, inclinometers were used to measure inclination on the T2 spinous process, the sacrum and the thigh of the participants and electromyography was used to measure levels of muscle activity. As in the current study lumbar curvature angle was measured while Mork and Westgaard (2009) on the other hand measured overall sagittal spinal angle, it is thus hard to compare the results of the 2 studies. Mork and Westgaard (2009) observed that pelvic posture influenced low back muscle activity during sitting and the low muscle activity in sitting was associated with exacerbation of low back pain. The authors suggested a dynamic back posture is assumed to be a better sitting posture.

In the current study, the angles of the lumbar spine during postural change/dynamic activities and postural adjustment movements were not quantified as the duration of each movement was short and varied a lot even within the same participant.

7.5.4 Relationship between changes in range of physiological movements and 3 hours of desk work activities

By relating all the variables during the 3 hour desk work activities with the change in mobility after 3 hours of desk work, possible weak associations (correlation coefficient of 0.20 to 0.46 and p values were between 0.057 to 0.435) were observed between changes in ranges of physiological movements and standing lumbar curvature, mean static sitting lumbar curvature, mean changes of lumbar curvature from standing to static sitting, total duration of dynamic activities, total duration and frequency of postural adjustment movement, and total occurrences of gross movement. A low lumbar curvature angle (flat or flexed back) during standing and sitting, and a larger change in angle between these 2 postures would result in decreased extension after 3 hours. Lack of dynamic movements also caused a decrease in extension ranges. As discussed in Section 2.4, a prolonged flexed posture is associated with larger fluid outflow from the intervertebral discs due to higher creep loading, and this may explain the lower range of extension when participants were seated in these conditions.

The longer time spent in postural adjustment movement and the more frequently this type of movement occurred appear to lead to a decrease in range of axial rotation. If gross movements occurred frequently, the changes in axial rotation range might be minimised. Postural adjustment movements referred to short movements between static postures that did not change postural angles by more than 2°. The mean angle change in static postures after a postural adjustment movement was between 0° to 1°. This indicated that participants were mostly seated at the same angle even after postural adjustment movements, and this may further suggest the participants engaged in a prolonged static posture. As described earlier, this would cause high loading on the intervertebral discs and result in lose of disc height. As the gap between vertebral bodies narrowed, axial rotation would be resisted further by the zygapophyseal joints.

However these associations between change of mobility and desk work parameters were weak and might not be statistically or clinically significant. Changes in lumbar spinal mobility are multifactorial and may not be predicted by just 1 or 2 parameters, although the multiple regression analysis did not show strong significant evidence between the parameters, possible weak associations might present. A study with a larger sample size and over longer hours of measurement may improve these findings. Nevertheless this study provided an insight into the sitting behaviours of desk workers in a normal daily working environment, and how their sitting habits may relate to changes in biomechanical properties of the lumbar spine that lead to change in lumbar spinal mobility.

The 3 case studies provided further detail of sitting behaviours of 3 participants, and further illustrated the relationship between sitting behaviours and changes in physiological movements after 3 hours of desk work activities.

7.6 Conclusions

Inertial measurement systems have been shown to be a valid measurement method for long term 3 dimensional spinal posture and motion measurement in a normal daily life environment outside the laboratory. They have also been shown to be suitable for monitoring postural and motion information over an extended period with minimal impact on the ability of participants to carry out their routine tasks where these are predominantly office based.

Changes in lumbar spinal mobility after 3 hours of desk work were weakly related to the desk workers' sitting behaviour, however the results suggested that there may be a relationship between the decrease in extension and axial rotation movements and lumbar curvature angles during standing and sitting, the amount of changes in lumbar curvature between standing and sitting, the duration spent in dynamic activities and postural adjustment, and the total occurrences of postural adjustment and gross movement. In short, a prolonged flexed sitting posture with little movement may aggravate the change in spinal mobility over time and a more lordosed sitting posture with dynamic movements may preserve the conditions of the lumbar spine.

Chapter 8. Overall discussion

8.1 Overview

Lumbar spinal posture and motion are important measures in order to gain understanding of how these parameters are associated with low back pain. Although there are a large number of studies into the relationships between different posture and motion with low back pain, there are limited reports of 3 dimensional spinal posture and motion measurement in normal daily life, over an extended period of time (Snuders et al. 1987; Van Riel et al. 1995; Wong and Wong 2008b; Wong and Wong 2008c). Non-continuous 2 dimensional studies performed in a constrained laboratory environment with predefined conditions and over short period of time do not fully reflect the real posture and motion of the normal population as the laboratory conditions may alter participants' performance during the study. Most of the 3 dimensional measurement tools available are expensive, not portable and unsuitable for measurements taken outside the laboratory, however inertial measurement systems can address these issues. An inertial measurement system was found to be a valid tool in spinal posture and motion measurement in this study and it was also found feasible for use in the long term measurement of normal daily working postures and movements of desk workers.

In this chapter, the outcomes of the previous chapters are discussed, together with their implications and possible applications. Limitations of the study, the contribution to knowledge and suggestion for future work are also elaborated. Finally conclusions drawn from the work in this thesis are included at the end of this chapter.

8.2 Measurement of lumbar spinal posture and motion using inertial measurement systems and possible applications

Back pain is a very common and costly disorder, however 85% to 90% of low back pain has been reported to have no pathological cause (DeFer 2004; Deyo and

Weinstein 2001; Manek and MacGregor 2005) and researchers have suggested that non-specific low back pain can be improved by adoption of proper daily postures and body mechanics (Hobbs and Aurora 1991; Scannell and McGill 2003).

There has been extensive research into the cause and prevention of low back pain, mainly focused on the load and failure mechanisms of spinal structures using cadaveric specimens, mathematical models or animal models (as discussed in Chapter 2). A number of these studies have produced contradictory findings and effective prevention of low back pain is still undefined. Thus there is a need for more studies to gain further understanding of how spinal posture and motion contribute into low back pain.

Most of the studies of spinal posture and motion measurement have been designed to take measurements either in 1 or 2 planes, over short period of time, under predefined conditions, in the constraints of a laboratory environment, or with a non-continuous measurement method. In order to gain a fuller understanding of spinal posture and motion in the normal population, it was necessary to conduct a study in a normal daily environment over an extended period of time. To achieve such a measurement study, a suitable measurement method needed to be identified. An inertial measurement system was found to be a potential tool for long term 3 dimensional spinal posture and motion measurement outside the laboratory due to its cost, size, and wireless and portable ability (as discussed in Chapter 3).

Although inertial measurement systems have been widely used in various studies of human movement, there have been limited studies carried out on spinal posture and motion measurement. Therefore there was a need to validate the system for posture and motion measurement before employing it in a study involving human participants. An inertial measurement system, Xsens was validated to be feasible for posture and motion measurement, by using the gravitational component to measure inclination; with validation of motion measurement through comparison with an established electromagnetic tracking system (Fastrak) (as discussed in Chapter 4). During the validation experiments, problems were encountered with magnetic interference between Xsens and Fastrak systems, however it was found that placing the 2 sensors as far apart from each other as possible (with a minimum of 100mm) combined with the source of Fastrak system being positioned as close as possible to the sensors, the problem was significantly reduced. However, this set up would not be feasible in human movement measurement, therefore in a later part of the study (Chapter 6) both the Xsens and Fastrak systems were used separately for the measurement of lumbar spinal motion.

As an inertial measurement system is a non-invasive in-vivo skin surface measurement method, similar to other skin surface measurements it is prone to errors due to skin movement, loose connection, and misaligned sensors (Bogduk 2005; Portek et al. 1983; Pope et al. 1986; Taylor and Twomey 1980). In order to understand how these errors affect the reliability of the results, studies were performed to identify the best sensor attachment method and the importance and impact of sensor alignment (as discussed in Chapter 5). The experiments that were reported in Chapter 5 showed that a misaligned moving sensor, even by just 5° produced large errors in the non-moving planes; however a misaligned reference sensor by as much as 15° did not seem to affect the results. This could be due to the reference sensor being stationary in this configuration and thus the rotational change remained zero even when the sensor was misaligned. However in human movement measurement, the reference sensor would not be stationary and therefore it was necessary to ensure both moving and reference sensors were aligned as close as possible to the reference plane of movement. In the later section of the same chapter, 4 different sensor attachment methods were tested and it was found that using a plastic plate on the skin as the base for sensor attachment yielded better results than direct attachment, and the security of attachment was further improved with the use of elastic straps. In Chapter 5, it was concluded that a secure sensor attachment method with well aligned sensors would minimise the common errors found in skin surface measurement.

Measurement of 3 dimensional lumbar spinal posture and motion was performed with 26 participants (in Chapter 6) in the laboratory to examine the feasibility of inertial measurement systems for these measurements. Participants were requested to perform 6 physiological movements, 6 static postures and 4 different dynamic activities. In the study, an electromagnetic tracking system (Fastrak) was again used to validate the results of the Xsens system in 6 different physiological movement measurements, where the regression analysis ($p < 0.004$), paired t-test ($p > 0.11$) and Bland and Altman (1986) (mean difference < ±1.3) analysis showed that both measurement systems were in good agreement with each other during motion measurement. The measured ranges of physiological movements in the current study were found to be in close agreement with the reported literature and this further validated the inertial measurement system in spinal motion measurement. Different physiological movements, static postures and dynamic activities were able to be identified by studying the output of the sensors. Standing and sitting were found to be harder to differentiate by just looking at the inclination angle of L1 and S1 spinous processes, however computation of the lumbar curvature angles showed the difference between standing and sitting to be significant and this was shown to be a more effective way in discriminating between these 2 postures. During dynamic activities, running was able to be differentiated from walking as the amplitude of the acceleration signal on the vertical axis during running was much higher (>1.8g) than walking (<1.1g). The peak frequency and magnitude of the frequency obtained from Fast Fourier transform (FFT) analysis was also found to be able to discriminate running (>2Hz) from walking (<2Hz). However different types of walking were not identifiable with the information available, this may be possible with an extra set of sensors monitoring the lower limb, therefore further studies need to be carried out to verify the possibility. From the study, it was concluded that the inertial measurement system (Xsens) was a valid and reliable tool for spinal studies by using gyroscopes to detect motion and accelerometers to estimate the inclination of posture.

A field study that measured and monitored 3 dimensional lumbar spinal posture and motion of 18 desk workers over 3 hours was carried out to study the sitting behaviour and its relationship to changes in spinal mobility before and after 3 hours of desk work activities (elaborated in Chapter 7). The study took place in the participants' work place. In the study, ranges of 6 physiological movements and standing lumbar curvature angle were measured before and after 3 hours of desk work activities. Participants were encouraged to perform normal desk work activities with no restriction on tasks performed. Three dimensional static sitting angles, 2 main seated movements (postural change and comfort adjustment), and dynamic activities during the 3 hours were analysed. It was found that ranges of extension, right and left axial rotation showed a significant decrease after 3 hours of desk work activities, while ranges of flexion and lateral flexions did not show any significant differences. Standing lumbar curvature angle was also found to have no difference before and/or after desk work activities. The changes in ranges of extension, right and left axial rotation could be due to a loss in intervertebral disc height during the desk work period. The relationships between these changes in spinal mobility were compared with all the monitored variables of desk work activities. The changes in lumbar spinal mobility are multifactorial, which may or may not be predicted by just 1 or 2 parameters. The analysis showed that individuals who possessed lower lumbar curvature angle during standing and sitting, with a large difference in lumbar curvature angle from standing to sitting, did not engage in much dynamic activity, with few gross movements, and/or spent more time and frequency in postural adjustment might have a higher probability of reduced mobility after 3 hours of desk work. From the study, it was also shown that inertial measurement system is feasible in long term spinal posture and motion measurement outside the laboratory setting.

From these studies, the inertial measurement system has been shown to be a powerful portable measurement system. It can provide 3 dimensional angular velocities, orientations, linear accelerations, linear velocities, positions and inclination information of the segments measured. Inertial measurement systems can be employed in various applications. In a clinical setting, inertial measurement system can be used to measure continuous 3 dimensional ranges of movements and also lumbar curvature angle and the pelvic tilt of patients. In rehabilitation, inertial measurement systems can be used to monitor spinal posture and motion of patients to assess recovery. With a proper design of sensors and a custom made waterproof casing, inertial measurement systems may also be used to monitor body posture and movement during hydrotherapy. Due to their portable features, inertial measurement systems could be useful in sport science research as they could minimise restriction of athletes' movement enabling experimentation to take place outside of the laboratory environment. The inertial measurement system could also be used as a monitoring system that could help asymptomatic individuals to improve their posture and body mechanics with a carefully studied algorithm. Other than spinal posture and motion, inertial measurements can also be used in other body segments such as head, upper limbs and lower limbs. The use of more sensors in different parts of body could provide a more complete study of human kinematics. Use of inertial measurement systems in monitoring posture and motion of different type of low back pain sufferers (acute and chronic) would provide insight into the relationship of posture and motion patterns with the type of symptoms. The system may also be useful in longitudinal study on the onset of low back pain or other symptoms related to posture and motion of body segments. It can also be used with other equipment such as electromyography and/or force platform to study the muscle activity or load of the spine or any body segment during different posture and motion. Inertial measurement systems would also be valuable in ergonomic studies or assessment in the working environment as has been shown to be viable in the current study.

8.3 Limitations of the study

In this study, the inertial measurement system used (Xsens) consisted of gyroscopes, accelerometers and magnetometers. The direction and signal of the magnetometers in the Xsens system have a tendency to distort in an area which has strong local magnetic disturbance. Although the Kalman filter used in the system is capable of correcting magnetic distortion caused by local magnetic fields (Roetenberg et al. 2005) for a short duration (20 to 30 seconds), if the sensors stay in a strong local magnetic field for a prolonged period, the direction of the magnetometers would adjust to the direction of the local magnetic field and hence cause errors in orientation estimation (De Vries et al. 2009). In Chapter 4 and Chapter 6, an electromagnetic tracking system, Fastrak was used as a reference system to validate the motion measurement of Xsens system. Due to the Fastrak system operating in an electromagnetic field generated by its own source, this system interfered with the magnetometers in the Xsens system. In order to minimise the interference, sensors of both systems have to be placed a minimum of 100mm apart with the source of the Fastrak system as near (a maximum of 50mm) to the Fastrak sensors as possible. However in spinal motion measurement this is not viable, by placing 2 sensors at least 100mm away on a spinal level would mean the sensors being placed on muscles, which could cause large errors due to skin movement and inconsistent measurement during asymmetry movement. Furthermore the source of the Fastrak system being positioned within 50mm of the sensors on the participants' spine would restrict and alter participants' movement patterns and performance. In order to compare the validity of Xsens system with Fastrak system, ideally, both systems should measure motion of the same spinal segments simultaneously, however due to the proximity issues mentioned above, in Chapter 6, the measurement of spinal motion was carried out in separate sessions by using both systems independently. This could contribute to the difference in comparison of spinal motions measured by the 2 systems, as participants are unlikely to repeat exactly the same movements each time due to motivation, tiredness, or warm up of spinal structures during measurement.

Similar to all skin surface measurements, both Xsens and Fastrak systems are prone to errors due to skin movement, loose sensor connection, problems in the identification of anatomical landmarks, and sensor misalignment. Although extra care was taken in ensuring secure sensor attachment with sensors aligned to the body reference frame as closely as possible, including using a trained physiotherapist for the identification of anatomical landmarks by palpation and ultrasound scanning. These errors were minimised but not eliminated completely, though the results from this study were found to be valid and reliable when compared to the Fastrak system and similar results reported in the literature.

Due to only 2 sensors being used on the lumbar spine, with no sensor attached to the lower limb, discrimination of more specific postures or movements was limited. In Chapter 6, although studying the signals of the lumbar spine could facilitate discrimination of 6 physiological movements, different lying postures, standing, sitting, running and walking; it wasn't possible to differentiate between level walking, or walking up or down steps. Furthermore, using lumbar curvature angles in differentiating standing and sitting seemed to be promising in Chapter 6, however this method may not be as sensitive in real life conditions as is shown in Chapter 7. By adjusting the furniture, such as leaning back to the backrest with a lumbar support, or sitting on a tilted seat, it is possible to imitate the lumbar curvature angle in standing while sitting (Bendix 1986; Mandal 1986; Occhipinti et al. 1986). However, by analysing the lumbar curvature angle together with the tilt angle of both the pelvis and L1 spinous processes would improve the discriminative algorithm for standing and sitting. Adding sensors to the legs would also provide a better discriminative analysis to differentiate different dynamic activities such as level walking, walking up and down stairs, allowing further analysis of spinal behaviour during different postures and motions.

In the field study that measured and monitored lumbar spinal posture and motion of desk workers in Chapter 7, the measurements were taken with participants working in their own workplace, with their own adjusted furniture. Furniture such as the desk and chair types were not controlled, although all participants were staff and students of the same university and thus using mostly standardised furniture, 17% of participants had different desk types than the rest of the participants as shown in Section 7.5.3. The chair adjustments were different from participant to participant, as some might have a more inclined back rest while others less inclination; some preferred higher seat heights and some had adjusted to lower; and some participants used a foot rest or armrests while others did not. These differences in furniture might cause different posture and motion to be adopted by participants in sitting (Bendix 1986; Mandal 1986; Occhipinti et al. 1986) reducing the standardisation of the study.

Although this study set out to explore lumbar spinal posture and motion of desk workers in general, different types of desk workers have different job descriptions, and each job description might require the desk worker to engage in different working tasks. For instance, administrative staff might need to spend most of their working time in dealing with paperwork, filing, making and answering telephone calls; while research staff might spent more times in static sitting in front of their computer to do read and/or type. As this study was to monitor normal daily desk work activities, the protocols did not restrict participants to only certain tasks but encouraged participants to perform their normal daily activities as usual. Therefore, the working tasks of each participant were not controlled, and they were different from participant to participant. However this might also contribute to differences in sitting behaviour as different tasks performed would initiate different posture and motion.   Yet the current study has provided an insight into the working patterns and sitting behaviours of desk workers in a university environment. Future research can be improved by studying a more specific group, such as monitoring workers who have similar job descriptions and work tasks in the same company or institute that uses standardised furniture and an ergonomic assessment programme, this may provide a more controlled study with a more normalised findings.

The discriminative algorithm used in the field study (Chapter 7) was found to be too sensitive especially in the condition where static sitting posture was included. As the current time threshold for static sitting was set to 1 second, there were many 1 second data sets included in the static sitting group of information and hence distorted the overall results and impact of this parameter. Further study is needed to further fine tune the appropriate threshold for the discrimination of static sitting posture from sitting movement. The discriminative algorithm used in the study was also found to be time consuming and could be subjected to human error as the current method required visual inspection of 1 minute plotted raw data to ensure the algorithm did not over or mis-detect any activity. A more sophisticated method such as frequency filtering may improve the discriminative algorithm. Before the use of such method, it is necessary to study the frequency components of different postures and motions in order to produce a more robust discriminative system.

During the field study, the researcher was present for the whole 3 hours of data collection time to ensure smooth data collection and to note unusual events, although the researcher was making every effort not to disturb or affect participants' daily work, a study that could eliminate the presence of the researcher may yield a better or more natural environment for the participants. This can be achieved with a more robust posture and motion discriminative algorithm, which can differentiate different postures and motions with high accuracy.

The sample size for the field study that monitored spinal posture and motion of desk workers was not large, and the period of monitoring was only for 3 hours. A larger scale study for a longer period of time may yield a stronger relationship between working and sitting behaviours and changes in spinal mobility.

Another limitation of the field study was the sensor attachment. Although the current sensor attachment method was found to be secure even for half a day of measurement, as the sensor that attached to the sacrum of participants was strapped around participants' lower waist, there was a possibility that the sensor would be moved with high waist clothing and also during bathroom breaks. In the current study, the researcher checked the sensor attachment and alignment after participants had taken a bathroom break. However an improved method of attachment would further benefit long term measurement, especially one without the presence of the researcher during data collection.

8.4 Contribution to knowledge

The results of this study have validated inertial measurement system as a feasible and reliable measurement tool in 3 dimensional spinal posture and motion measurement. The study has also shown that inertial measurement systems can be used in a normal daily environment for an extended period of time. With these features, inertial measurement systems provide a much wider research opportunity than has been previously available.

It was found that accurate alignment of sensors coupled with secure attachment is imperative in ensuring the reliability and accuracy of the results when measurements are made using skin surface measurement systems.

The findings of this study suggest that with just 2 sensors attached to the lumbar spine, an appropriate discriminative algorithm can enable discrimination of different spinal postures, motions and dynamic activities.

This study has shown inertial measurement systems to be a feasible and valid method for continuous lumbar curvature angle and lateral lumbar tilt measurement; the system also provides inclination information of separate body segments, such as the inclinations of L1 spinous process and the pelvis.

The study has also shown how different desk work activities may affect spinal mobility in the short term. Possible relationships between sitting behaviours and changes in physiological movements have been established.

8.5 Suggestions for future work

Due to the versatility of inertial measurement systems in continuous 3 dimensional portable inclination and motion measurement, such systems have good potential for human kinematic studies. The main areas for future work enabled and emphasized by this study are summarised below.

1. Developing smaller and wireless inertial measurement systems for spinal posture and motion measurement. The inertial measurement system used in current study although portable, require a separate computer to be set up for data transmission and storage, the sensors are rather big and there are wires running from sensors to the transmission unit. Current MEMS technology has been used by electronics manufacturers to develop triaxial accelerometers and biaxial gyroscopes in single microchips, these could enable the design of smaller sensors. By incorporating micro-SD storage and an internal battery pack, a wireless device for remote real time analysis in a single unit could be develop to eliminate the need for wires and computer set ups in the measurement environment. This could enable the improvement of the security of sensor attachment, the comfort of participants and allow the absence of the researcher during data collection.

2. Develop and examine the feasibility and validity of an inertial measurement system using multiaxial accelerometer (6 to 12 axes), without the use of gyroscopes for spinal posture and motion measurement. As it was discussed in Section 3.3, gyroscopes suffer from drift over time, an inertial measurement system without gyroscope may address this issue, however the validity and feasibility of this system has not currently been further studied.

3. Developing a robust posture, motion and activities discriminative algorithm. The current study identified the main characteristics of different postures, motions and dynamic activities; however the validity in discrimination was not tested with a large sample size. It is also necessary to improve the current discriminative algorithm for static sitting posture and sitting movements. With an effective discriminative algorithm, the researcher would not be required to be present during the field work and this could encourage more natural behaviours in the participants.

4. Carry out further field studies of spinal posture and motion patterns of specific groups of desk workers with a larger sample size. As discussed earlier in Section 8.3, different job descriptions and tasks could subject different desk workers to various working patterns. A controlled study of specific groups can provide a better understanding of the types of tasks that affect different posture and motion patterns, and how these patterns affect the biomechanical properties of the spine. A longer period of monitoring (e.g. 1 whole working day, or a week) would also provide stronger results as some workers perform different tasks at different times of the day.

5. Study the differences in spinal posture and motion patterns of healthy desk workers and desk workers with low back pain, and between desk workers with different types or grades of low back pain (acute and chronic, non-specific and pathological back pain). Studying the differences between these groups of participants could provide insight into the differences in working patterns and this could possibly lead to effective prevention strategies.

6. Perform a longitudinal study (e.g. 3 to 6 months) of the spinal posture and motion patterns in order to monitor onsets and/or recovery of low back

pain. To monitor the postural behaviour of adolescents and/or elderly who do or do not suffer low back pain in order to gain further understanding in the postural differences and the relation to aging of the spinal structures of these groups.

7. Similar studies can be employed in other occupations, or used to compare the spinal posture and motion patterns between occupations, environments, age groups, or genders.

8.6 Conclusions

This study has examined the feasibility and validity of inertial measurement systems in spinal posture and motion measurement. The inertial measurement system has been shown to be valid for motion measurement when compared to an electromagnetic tracking system.

Skin surface measurement methods are mostly prone to errors due to skin movement, loose sensor attachment and misaligned sensors. It is important to ensure that sensors are aligned and securely attached as the study showed that the influence of these factors could cause significant errors in measurement results, which would in turn impair the reliability of the study.

With just 2 sensors on the lumbar spine, 6 different physiological movements (flexion, extension, lateral flexion and axial rotation to both sides), 6 different static postures (standing, sitting, supine, prone, left and right side lying) and 2 different dynamic activities (running and walking) can be identified by using the data from the inertial measurement systems. However further work is required on the discriminatory algorithm to improve the reliability of the identification.

The field study that measured and monitored spinal posture and motion patterns of desk workers has provided comprehensive descriptions of the normal spinal posture and motion patterns of these participants over a period of 3 hours. The findings suggested that different sitting behaviours may result in a change in spinal mobility. Significant changes in physiological movements after 3 hours of desk work were found in extension and axial rotation movements. The factors that might affect changes in spinal mobility included standing lumbar curvature angles, mean adopted lumbar curvature angle during static sitting, the average change in lumbar curvature from standing to static sitting, total time spent in engaging dynamic activities, total time spent in postural adjustment movements, number of occurrences of postural adjustment movements, and the number of occurrences of gross movements. Although the association between these parameters were not strong and might not be statistically and clinically significant (noting the relatively small sample size), it provided further understanding on how sitting behaviour may possibly affect the kinematics and functionality of the lumbar structures. The observations of the current study were in agreement with the literature that a prolonged flexed posture with lack of dynamic movements might cause loss in intervertebral disc heights thus resulting in decrease in ranges of extension and axial rotation movements.

The study has shown inertial measurement systems provide an advantageous, valid and reliable measurement method in studying posture and motion patterns and the use of this method can be applied in various applications, which will enable research into a more realistic measurement of the normal population in everyday life.

In conclusion, this study has shown that inertial measurement systems that consist of triaxial accelerometers, gyroscopes and magnetometers are valid and reliable in providing 3 dimensional continuous inclination and motion measurements inside or outside the laboratory environment over an extended period of time, and that there may be a relationship between the changes in spinal mobility over a period of office based work and the lumbar curvature angle during standing and sitting, the changes in lumbar curvature angle between standing and sitting, the time spent in dynamic activities and postural adjustment, and total occurrences of postural adjustment and gross movement during that period.

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Glossary

Accuracy	Agreement between a measured values and the true value
Coriolis effect	An effect when a moving object in a rotating reference frame experiences the Coriolis force acting perpendicular to the direction of movement and to the axis of rotation; on Earth the Coriolis effect deflects moving objects to the right in the northern hemisphere and to the left in the southern hemisphere
Lumbar lordosis	Inward curve of the lumbar spine
Feasibility	Capable of being accomplished or brought about
Kyphosis	Rounding of the lordotic posture, as seen in flexed posture
Parallax	The apparent displacement or change in orientation of an object when viewed from 2 different positions
Proprioception	The sense of the relative position or movement of body parts by stimuli arises within the body
Precession	A change in direction of a rotation axis
Reliability	To which a test is repeatable and yields consistent scores
Stature	Height of an individual in an upright position
Validity	The extent to which a test measures what it is supposed to measure

List of Abbreviations

ASIS	Anterior Superior Iliac Spine
AF	After
BF	Before
BMI	Body Mass Index
C1	First cervical vertebra
FFT	Fast Fourier Transform
INS	Inertial Navigation Systems
L1	First lumbar vertebra
LC	Lumbar Curvature
LED	Light Emitting Diode
LF	Lateral Flexion
MATLAB	Matrix Laboratory (software)
MEMS	Micro-Electromechanical Systems
P1	Participant 1
PSIS	Posterior Superior Iliac Spine
RMS	Root Mean Square
RPM	Revolution Per Minute
S1	First sacral vertebra
SD	Secure Digital (non-volatile memory)
SPSS	Statistical Package for the Social Sciences (software)
T1	First thoracic vertebra
WHO	World Health Organisation
Wi-Fi	Wireless Fidelity

Appendices

A1.1a Letter of Ethics and Governance approval for "Measurement of spinal posture and motion" (Chapter 6)

Faculty of Health

University of Brighton

Direct line 01273 644763

Tshui Hung Ha
Human Movement Laboratory
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8th March 2007

Dear Ha

Ethics & Governance Approval

We are writing to confirm that you have completed all the actions and procedures required by the Faculty of Health Research Ethics and Governance Committee and work on your research entitled 'Measurement of Spinal Posture and Motion Using Inertial Sensors' may commence.

The committee is interested in the results of studies that it has approved, and on completion of your research a brief summary of the conclusion should be submitted to FREGC (administrator).

Yours sincerely

Jayne Hughes

Ms Marion Trew - Dean
MSc, BA, MCSP, DipTP
Chair of Faculty of Health Research Ethics Committee

A1.1b Letter of Ethics and Governance approval for “Study to monitor spinal posture and motion of desk workers” (Chapter 7)

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Direct line 01273 644763

Tshui Hung Ha
Human Movement Laboratory
University of Brighton
Robert Dodd Annex
Eastbourne

19 February 2009

Dear Ha

Title of Proposal: 07/08a
FREGC Application Number: Measurement of Spinal Posture and Motion Using Inertial Sensors

We are writing to confirm that the above-mentioned proposal amendment has been approved by the Research Ethics and Governance Committee of the Faculty of Health and Social Science (FREGC) after an independent scientific and ethics review.

Although approval has been given to start the research work, it is the ultimate responsibility of the researchers to ensure that the work is conducted within the Research Ethics and Governance Framework of the University of Brighton, and if applicable, those of the Department of Health and any funding body. Approval of project is given for the duration of the research indicated in the application form, although FREGC may review this decision at any time and has the right to suspend or terminate this approval.

You are required to notify the Committee in writing if there any substantial changes in the research methodology or any serious adverse events or accidents during the conduct of the study. As a requirement of the Governance Framework, please submit annual progress and completion reports to the Committee. You may not be need to prepare a separate progress report for the Committee as we would be happy to receive a copy of annual report submitted to funding body, NHS or other relevant body to satisfy this requirement. Please see the Guidance Notes of the Application Pack (Section 7) for further information.

Yours sincerely

Professor Julie Scholes PhD
Chair of Faculty of Health Research Ethics & Governance Committee

A1.2a Recruitment poster for “Measurement of spinal posture and motion” (Chapter 6)

Are you interested in having your spinal posture and motion measured?

 You are invited to participate in a research  that measures posture

 and motion  of the back by using miniature motion sensors.

If you are 

- 20-44 years old
- Healthy and have never experience any low back pain in the past, or
- Healthy and experienced low back pain in the past but not requiring any medical attention
- Willing to participate in this research study at Eastbourne campus
- Interested in finding out more details about this study

Please contact TH Ha by

Email: T.H.Ha@brighton.ac.uk

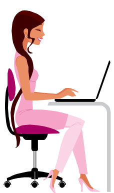
Tel: 01273-644166

Thank you very much for you attention.

A1.2b Recruitment poster for "Study to monitor spinal posture and motion of desk workers" (Chapter 7)

Do you always spend hours working on a desk or in front of a computer?

You are invited to participate in a research that measure and monitor spinal posture and motion of healthy desk workers by using miniature motion sensors.



Data collection will be set up in your workplace, i.e. you can work as usual throughout the study.

- 20-44 years old
- A desk worker
- Healthy and have never experience any low back pain in the past, or experienced low back pain in the past but not requiring any medical attention
- Willing to participate in this research study at Eastbourne campus
- Interested in finding out more details about this study

Please contact TH Ha by
Email: T.H.Ha@brighton.ac.uk
Tel: 01273-644166

Thank you very much for you attention.

A1.3a Information sheet for "Measurement of spinal posture and motion" (Chapter 6)

Measurement of Spinal Posture and Motion Using Inertial Sensors

Participant Information Sheet

You are invited to participate in a research programme that measures posture and motion of the trunk by using miniature motion sensors. The main objective of this research is to examine the feasibility of measuring trunk posture and movement using miniature motion sensors.

This research will be conducted by TH Ha (research student), Professor Ann Moore (Director of the Clinical Research Centre for Health Professions), Dr. Kambiz Saber-Sheikh (Research officer) and Dr. Mark Jones (Head of Collaborative Training Centre) at the University of Brighton. This research has been reviewed and approved by the University of Brighton's ethics and governance committee.

23 healthy participants (aged 20-44 years) will be recruited for this study. If you agree to take part in this study, you will be requested to answer a few questions and sign a consent form. Before the study takes place, your body weight, height and leg length will be measured.

In this study, two motion sensors will be attached to your trunk; these sensors will be attached using hypoallergenic double sided tapes. There will be a certain level of undress required as we need to attach the sensors onto the skin. Any level of undress will be carried out in a private area.

You will be required to perform some postures (standing, sitting, lying on your back, lying on your stomach and lying on both sides), some movements of your trunk (forward and backward bending, side bending and twisting), walking and running on level ground, walking up and down stairs. The researcher will demonstrate the movements and show you how they should be carried out. The movement procedure will be repeated using two different measurement methods. The whole data collection process will take approximately 1 hour.

The measurement procedures will be held in the Human Movement Laboratory in the Robert Dodd Annexe 1 building, in the University of Brighton at Darley Road, Eastbourne.

You should not experience any pain or discomfort during these measurements and there is no known risk associated with this research. Participation in this research is entirely voluntary. You are not obliged to participate, and if you agree to participate, you can withdraw at any time without giving a reason and without penalty or prejudice. Unfortunately we have no funding to reimburse any travel expenses.

All aspects of this research including the participant's personal information and study results will be strictly confidential and only the researchers named above will have access to this information. Participants will have the right to request access to own personal data or their performance in the study. A report of the study may be submitted for publication in international journals, but individual participants will not be identifiable in any such report.

The procedure will be explained to you clearly by the researcher. If you have any questions or concerns at any stage, please feel free to contact TH Ha, research student of the University of Brighton at 01273-644166 or email T.H.Ha@brighton.ac.uk

If you have any complaint about the conduct of this study at any time, please contact Professor Ann Moore, Director of the Clinical Research Centre for Health Professions, University of Brighton, Aldro Building, 49 Darley Road, Eastbourne, BN20 7UR. Tel: 01273-643647 or email a.p.moore@brighton.ac.uk

This information sheet is for you to keep. Thank you for your participation.

A1.3b Information sheet for "Study to monitor spinal posture and motion of desk workers" (Chapter 7)

Measurement of Spinal Posture and Motion Using Inertial Sensors – Study to monitor spinal posture and motion of desk workers

Participant Information Sheet

You are invited to participate in a research programme that measures posture and motion of the spine by using miniature motion sensors (inertial sensors). The purposes of this study are to look at the feasibility of using portable inertial sensors to monitor the patterns of spinal posture and motion of healthy desk workers in order to obtain an understanding on how posture and motion patterns affect the way the spine functions.

This research will be conducted by TH Ha (research student), Professor Ann Moore (Director Clinical Research Centre for Health Processions), Dr. Mark Jones (Head of Collaborative Training Centre) and Dr. Kambiz Saber-Sheikh (Research Officer) at the University of Brighton. This research has been reviewed and approved by the University of Brighton Faculty of Health and Social Science Research Ethics and Governance Committee.

If you agree to take part in this research, you will be invited to attend the Human Movement Laboratory in the Robert Dodd Annexe 1 building, in the University of Brighton at Darley Road, Eastbourne. Initially, you will be requested to answer a few questions about your health history (if there is any history of back pain or leg pain in the past; any difficulty or limitation in performing daily activities; any disorders or previous injury that could be related to the spine; to rule out spinal problem that may affect the measurement results) and sign a consent form. At the start of the study, the researcher, TH Ha will measure you body weight, height and lower leg length. Following this, two small inertial sensors (38x53x21mm) will be attached to your lower spine by using non-allergic double sided tapes and secured with Velcro straps. There will be a minimal level of undress required in order to attach the sensors to your spine. Any level of undress will be carried out in a private area. The sensors once attached will remain in place underneath your clothing.

After the sensors are attached, you will be asked to return to your workplace, accompanied by the researcher, TH Ha, to resume your desk work. A laptop will be set up by the researcher at your workplace for data logging. You are encouraged to perform all your normal work activities as usual. The data collection will take 3 hours and the researcher will be present for the 3 hour period in order to ensure data collection runs smoothly. Every effort will be undertaken to ensure that your working patterns will not be disturbed by either the equipment or the researcher. Rest assured you will not be restricted in your movement (i.e. not restricted to your seat) for the whole 3 hour period; the researcher will keep a log on your activities. You will not be required to return to the Human Movement Laboratory after the 3 hour data collection period. You will also be requested to perform some spinal movements (forward and backward bending, side bending and twisting) before and after the 3 hour period of desk work in order to compare the mobility of your spine.

You should experience no pain or discomfort during these measurements. There is no known risk associated with this research. Participation in this research is entirely voluntary. You are not obliged to participate, and if you agree to participate, you can withdraw at any time without penalty or prejudice. Unfortunately we have no funding to reimburse any travel expenses.

All aspects of this research including your personal information and study results will be strictly confidential and only the researchers named above will have access to this information. You will have the right to request access to your own personal data. A report of the study may be submitted for publication in international journals, but individual participants will not be identifiable in any such report.

The procedure will be explained to you clearly. If you have any questions or concerns at any stage, please feel free to contact TH Ha, research student of the University of Brighton at 01273-644166 or email T.H.Ha@brighton.ac.uk. If you have any concern or complaint about the conduct of this study at any time, please contact Professor Ann Moore, Director of the Clinical Research Centre for Health Professions, University of Brighton, Aldro Building, 49 Darley Road, Eastbourne, BN20 7UR. Tel: 01273-643647 or email a.p.moore@brighton.ac.uk. This information sheet is for you to keep. Thank you for your participation.

A1.4a Consent form for "Measurement of spinal posture and motion" (Chapter 6)

Measurement of Spinal Posture and Motion Using Inertial Sensors

Participant Consent Form

- I agree to take part in this research which is to measure trunk posture and movements by using motion sensors.

- The researcher has explained to my satisfaction the purpose of the study and the possible risks involved.

- I have had the principles and the procedure explained to me and I have also read the information sheet. I understand the principles and procedures fully.

- I am aware that I will be required to answer some questions, have my height, weight and leg length measured, have 2 motion sensors attached to my trunk and will be asked to perform some postures, movements and activities that I usually perform in my normal everyday life.

- I understand that any confidential information will be seen only by the researchers and will not be revealed to anyone else.

- I understand that I am free to withdraw from the investigation at any time.

- I agree that if I do decide to withdraw from the study, the researcher may use any information supplied by myself up to that point.

Name (please print) ……………………………………………………………………..

Signed ………………………………………………………………………

Date ………………………………………………………………………

A1.4b Consent form for “Study to monitor spinal posture and motion of desk workers” (Chapter 7)

Measurement of Spinal Posture and Motion Using Inertial Sensors

Participant Consent Form

- I agree to take part in this research which is to measure spinal postures and movements using inertial sensors.

- The researcher has explained to my satisfaction the purpose of the study and the possible risks involved.

- I have had the principles and the procedure explained to me and I have also read the information sheet. I understand the principles and procedures fully.

- I am aware that I will be required to answer some questions, have my height, weight and lower leg length measured, have 2 inertial sensors attached to my spine, and will be asked to perform some spinal movements. I am also aware that my movements and posture during activities that I usually perform in my normal working environment will be monitored for 3 hours and that the researcher will be present throughout.

- I understand that any confidential information will be seen only by the researchers and will not be revealed to anyone else.

- I understand that I am free to withdraw from the investigation at any time.

- I agree that if I do decide to withdraw from the study, the researcher may use any information supplied by myself up to that point.

Name (please print) ....

Signed ....

Date ....

A1.5 Participant information form

Measurement of Spinal Posture and Motion Using Inertial Sensors

Participant's Information Form

Name	:	________________________________	
Participant No	:	________________________________	
Age	:	________________________________	
Gender	:	________________________________	
Height	:	________________________________	M
Weight	:	________________________________	KG
BMI	:	________________________________	KG/M^2
Left Leg Length	:	________________________________	M
Right Leg Length	:	________________________________	M
Difference	:	________________________________	M

Have you suffered any history of back pain or leg pain that required medical attention/treatment in the past 12 months?	Yes / No
Do you have any difficulties and limitations in performing daily physical activity?	Yes / No
Are you pregnant?	Yes / No
Do you suffer any known musculoskeletal disorders; joint dislocation; cancer; asthma; any neurological or orthopaedic disorders; rheumatoid arthritis; coronary heart diseases?	Yes / No
Do you have any abnormality in spinal structure; previous injury, surgery, infection, bone fracture or dislocation, or diseases related to the spine?	Yes / No
Do you have any allergy or hypersensitive to adhesive tapes?	Yes / No

Notes:____

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to	tshuihung@gmail.com
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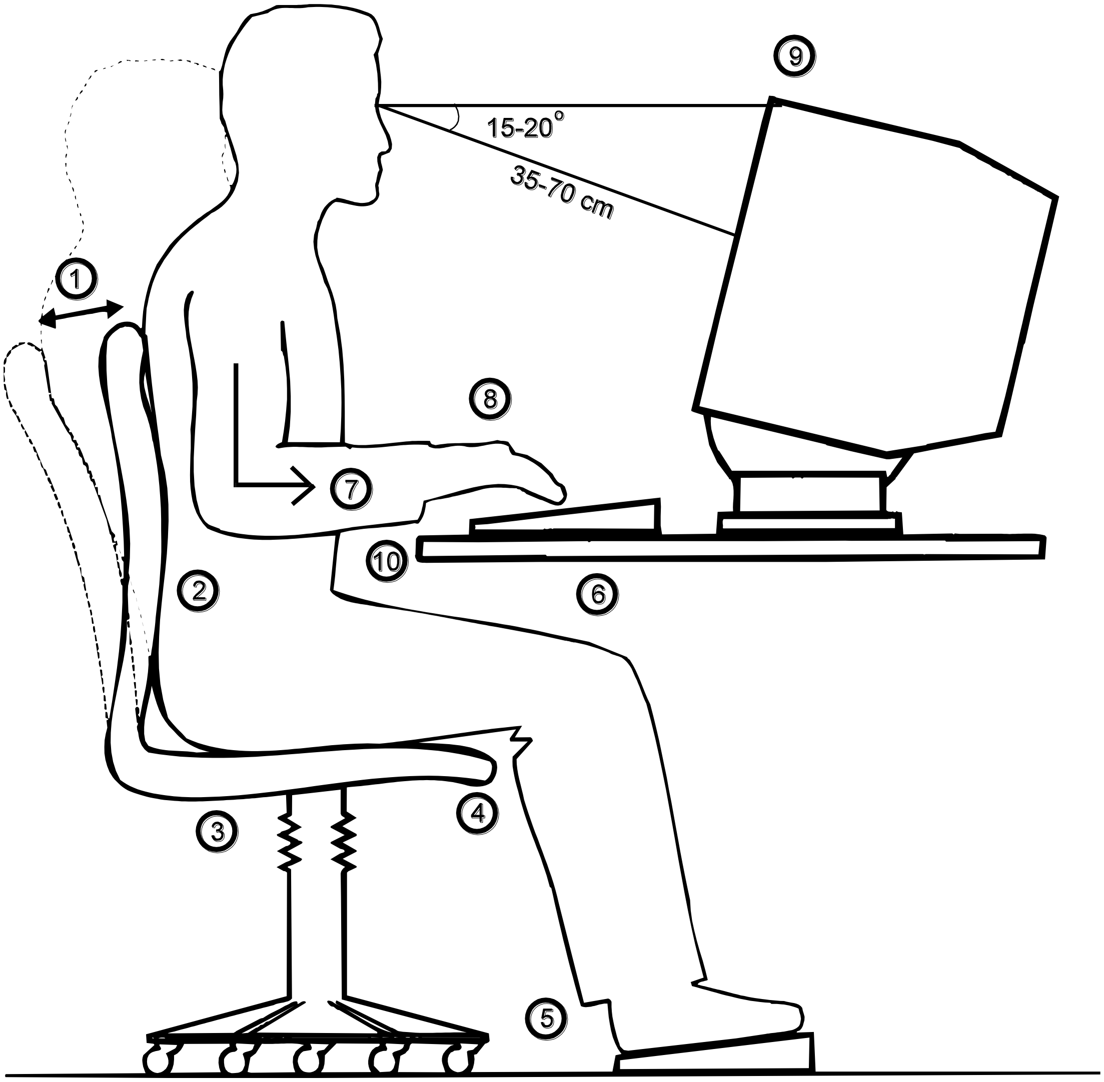


SEATING AND POSTURE

1 Seat back adjustability
2 Good lumbar support
3 Seat height adjustability
4 No excess pressure on underside of thighs and backs of knees
5 Foot support if needed
6 Space for postural change, no obstacles under desk
7 Forearms approximately horizontal
8 Minimal extension, flexion or deviation of wrists
9 Screen height and angle to allow comfortable head position
10 Space in front of keyboard to support hands/wrists during pauses in keying

A2 Raw results for "Measurement of spinal posture and motion" (Chapter 6)

Physiological movements

Table A2.1 Ranges of flexion for all 26 participants measured by both Fastrak and Xsens systems (bold = main movement plane)

ROM	Flexion (Fastrak)			Flexion (Xsens)		
Participants	FX	**FY**	FZ	XX	**XY**	XZ
P1	3.1	**66.7**	-7.3	-4.1	**69.1**	-3.4
P2	3.2	**53.2**	8.4	4.8	**53.8**	-6.9
P3	4.4	**68.9**	-4.8	6.5	**70.7**	-8.0
P4	2.7	**52.9**	-3.9	3.1	**55.3**	-2.7
P5	3.2	**57.9**	-4.2	-4.4	**58.9**	-4.8
P6	-3.6	**53.0**	-1.4	4.9	**42.7**	-11.8
P8	2.0	**44.6**	-3.4	3.6	**46.9**	2.7
P9	1.0	**58.0**	2.8	-6.4	**53.6**	3.2
P10	1.3	**47.0**	1.3	-4.8	**47.7**	6.3
P11	-2.5	**56.5**	-1.7	-4.9	**54.2**	-2.4
P12	6.7	**62.6**	-5.0	-8.1	**59.2**	-9.3
P13	-6.6	**51.3**	6.6	-3.7	**50.4**	3.5
P15	3.3	**53.2**	-2.2	-4.0	**50.0**	-3.4
P17	-3.1	**49.9**	4.2	-5.2	**48.6**	4.3
P18	-10.8	**62.1**	10.9	7.8	**61.8**	4.7
P20	4.6	**56.3**	-1.9	5.7	**63.1**	-7.3
P21	3.7	**68.9**	-7.4	3.4	**69.5**	-2.4
P22	3.9	**49.7**	-6.4	-7.9	**48.3**	-5.6
P23	-3.3	**63.2**	-2.9	-4.8	**64.2**	-2.4
P24	-11.8	**75.6**	12.2	-3.5	**71.3**	2.2
P25	2.3	**60.8**	-3.0	3.7	**62.5**	8.8
P26	6.2	**61.4**	-6.3	1.4	**64.1**	2.7
P27	2.6	**48.0**	-3.9	-4.5	**56.3**	5.7
P28	3.8	**58.2**	-4.8	-4.3	**62.9**	4.5
P29	-4.2	**52.6**	10.9	2.6	**46.9**	3.7
P30	1.0	**46.8**	-1.7	3.1	**40.0**	3.7
Minimum	-11.8	**44.6**	-7.4	-8.1	**40.0**	-11.8
Maximum	6.7	**75.6**	12.2	7.8	**71.3**	8.8
Mean	0.5	**56.9**	-0.6	-0.8	**56.6**	-0.6
Stand. deviation	4.8	**7.8**	5.9	5.0	**8.9**	5.5

Table A2.2 Ranges of extension for all 26 participants measured by both Fastrak and Xsens systems (bold = main movement plane)

ROM	Extension (Fastrak)			Extension (Xsens)		
Participants	FX	**FY**	FZ	XX	**XY**	XZ
P1	-3.2	**-33.8**	-2.1	-3.4	**-29.2**	-3.9
P2	-1.6	**-24.7**	-1.9	-2.6	**-26.7**	2.2
P3	1.9	**-24.0**	1.0	-2.1	**-24.9**	8.0
P4	3.5	**-23.0**	1.8	1.7	**-27.5**	5.0
P5	-3.0	**-16.5**	-2.1	-3.6	**-19.0**	-1.3
P6	1.4	**-19.2**	0.7	-1.7	**-19.9**	-1.8
P8	0.8	**-33.6**	1.5	-2.8	**-33.3**	-2.2
P9	-1.7	**-19.8**	-2.9	3.8	**-19.5**	-2.3
P10	1.7	**-16.5**	0.8	2.6	**-32.5**	-2.2
P11	1.8	**-27.6**	-2.3	-2.4	**-28.3**	-0.8
P12	-2.6	**-21.8**	-0.9	-1.3	**-16.7**	1.5
P13	1.5	**-30.3**	-1.8	2.7	**-33.4**	4.0
P15	-1.6	**-14.4**	-1.7	-2.7	**-15.4**	2.8
P17	2.6	**-33.6**	-4.0	-3.1	**-31.7**	-3.7
P18	-5.5	**-29.6**	-2.0	-3.3	**-18.2**	2.4
P20	1.9	**-32.1**	-1.7	2.0	**-35.4**	1.7
P21	1.1	**-35.3**	1.5	-4.0	**-34.1**	2.0
P22	2.1	**-23.2**	-1.6	3.1	**-22.4**	1.6
P23	2.3	**-22.6**	3.7	-2.0	**-21.9**	2.1
P24	2.9	**-29.0**	-3.1	2.9	**-23.8**	-2.6
P25	-1.5	**-17.6**	-1.2	3.0	**-21.2**	2.7
P26	-1.1	**-30.7**	-2.2	-1.6	**-44.9**	-3.1
P27	3.6	**-52.7**	4.2	-2.3	**-37.2**	-3.4
P28	1.5	**-46.7**	-1.6	-3.3	**-28.3**	-1.2
P29	-1.9	**-27.9**	1.5	2.1	**-22.3**	4.2
P30	-1.3	**-9.0**	1.1	1.3	**-13.1**	-0.6
Minimum	-5.5	**-52.7**	-4.0	-4.0	**-44.9**	-3.9
Maximum	3.6	**-9.0**	4.2	3.8	**-13.1**	8.0
Mean	0.2	**-26.7**	-0.6	-0.6	**-26.2**	0.4
Stand. deviation	2.4	**9.6**	2.1	2.7	**7.7**	3.1

Table A2.3 Ranges of right flexion for all 26 participants measured by both Fastrak and Xsens systems (bold = main movement plane)

ROM	**Right flexion (Fastrak)**			**Right flexion (Xsens)**		
Participants	FX	FY	**FZ**	XX	XY	**XZ**
P1	-10.3	4.8	**-20.6**	4.5	8.8	**-25.6**
P2	-2.8	16.6	**-18.0**	5.6	10.7	**-21.6**
P3	-10.7	9.1	**-29.3**	6.6	11.1	**-32.5**
P4	3.7	15.1	**-22.9**	12.3	12.3	**-21.6**
P5	4.3	17.8	**-34.6**	9.7	11.1	**-34.0**
P6	-2.6	8.9	**-16.6**	2.7	3.9	**-13.2**
P8	-4.7	-3.2	**-14.7**	-3.8	-6.0	**-14.4**
P9	-3.2	11.6	**-20.7**	8.7	11.1	**-28.4**
P10	-3.7	-6.1	**-22.6**	5.5	7.3	**-23.4**
P11	-3.7	13.3	**-25.2**	11.0	22.1	**-27.1**
P12	9.5	32.9	**-22.8**	3.6	22.3	**-36.5**
P13	-4.0	-2.5	**-23.7**	3.0	2.9	**-25.7**
P15	-4.2	3.7	**-19.1**	5.0	6.9	**-19.2**
P17	-2.8	8.3	**-38.0**	11.9	11.6	**-33.8**
P18	6.9	19.1	**-29.5**	8.4	11.6	**-33.2**
P20	2.4	3.2	**-26.9**	2.3	-8.5	**-25.8**
P21	6.4	25.8	**-47.2**	14.3	23.0	**-44.2**
P22	-3.9	9.7	**-27.4**	2.5	-6.0	**-27.2**
P23	-4.8	8.5	**-21.7**	3.4	6.6	**-21.3**
P24	-10.7	7.1	**-35.0**	9.2	7.5	**-40.3**
P25	-4.1	13.0	**-26.4**	10.0	14.7	**-30.3**
P26	6.4	14.9	**-26.7**	12.7	14.7	**-25.3**
P27	-1.6	-5.2	**-28.0**	5.5	8.6	**-30.5**
P28	4.2	23.7	**-30.7**	-4.4	-5.7	**-29.3**
P29	7.4	12.0	**-26.0**	12.2	10.4	**-24.4**
P30	4.2	8.9	**-23.9**	7.0	6.3	**-22.5**
Minimum	-10.7	-6.1	**-47.2**	-4.4	-8.5	**-44.2**
Maximum	9.5	32.9	**-14.7**	14.3	23.0	**-13.2**
Mean	-0.9	10.4	**-26.1**	6.5	8.4	**-27.3**
Stand. deviation	5.8	9.3	**7.1**	4.8	8.2	**7.2**

Table A2.4 Ranges of left flexion for all 26 participants measured by both Fastrak and Xsens systems (bold = main movement plane)

ROM	**Left flexion (Fastrak)**			**Left flexion (Xsens)**		
Participants	FX	FY	**FZ**	XX	XY	**XZ**
P1	5.4	3.6	**20.1**	-4.6	7.7	**21.1**
P2	6.1	14.3	**23.6**	-3.9	15.7	**24.2**
P3	8.1	11.5	**32.1**	-7.1	13.3	**32.2**
P4	-2.3	11.2	**22.5**	-6.4	14.7	**21.9**
P5	3.1	14.3	**26.8**	-7.0	13.1	**30.3**
P6	-2.1	20.7	**15.2**	-2.6	15.4	**14.6**
P8	5.5	-3.6	**19.8**	-1.5	3.5	**17.3**
P9	3.8	9.5	**16.6**	-6.6	8.4	**21.8**
P10	3.4	5.5	**19.8**	2.5	-4.2	**19.2**
P11	2.4	13.3	**27.6**	-6.3	12.2	**27.7**
P12	-8.0	33.2	**24.6**	-6.9	31.1	**34.7**
P13	5.7	3.5	**22.2**	-2.8	6.9	**23.2**
P15	4.6	9.1	**21.9**	-4.8	13.1	**21.2**
P17	2.4	7.1	**25.1**	-4.4	5.9	**26.4**
P18	-17.1	29.9	**36.3**	-13.8	26.3	**38.9**
P20	4.8	-4.0	**31.4**	2.3	-7.3	**32.6**
P21	-7.5	26.8	**43.3**	-14.3	23.5	**37.5**
P22	8.0	-4.8	**21.5**	3.1	5.7	**25.9**
P23	4.6	11.8	**24.7**	-2.7	4.7	**27.6**
P24	2.0	15.6	**39.8**	-14.7	21.7	**41.2**
P25	4.5	8.5	**25.0**	-7.8	5.2	**26.8**
P26	-3.3	9.7	**25.5**	-7.8	8.4	**23.6**
P27	-4.1	12.0	**27.0**	-5.6	-4.8	**27.9**
P28	7.3	-4.5	**30.7**	-3.3	8.0	**27.8**
P29	-2.6	6.8	**27.7**	-11.0	13.3	**28.3**
P30	-2.1	5.2	**19.3**	-5.1	5.0	**17.7**
Minimum	-17.1	-4.8	**15.2**	-14.7	-7.3	**14.6**
Maximum	8.1	33.2	**43.3**	3.1	31.1	**41.2**
Mean	1.3	10.2	**25.8**	-5.5	10.3	**26.6**
Stand. deviation	5.9	9.8	**6.7**	4.6	9.1	**6.7**

Table A2.5 Ranges of right axial rotation for all 26 participants measured by both Fastrak and Xsens systems (bold = main movement plane)

ROM	**Right axial rotation (Fastrak)**			**Right axial rotation (Xsens)**		
Participants	**FX**	FY	FZ	**XX**	XY	XZ
P1	**-7.0**	-6.5	3.7	**-13.0**	-4.5	7.9
P2	**-9.7**	-7.2	5.6	**-13.4**	-5.9	9.6
P3	**-17.1**	-2.5	-6.0	**-15.9**	-11.1	-2.4
P4	**-16.1**	-8.2	-6.0	**-8.0**	-10.9	10.3
P5	**-9.2**	2.3	4.2	**-10.7**	-3.1	3.3
P6	**-15.5**	-8.1	-3.7	**-11.2**	-4.9	7.2
P8	**-12.3**	-3.9	3.7	**-14.8**	-2.8	2.6
P9	**-13.0**	-3.1	-2.6	**-14.4**	-7.5	4.8
P10	**-15.1**	-7.1	4.4	**-13.3**	-6.7	8.3
P11	**-14.1**	3.6	-1.0	**-13.5**	1.4	-1.6
P12	**-23.0**	9.1	7.2	**-21.2**	4.7	-3.0
P13	**-11.2**	-12.9	4.9	**-11.4**	-4.7	14.0
P15	**-14.2**	-6.8	7.4	**-13.4**	-2.7	6.8
P17	**-15.8**	-10.2	-7.1	**-12.6**	6.2	-6.4
P18	**-18.4**	-2.5	4.2	**-14.8**	-3.4	7.1
P20	**-15.7**	-10.6	1.7	**-15.8**	-4.5	3.7
P21	**-19.3**	-5.8	2.5	**-18.1**	-6.7	13.7
P22	**-15.2**	-7.3	-1.8	**-8.9**	-7.5	5.0
P23	**-12.5**	-5.8	5.5	**-14.4**	-3.9	3.8
P24	**-22.9**	7.9	16.9	**-24.6**	6.5	7.3
P25	**-15.9**	-6.1	6.5	**-16.0**	-4.0	4.1
P26	**-10.8**	-6.9	3.8	**-12.0**	-5.9	5.7
P27	**-18.9**	-6.6	10.4	**-19.3**	-6.1	8.0
P28	**-13.7**	-18.8	-3.3	**-14.2**	-11.3	9.5
P29	**-14.6**	2.4	2.9	**-11.3**	-1.9	3.3
P30	**-12.9**	-9.3	4.6	**-13.9**	-7.4	8.2
Minimum	**-23.0**	-18.8	-7.1	**-24.6**	-11.3	-6.4
Maximum	**-7.0**	9.1	16.9	**-8.0**	6.5	14.0
Mean	**-14.8**	-5.0	2.6	**-14.2**	-4.2	5.4
Stand. deviation	**3.8**	6.1	5.4	**3.6**	4.7	4.8

Table A2.6 Ranges of left axial rotation for all 26 participants measured by both Fastrak and Xsens systems (bold = main movement plane)

ROM	**Left axial rotation (Fastrak)**			**Left axial rotation (Xsens)**		
Participants	**FX**	FY	FZ	**XX**	XY	XZ
P1	**12.4**	-10.2	-1.8	**17.2**	-4.9	-8.4
P2	**11.5**	-5.6	-3.9	**14.9**	-6.1	-4.7
P3	**21.0**	4.8	11.9	**22.5**	-18.9	12.7
P4	**16.0**	-3.7	4.2	**15.5**	-3.8	-3.8
P5	**9.4**	-2.9	-1.6	**14.5**	-2.9	1.2
P6	**14.4**	11.9	1.3	**12.2**	4.3	8.6
P8	**13.2**	-1.9	-3.0	**18.5**	-1.8	-1.5
P9	**11.5**	-9.0	-1.8	**18.1**	-9.8	-11.9
P10	**13.7**	-7.4	-4.1	**14.7**	-6.5	-9.8
P11	**17.6**	-3.6	4.4	**14.7**	-3.3	3.4
P12	**23.7**	12.7	-6.0	**22.3**	5.2	6.9
P13	**11.6**	-9.6	-4.2	**13.9**	-4.3	-9.0
P15	**12.7**	-6.0	-4.1	**14.6**	-3.5	-5.5
P17	**18.1**	3.4	3.3	**16.7**	3.7	6.6
P18	**16.1**	3.2	3.4	**17.6**	-5.3	-5.1
P20	**18.2**	-7.2	-5.5	**19.3**	2.1	1.4
P21	**18.2**	-4.0	-4.8	**15.5**	-3.9	-4.0
P22	**13.5**	-7.1	3.8	**7.1**	-5.2	-5.0
P23	**15.8**	-4.8	-3.0	**17.0**	-2.4	1.2
P24	**22.5**	-11.0	-5.2	**17.1**	3.9	-6.4
P25	**16.3**	-1.9	-8.3	**19.2**	4.3	-3.6
P26	**12.4**	-7.8	-3.3	**12.9**	-6.5	-8.0
P27	**16.1**	-10.8	-3.4	**19.9**	-3.9	-6.9
P28	**14.1**	-12.0	-1.8	**13.5**	-5.7	-7.1
P29	**14.9**	-5.4	3.4	**14.3**	-3.2	-2.0
P30	**17.1**	-2.0	-4.9	**15.4**	-1.6	-2.9
Minimum	**9.4**	-12.0	-8.3	**7.1**	-18.9	-11.9
Maximum	**23.7**	12.7	11.9	**22.5**	5.2	12.7
Mean	**15.5**	-3.8	-1.4	**16.1**	-3.1	-2.5
Stand. deviation	**3.5**	6.4	4.5	**3.2**	5.1	6.1

Table A2.7 Gravitational component (g) of S1 and L1 spinous processes for all 26 participants during standing

Standing	**Gravitational component on S1 (g)**			**Gravitational component on L1 (g)**		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	0.9499	0.0661	0.3044	0.9478	-0.0306	-0.3143
P2	0.9596	0.0323	0.2778	0.9726	0.0082	-0.2245
P3	0.9210	-0.0387	0.3858	0.9600	0.0094	-0.2759
P4	0.9662	0.0825	0.2396	0.9817	-0.0125	-0.1859
P5	0.9307	0.0352	0.3619	0.9927	0.0046	-0.1122
P6	0.9180	0.0271	0.3920	0.9877	0.0004	-0.1485
P8	0.8182	0.0884	0.5662	0.9567	0.0135	-0.2872
P9	0.9480	0.0021	0.3177	0.9607	0.0252	-0.2713
P10	0.8682	0.0351	0.4946	0.9710	-0.0523	-0.2294
P11	0.9250	0.0149	0.3787	0.9646	0.0100	-0.2588
P12	0.9516	0.0264	0.3056	0.9641	0.0108	-0.2613
P13	0.9454	-0.0079	0.3243	0.9753	-0.0010	-0.2169
P15	0.9784	-0.0015	0.2054	0.9605	-0.0216	-0.2733
P17	0.9298	0.0631	0.3609	0.9757	-0.0083	-0.2131
P18	0.9208	-0.0025	0.3895	0.9842	-0.0146	-0.1716
P20	0.9454	0.0005	0.3240	0.9643	0.0044	-0.2621
P21	0.9882	0.0058	0.1500	0.9698	-0.0332	-0.2379
P22	0.9483	0.0138	0.3135	0.9565	0.0098	-0.2881
P23	0.9656	-0.0100	0.2557	0.9513	0.0007	-0.3054
P24	0.9406	0.0174	0.3367	0.9395	-0.0223	-0.3393
P25	0.9511	-0.0096	0.3055	0.9301	-0.0479	-0.3612
P26	0.9143	0.0414	0.4002	0.9653	-0.0283	-0.2554
P27	0.9155	-0.0135	0.4000	0.9822	-0.0188	-0.1842
P28	0.9580	0.0233	0.2823	0.9416	0.0384	-0.3320
P29	0.9292	0.0329	0.3651	0.9832	-0.0084	-0.1789
P30	0.9732	0.0273	0.2236	0.9645	-0.0072	-0.2600
Minimum	**0.8182**	**-0.0387**	**0.1500**	**0.9301**	**-0.0523**	**-0.3612**
Maximum	**0.9882**	**0.0884**	**0.5662**	**0.9927**	**0.0384**	**-0.1122**
Mean	**0.9369**	**0.0212**	**0.3331**	**0.9655**	**-0.0066**	**-0.2480**
Stand. deviation	**0.0348**	**0.0303**	**0.0869**	**0.0155**	**0.0214**	**0.0606**

Table A2.8 Gravitational component (g) of S1 and L1 spinous processes for all 26 participants during sitting

Sitting	**Gravitational component on S1 (g)**			**Gravitational component on L1 (g)**		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	0.9905	0.0512	0.1239	0.9965	-0.0107	-0.0732
P2	0.9988	-0.0020	0.0150	0.9992	0.0144	-0.0164
P3	0.9977	-0.0393	-0.0395	0.9986	-0.0133	-0.0337
P4	0.9958	0.0678	0.0409	0.9952	-0.0052	-0.0894
P5	0.9855	-0.0331	0.1568	0.9990	0.0021	0.0206
P6	0.9906	0.0593	0.1147	0.9987	0.0181	0.0345
P8	0.8670	0.0431	0.4940	0.9786	-0.0244	-0.2010
P9	0.9886	-0.0273	0.1462	0.9974	-0.0156	0.0131
P10	0.9890	0.0261	0.1427	0.9945	-0.0469	-0.0873
P11	0.9987	0.0207	-0.0076	0.9963	0.0239	-0.0693
P12	0.9982	-0.0008	-0.0361	0.9929	0.0164	-0.1080
P13	0.9845	-0.0351	0.1682	0.9901	-0.0161	-0.1331
P15	0.9864	0.0153	-0.1591	0.9953	-0.0098	-0.0868
P17	0.9874	-0.0027	0.1547	0.9922	-0.0353	0.1131
P18	0.9868	-0.0162	0.1447	0.9955	-0.0327	0.0778
P20	0.9943	-0.0072	0.0948	0.9966	-0.0023	-0.0461
P21	0.9921	0.0056	-0.0811	0.9935	-0.0309	-0.0995
P22	0.9758	-0.0077	0.2113	0.9800	0.0231	-0.1777
P23	0.9893	-0.0079	-0.1257	0.9745	0.0043	-0.2205
P24	0.9971	0.0251	0.0534	0.9926	-0.0134	-0.1093
P25	0.9700	-0.0633	-0.0363	0.9823	-0.0677	-0.1477
P26	0.9975	-0.0020	0.0473	0.9968	-0.0315	-0.0530
P27	0.9906	0.0132	0.1268	0.9980	-0.0073	-0.0561
P28	0.9891	-0.0536	-0.1277	0.9986	-0.0277	0.0382
P29	0.9866	0.0745	0.1312	0.9996	-0.0025	-0.0006
P30	0.9970	0.0006	-0.0520	0.9902	0.0091	-0.1311
Minimum	**0.8670**	**-0.0633**	**-0.1591**	**0.9745**	**-0.0677**	**-0.2205**
Maximum	**0.9988**	**0.0745**	**0.4940**	**0.9996**	**0.0239**	**0.1131**
Mean	**0.9856**	**0.0040**	**0.0654**	**0.9932**	**-0.0109**	**-0.0632**
Stand. deviation	**0.0251**	**0.0357**	**0.1365**	**0.0069**	**0.0224**	**0.0829**

Table A2.9 Lumbar curvature angles (°) for all 26 participants during standing and sitting; and lumbar curvature angles (°) between males and females during standing

	Lumbar curvature angle (°)		Standing lumbar curvature angle (°)	
Participants	**Standing**	**Sitting**	**Male**	**Female**
P1	36.0	11.3	36.0	
P2	29.1	1.8	29.1	
P3	38.7	-0.3	38.7	
P4	24.6	7.5	24.6	
P5	27.7	7.8	27.7	
P6	31.6	4.6		31.6
P8	35.5	21.6		35.5
P9	34.3	7.7		34.3
P10	42.9	13.2		42.9
P11	37.3	3.5	37.3	
P12	32.9	4.1	32.9	
P13	31.4	17.3		31.4
P15	27.7	-4.2		27.7
P17	33.5	2.4		33.5
P18	32.8	3.9		32.8
P20	34.1	8.1		34.1
P21	22.4	1.1	22.4	
P22	35.0	22.4	35.0	
P23	32.6	5.5	32.6	
P24	39.5	9.3		39.5
P25	39.0	6.4	39.0	
P26	38.4	5.8		38.4
P27	34.2	10.5		34.2
P28	35.8	-9.5		35.8
P29	31.7	7.6		31.7
P30	28.0	4.6	28.0	
Minimum	**22.4**	**-9.5**	**22.4**	**27.7**
Maximum	**42.9**	**22.4**	**39.0**	**42.9**
Mean	**33.3**	**6.7**	**31.9**	**34.5**
Standard Deviation	**4.8**	**7.0**	**5.5**	**3.8**

Table A2.10 Gravitational component (g) of S1 and L1 spinous processes for all 26 participants during supine lying

Supine lying	Gravitational component on S1 (g)			Gravitational component on L1 (g)		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	0.0816	-0.0116	-0.9988	-0.1012	0.0145	-0.9935
P2	0.1706	-0.0183	-0.9872	0.0148	0.0112	-0.9985
P3	0.2497	-0.0231	-0.9701	-0.1328	0.1045	-0.9842
P4	0.2526	0.0504	-0.9682	-0.1271	0.0459	-0.9896
P5	0.2397	-0.0647	-0.9706	-0.2018	0.0012	-0.9782
P6	0.2254	0.0248	-0.9760	-0.0050	0.0567	-0.9970
P8	0.3375	0.0906	-0.9383	-0.0932	0.0114	-0.9943
P9	0.0781	0.0481	-0.9988	-0.0445	0.0380	-0.9967
P10	0.4229	-0.0132	-0.9068	-0.0332	-0.0285	-0.9975
P11	0.2715	-0.0084	-0.9640	-0.0876	0.0172	-0.9948
P12	0.2697	0.0636	-0.9625	-0.0773	0.0266	-0.9953
P13	0.2691	0.0458	-0.9635	-0.0737	0.0716	-0.9932
P15	0.3482	0.1336	-0.9293	0.0302	0.0167	-0.9979
P17	0.3448	0.0317	-0.9395	-0.2280	0.0574	-0.9707
P18	0.2941	0.0547	-0.9558	-0.1523	0.0007	-0.9869
P20	0.2126	0.0466	-0.9779	-0.1092	0.0457	-0.9916
P21	0.3051	0.0153	-0.9537	-0.0991	0.0303	-0.9932
P22	0.2673	-0.0789	-0.9616	-0.0610	0.0379	-0.9960
P23	0.1580	-0.1013	-0.9841	-0.2312	-0.0889	-0.9677
P24	0.2205	0.0111	-0.9773	-0.1435	0.0578	-0.9866
P25	0.2699	-0.0872	-0.9605	-0.1615	-0.0127	-0.9856
P26	0.2001	0.0252	-0.9814	-0.2184	0.0067	-0.9743
P27	0.2113	0.0633	-0.9771	-0.2410	-0.0061	-0.9692
P28	0.3904	0.1517	-0.9089	-0.0982	0.0748	-0.9909
P29	0.2913	-0.0671	-0.9556	-0.0624	0.0331	-0.9960
P30	0.1426	-0.0389	-0.9911	-0.1471	0.0319	-0.9872
Minimum	**0.0781**	**-0.1013**	**-0.9988**	**-0.2410**	**-0.0889**	**-0.9985**
Maximum	**0.4229**	**0.1517**	**-0.9068**	**0.0302**	**0.1045**	**-0.9677**
Mean	**0.2510**	**0.0132**	**-0.9638**	**-0.1110**	**0.0252**	**-0.9887**
Stand. deviation	**0.0838**	**0.0641**	**0.0238**	**0.0744**	**0.0378**	**0.0094**

Table A2.11 Gravitational component (g) of S1 and L1 spinous processes for all 26 participants during prone lying

Prone lying	**Gravitational component on S1 (g)**			**Gravitational component on L1 (g)**		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	-0.3623	0.0535	0.9270	0.2698	0.0629	0.9607
P2	-0.2430	-0.0327	0.9663	0.3362	-0.0665	0.9401
P3	-0.2977	-0.0966	0.9461	0.3511	-0.1526	0.9251
P4	-0.2782	-0.0388	0.9559	0.2905	-0.0787	0.9546
P5	-0.2934	0.0025	0.9524	0.1263	-0.0362	0.9918
P6	-0.4491	0.0392	0.8887	0.0501	-0.0132	0.9990
P8	-0.4806	-0.1364	0.8624	0.3185	-0.1300	0.9400
P9	-0.2011	0.0173	0.9752	0.3173	-0.0312	0.9485
P10	-0.4301	0.0948	0.8930	0.2113	0.0523	0.9762
P11	-0.3357	0.0466	0.9362	0.2824	0.0243	0.9591
P12	-0.3484	-0.0097	0.9329	0.1351	-0.0198	0.9910
P13	-0.2592	0.0150	0.9617	0.3369	-0.0593	0.9403
P15	-0.2807	0.0992	0.9500	0.2420	-0.0254	0.9704
P17	-0.4543	0.0216	0.8858	0.0348	-0.0518	0.9987
P18	-0.3927	-0.0430	0.9144	0.1680	0.0084	0.9862
P20	-0.3480	0.0196	0.9333	0.1846	-0.0192	0.9829
P21	-0.2826	0.1212	0.9471	0.3032	0.0320	0.9513
P22	-0.2908	0.0103	0.9529	0.3180	-0.1222	0.9409
P23	-0.1546	0.0287	0.9838	0.2913	0.0302	0.9562
P24	-0.2971	0.1458	0.9394	0.2537	-0.0384	0.9669
P25	-0.2708	0.1165	0.9516	0.3212	0.0175	0.9469
P26	-0.3734	0.0398	0.9229	0.2281	-0.0573	0.9726
P27	-0.3694	0.0854	0.9212	0.2625	0.0932	0.9601
P28	-0.3060	0.0192	0.9479	0.3254	-0.0793	0.9429
P29	-0.2407	0.0985	0.9618	0.1417	-0.0204	0.9903
P30	-0.2765	0.0171	0.9571	0.3055	0.0138	0.9524
Minimum	**-0.4806**	**-0.1364**	**0.8624**	**0.0348**	**-0.1526**	**0.9251**
Maximum	**-0.1546**	**0.1458**	**0.9838**	**0.3511**	**0.0932**	**0.9990**
Mean	**-0.3199**	**0.0282**	**0.9372**	**0.2464**	**-0.0257**	**0.9633**
Stand. deviation	**0.0790**	**0.0658**	**0.0291**	**0.0894**	**0.0595**	**0.0209**

Table A2.12 Gravitational component (g) of S1 and L1 spinous processes for all 26 participants during left side lying

Left side lying	**Gravitational component on S1 (g)**			**Gravitational component on L1 (g)**		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	0.2107	-0.9691	-0.1270	0.1158	-0.9950	0.0225
P2	0.0762	-0.9939	0.0785	0.2293	-0.9714	0.0909
P3	0.1700	-0.9761	-0.1344	0.1393	-0.9923	0.0138
P4	0.2070	-0.9696	-0.1287	0.0922	-0.9904	-0.1185
P5	0.0702	-0.9974	0.0039	0.1565	-0.9896	0.0098
P6	0.1581	-0.9840	0.0791	0.0918	-0.9851	0.1601
P8	0.2578	-0.9643	0.0546	0.0363	-0.9822	-0.1918
P9	-0.0504	-0.9698	0.2371	0.2279	-0.9499	0.2250
P10	-0.0183	-0.9900	0.1397	0.0783	-0.9926	0.1133
P11	0.1250	-0.9881	0.0898	0.1172	-0.9924	0.0750
P12	0.2144	-0.9750	-0.0595	0.0687	-0.9861	-0.1618
P13	-0.0008	-0.9998	0.0231	0.1395	-0.9828	-0.1347
P15	0.2468	-0.9582	-0.1456	0.0674	-0.9974	-0.0665
P17	0.1040	-0.9930	-0.0610	0.0759	-0.9977	-0.0496
P18	0.0303	-0.9975	0.0641	0.0379	-0.9925	0.1349
P20	0.0498	-0.9979	0.0445	0.0902	-0.9915	0.1145
P21	0.0968	-0.9874	-0.1283	0.0259	-0.9632	-0.2722
P22	0.0008	-1.0001	0.0060	0.1557	-0.9892	-0.0280
P23	0.0058	-0.9819	0.1882	0.1101	-0.9958	0.0112
P24	0.1348	-0.9895	-0.0557	0.0716	-0.9984	-0.0411
P25	-0.1306	-0.9836	0.1246	0.0994	-0.9711	0.2270
P26	0.0559	-0.9983	0.0245	0.0724	-0.9980	0.0527
P27	0.1658	-0.9848	-0.0531	0.1382	-0.9898	-0.0690
P28	0.0321	-0.9994	-0.0257	0.0532	-1.0004	-0.0023
P29	0.1164	-0.9929	-0.0240	0.0444	-0.9917	-0.1335
P30	0.0374	-0.9773	0.2075	0.1822	-0.9618	0.2143
Minimum	**-0.1306**	**-1.0001**	**-0.1456**	**0.0259**	**-1.0004**	**-0.2722**
Maximum	**0.2578**	**-0.9582**	**0.2371**	**0.2293**	**-0.9499**	**0.2270**
Mean	**0.0910**	**-0.9853**	**0.0162**	**0.1045**	**-0.9865**	**0.0075**
Stand. deviation	**0.0967**	**0.0121**	**0.1089**	**0.0545**	**0.0128**	**0.1319**

Table A2.13 Gravitational component (g) of S1 and L1 spinous processes for all 26 participants during right side lying

Right side lying	Gravitational component on S1 (g)			Gravitational component on L1 (g)		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	0.1618	0.9749	0.1477	0.1294	0.9760	0.1570
P2	0.2663	0.9591	-0.0924	0.1706	0.9813	-0.0462
P3	0.1502	0.9831	0.0995	0.1955	0.9237	0.3206
P4	0.1551	0.9866	-0.0461	0.2169	0.9724	-0.0336
P5	0.2869	0.9433	-0.1655	0.0546	0.9928	-0.0744
P6	0.0792	0.9919	-0.0982	0.0999	0.9890	-0.0772
P8	0.0528	0.9982	0.0019	0.0710	0.9845	-0.1421
P9	0.0801	0.9923	0.0841	0.0277	0.9907	0.1082
P10	0.0641	0.9939	0.0807	0.1675	0.9809	0.0621
P11	0.0299	0.9976	-0.0594	0.0457	0.9960	0.0113
P12	0.0400	0.9985	0.0206	0.1028	0.9916	0.0003
P13	0.2562	0.9652	-0.0405	0.0473	0.9877	-0.1271
P15	0.1544	0.9832	-0.0921	0.1054	0.9915	0.0045
P17	0.0308	0.9981	0.0362	0.1231	0.9854	0.0887
P18	0.1637	0.9850	-0.0420	0.0922	0.9862	-0.1138
P20	0.0630	0.9919	0.1016	0.0577	0.9722	0.2146
P21	0.2051	0.8802	-0.4288	0.0527	0.9360	-0.3396
P22	0.2037	0.9720	-0.1123	0.1096	0.9893	-0.0623
P23	0.0992	0.9943	-0.0059	0.0421	0.9761	-0.1992
P24	0.0923	0.9950	-0.0086	0.2763	0.9503	0.1223
P25	0.0623	0.9974	0.0055	0.2385	0.9661	0.0606
P26	0.1563	0.9862	-0.0383	0.1186	0.9832	-0.1169
P27	0.2548	0.9641	-0.0632	0.1033	0.9887	-0.0790
P28	0.0340	0.9988	-0.0061	0.0859	0.9929	-0.0382
P29	0.2914	0.9308	-0.2188	0.0711	0.9936	-0.0451
P30	0.1066	0.9815	-0.1573	0.1696	0.9806	-0.0628
Minimum	**0.0299**	**0.8802**	**-0.4288**	**0.0277**	**0.9237**	**-0.3396**
Maximum	**0.2914**	**0.9988**	**0.1477**	**0.2763**	**0.9960**	**0.3206**
Mean	**0.1362**	**0.9786**	**-0.0422**	**0.1144**	**0.9792**	**-0.0157**
Stand. deviation	**0.0848**	**0.0267**	**0.1181**	**0.0652**	**0.0177**	**0.1356**

Table A2.14 Amplitude (g) of S1 and L1 spinous processes for all 26 participants during level walking

Walking	Amplitude on S1 (g)			Amplitude on L1 (g)		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	1.3130	0.9550	0.7572	0.8633	0.6088	0.6616
P2	1.0729	0.7724	0.7767	0.8553	0.5120	0.7291
P3	0.9089	1.0167	0.9046	1.1357	0.9542	0.6280
P4	1.0337	1.1715	0.9917	1.1446	0.8466	0.6877
P5	0.7666	0.7653	0.5802	0.9466	0.6528	0.6645
P6	1.0974	0.8001	1.1166	1.1319	0.6737	0.5933
P8	0.7603	0.8147	0.6722	0.7903	0.5299	0.5356
P9	1.2486	0.7682	0.7893	1.0617	0.4084	0.7042
P10	1.0278	1.1464	0.9929	0.7551	0.6777	0.5414
P11	0.8013	0.9715	0.6077	0.7295	0.5268	0.5064
P12	1.0565	1.0297	0.8469	0.7699	0.5192	0.7669
P13	0.9174	0.8791	0.8955	0.9035	0.5027	0.6152
P15	0.8780	0.9512	0.8985	0.9803	0.6605	0.7289
P17	0.9042	0.7189	0.6558	0.7974	0.4459	0.5588
P18	0.8218	0.8014	0.7752	0.8887	0.6638	1.2802
P20	0.9891	1.1081	0.7038	0.6764	0.4872	0.4499
P21	0.9081	0.9894	0.6269	0.9123	0.4847	0.5130
P22	1.0622	0.6660	0.6301	0.8474	0.6545	0.4940
P23	0.8478	0.7273	0.6369	0.8206	0.5170	0.5699
P24	1.0899	0.7010	0.6367	1.0052	0.5015	0.6119
P25	1.3381	1.1734	0.9688	1.1328	0.8440	1.0014
P26	1.2112	0.9763	0.8684	1.2011	0.5922	0.9200
P27	0.6393	0.6554	0.5832	0.6503	0.3748	0.4900
P28	0.9462	0.6552	0.6524	0.4946	0.5130	0.6865
P29	0.6492	0.5703	0.5552	0.5028	0.4516	0.3957
P30	1.0712	0.9986	0.9237	1.1077	0.5033	0.9425
Minimum	**0.6393**	**0.5703**	**0.5552**	**0.4946**	**0.3748**	**0.3957**
Maximum	**1.3381**	**1.1734**	**1.1166**	**1.2011**	**0.9542**	**1.2802**
Mean	**0.9754**	**0.8763**	**0.7710**	**0.8886**	**0.5810**	**0.6645**
Stand. deviation	**0.1844**	**0.1752**	**0.1560**	**0.1935**	**0.1398**	**0.1945**

Table A2.15 Amplitude (g) of S1 and L1 spinous processes for all 26 participants during running

Running	Amplitude on S1 (g)			Amplitude on L1 (g)		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	3.1214	3.4395	2.9298	2.0934	2.4584	2.1365
P2	2.9433	2.7995	2.1141	2.0319	1.3611	1.7715
P3	2.7321	2.9460	1.9521	2.3327	1.6586	2.7322
P4	2.6630	3.2055	2.4874	2.1467	1.6651	1.7438
P5	2.3959	1.8390	1.4942	2.0807	1.7479	2.0058
P6	2.5760	3.3782	3.2434	2.1369	2.1129	2.5591
P8	2.6070	2.9713	3.2410	2.1601	1.0906	1.1787
P9	2.2847	2.2561	2.4768	1.8461	0.9373	1.3250
P10	2.8358	3.6103	2.5957	1.9756	1.7038	2.3901
P11	2.3608	3.3848	1.7163	1.9810	1.4398	1.6789
P12	2.8485	3.5802	3.1323	2.4990	2.2151	3.1708
P13	2.5560	3.6813	2.1509	2.3134	1.4753	2.0211
P15	2.6293	3.5763	2.6113	1.9809	1.6331	1.2041
P17	2.3784	2.8524	1.5850	1.9425	1.0137	0.9686
P18	3.0483	3.5667	2.8737	2.0637	1.7666	1.5742
P20	3.1600	3.7477	3.0964	2.2464	1.4886	2.2855
P21	2.8757	3.2860	1.5577	2.1665	1.4668	1.1852
P22	2.6759	3.1239	2.5556	2.0446	1.6242	1.4839
P23	2.6761	2.6336	3.0520	2.2331	1.3415	1.3844
P24	2.8408	3.3281	2.8252	2.1689	2.3716	1.6891
P25	2.9519	3.3799	1.8337	2.2701	2.0281	2.3198
P26	2.8879	3.5711	2.3474	2.2939	1.5071	2.7436
P27	2.7834	3.2789	2.0273	2.1406	2.7582	2.3502
P28	2.9662	3.0631	2.6709	2.3580	1.5536	1.9656
P29	2.2096	2.7709	2.4597	1.9089	1.3786	1.3247
P30	3.0108	2.9775	3.3326	2.4068	1.8914	3.0870
Minimum	**2.2096**	**1.8390**	**1.4942**	**1.8461**	**0.9373**	**0.9686**
Maximum	**3.1600**	**3.7477**	**3.3326**	**2.4990**	**2.7582**	**3.1708**
Mean	**2.7315**	**3.1634**	**2.4755**	**2.1470**	**1.6803**	**1.9338**
Stand. deviation	**0.2596**	**0.4530**	**0.5635**	**0.1631**	**0.4374**	**0.6135**

Table A2.16 Amplitude (g) of S1 and L1 spinous processes for all 26 participants during walking up steps

Walking up steps	Amplitude on S1 (g)			Amplitude on L1 (g)		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	0.9855	0.6412	0.6077	0.9187	0.5921	0.6236
P2	0.9118	0.7930	0.8220	0.8387	0.3750	0.7441
P3	0.5950	0.7748	0.5545	0.5676	0.6125	0.5924
P4	0.6935	0.4747	0.5722	0.4994	0.4943	0.5575
P5	0.4141	0.4327	0.4227	0.4261	0.3727	0.4758
P6	0.9469	0.4340	0.4504	0.8322	0.4918	0.5474
P8	0.8673	0.4353	0.6756	0.6467	0.5749	0.5994
P9	1.0290	0.6693	0.6627	1.0211	0.6224	0.6443
P10	1.1207	0.8789	0.8543	0.8936	0.5870	0.6613
P11	0.6629	0.9960	0.7055	0.7130	0.3990	0.6544
P12	0.9157	0.5926	0.4425	0.6504	0.3840	0.5805
P13	1.2899	0.8305	0.8125	0.9780	0.4743	0.9227
P15	0.7822	0.7500	0.8203	0.9251	0.6603	0.7620
P17	0.9661	0.7466	0.9438	0.8377	0.4458	0.8039
P18	0.7811	0.8016	0.4981	0.6569	0.5273	0.6403
P20	0.9647	0.7116	0.5963	0.6126	0.4744	0.6864
P21	0.6393	0.6066	0.4202	0.6022	0.3109	0.4956
P22	0.6551	0.5417	0.5260	0.6410	0.5382	0.6787
P23	1.0219	0.6983	0.7223	0.8691	0.5078	0.6216
P24	0.5699	0.5200	0.5133	0.5817	0.3772	0.5405
P25	1.0489	0.8952	1.0232	1.2011	0.6399	0.8212
P26	0.9190	0.6938	0.6589	0.7676	0.4747	0.6891
P27	1.3711	0.7591	0.7673	0.9423	0.6004	1.0231
P28	1.1803	0.7277	0.7742	1.0120	0.4394	0.7227
P29	1.3574	0.7433	1.0788	0.7908	0.5775	0.8631
P30	0.6841	0.6614	0.5295	0.6443	0.4927	0.5051
Minimum	**0.4141**	**0.4327**	**0.4202**	**0.4261**	**0.3109**	**0.4758**
Maximum	**1.3711**	**0.9960**	**1.0788**	**1.2011**	**0.6603**	**1.0231**
Mean	**0.8990**	**0.6850**	**0.6713**	**0.7719**	**0.5018**	**0.6714**
Stand. deviation	**0.2469**	**0.1485**	**0.1835**	**0.1859**	**0.0955**	**0.1340**

Table A2.17 Amplitude (g) of S1 and L1 spinous processes for all 26 participants during walking down steps

Walking down steps	Amplitude on S1 (g)			Amplitude on L1 (g)		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	1.4741	1.1014	0.7073	1.4038	0.9944	0.4985
P2	0.7540	0.8864	0.6893	0.8415	0.6984	0.3895
P3	1.0455	1.0481	0.6361	1.0804	0.9794	0.4133
P4	1.2310	1.4263	0.7913	1.0489	0.7848	0.4135
P5	0.5586	0.4922	0.4642	0.6881	0.4498	0.4506
P6	0.7627	0.6833	0.6788	0.9894	0.5504	0.6081
P8	0.8859	0.8724	0.9600	1.0535	0.6322	0.4129
P9	0.9446	0.5013	0.7133	0.7470	0.4461	0.3703
P10	1.4413	1.6139	1.2423	1.1944	1.1869	0.7988
P11	0.8166	1.1489	0.7553	0.7567	0.6163	0.6257
P12	0.7075	0.6864	0.6139	0.9152	0.5541	0.4257
P13	1.2758	0.6729	1.0969	1.3489	0.5124	0.6624
P15	1.2781	1.1062	1.0817	1.3673	0.7540	0.6419
P17	0.8877	0.8237	0.9081	1.0064	0.4653	0.7150
P18	0.7597	1.2132	0.6926	0.7979	0.3965	0.6591
P20	0.9143	0.9089	0.6289	0.8829	0.6530	0.4226
P21	1.3409	1.2868	0.7187	1.2691	0.8766	0.3961
P22	0.8796	0.8236	0.7385	1.0078	0.4944	0.4450
P23	1.5780	0.9845	0.8937	1.1973	0.7793	0.6334
P24	0.8646	1.0979	0.7485	1.2277	0.8610	0.4389
P25	1.7205	2.3373	1.6238	1.4697	1.4837	1.1178
P26	1.2596	0.7854	0.8165	1.2042	0.7331	0.5445
P27	1.3971	0.7591	0.6931	1.0649	0.6004	0.7335
P28	1.2079	1.1705	0.8096	1.2246	0.6679	0.5638
P29	1.2432	0.9872	0.9569	1.1980	0.8334	0.6211
P30	1.0694	1.0718	0.6419	0.9442	0.7307	0.5988
Minimum	**0.5586**	**0.4922**	**0.4642**	**0.6881**	**0.3965**	**0.3703**
Maximum	**1.7205**	**2.3373**	**1.6238**	**1.4697**	**1.4837**	**1.1178**
Mean	**1.0884**	**1.0188**	**0.8193**	**1.0742**	**0.7206**	**0.5616**
Stand. deviation	**0.3023**	**0.3780**	**0.2377**	**0.2150**	**0.2465**	**0.1678**

Table A2.18 Frequency (Hz) of S1 and L1 spinous processes for all 26 participants during level walking

Walking	Frequency on S1 (Hz)			Frequency on L1 (Hz)		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	1.758	8.008	1.758	1.758	8.008	1.758
P2	1.758	6.445	1.758	1.758	0.977	1.758
P3	1.758	8.203	1.758	1.758	0.977	1.758
P4	1.758	9.570	1.758	1.758	0.781	1.758
P5	1.758	6.250	1.758	1.758	0.977	1.758
P6	1.758	0.977	1.758	1.758	0.977	1.758
P8	1.563	2.344	1.563	1.563	0.781	1.563
P9	1.563	0.781	1.563	1.563	0.781	1.563
P10	1.563	5.469	1.563	1.563	0.781	1.563
P11	1.563	6.836	1.563	1.563	0.781	1.563
P12	1.758	4.297	1.758	1.758	0.781	1.758
P13	1.953	2.930	1.953	1.953	0.977	1.953
P15	1.758	2.734	1.758	1.758	2.734	1.758
P17	1.563	2.344	1.563	1.563	2.344	1.563
P18	1.758	0.977	1.758	1.758	0.977	1.758
P20	1.563	3.906	1.563	1.563	0.781	1.563
P21	1.758	11.130	1.758	1.758	0.781	1.758
P22	1.563	4.102	1.563	1.563	0.781	1.563
P23	1.563	4.102	1.758	1.758	9.180	1.758
P24	1.563	0.781	1.563	1.563	0.781	1.563
P25	1.758	2.734	1.758	1.758	2.734	1.758
P26	1.758	4.492	1.758	1.758	0.977	1.758
P27	1.758	7.617	1.758	1.758	0.781	1.758
P28	1.367	6.055	1.367	1.367	1.953	1.367
P29	1.758	6.055	1.758	1.758	0.781	1.758
P30	1.758	2.734	1.758	1.758	0.977	1.758
Minimum	**1.367**	**0.781**	**1.367**	**1.367**	**0.781**	**1.367**
Maximum	**1.953**	**11.130**	**1.953**	**1.953**	**9.180**	**1.953**
Mean	**1.683**	**4.687**	**1.690**	**1.690**	**1.698**	**1.690**
Stand. deviation	**0.124**	**2.806**	**0.123**	**0.123**	**2.123**	**0.123**

Table A2.19 Frequency (Hz) of S1 and L1 spinous processes for all 26 participants during running

Running	Frequency on S1 (Hz)			Frequency on L1 (Hz)		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	2.734	6.641	10.740	2.734	1.367	2.734
P2	2.734	2.734	2.734	2.734	1.367	2.734
P3	2.930	15.630	2.930	2.930	4.297	2.930
P4	2.539	11.720	2.539	2.734	1.367	2.734
P5	2.539	11.520	2.539	2.539	1.367	2.539
P6	2.930	10.160	2.930	2.930	4.297	2.930
P8	2.344	3.516	2.344	2.344	1.172	2.344
P9	2.734	13.670	2.734	2.539	1.367	2.539
P10	2.734	12.110	2.734	2.734	1.367	2.734
P11	2.539	3.906	2.539	2.539	1.367	2.539
P12	2.539	6.250	2.539	2.539	1.172	2.539
P13	2.734	12.500	2.734	2.734	1.367	2.734
P15	2.734	6.641	2.734	2.734	3.906	2.734
P17	2.539	1.172	2.539	2.539	1.172	2.539
P18	2.930	9.961	2.734	2.734	1.367	2.734
P20	2.539	8.789	2.539	2.539	1.172	2.539
P21	2.734	1.367	2.734	2.734	1.367	2.734
P22	2.539	11.130	2.539	2.539	1.172	2.539
P23	2.930	15.630	2.930	2.930	1.367	2.930
P24	2.734	9.375	2.734	2.734	4.102	2.734
P25	2.539	6.445	2.539	2.539	3.906	2.539
P26	2.539	3.906	2.539	2.539	3.906	2.539
P27	2.539	3.906	2.539	2.539	3.906	2.539
P28	2.539	3.906	2.539	2.539	3.906	2.539
P29	2.930	7.227	8.594	2.930	4.297	2.930
P30	2.539	3.711	2.539	2.539	1.172	2.539
Minimum	**2.344**	**1.172**	**2.344**	**2.344**	**1.172**	**2.344**
Maximum	**2.930**	**15.630**	**10.740**	**2.930**	**4.297**	**2.930**
Mean	**2.667**	**7.828**	**3.185**	**2.659**	**2.254**	**2.659**
Stand. deviation	**0.165**	**4.316**	**1.938**	**0.157**	**1.346**	**0.157**

Table A2.20 Magnitude of peak frequency of S1 and L1 spinous processes for all 26 participants during level walking

Walking	Magnitude of peak frequency on S1			Magnitude of peak frequency on L1		
Participants	XX	XY	XZ	XX	XY	XZ
P1	29.03	16.68	35.31	31.90	17.99	36.28
P2	42.51	24.21	27.81	52.19	20.75	23.14
P3	29.54	20.45	25.30	30.25	28.53	17.65
P4	63.55	21.08	45.61	68.41	17.05	21.21
P5	31.33	14.08	24.22	25.04	22.79	17.00
P6	26.41	12.72	48.03	37.62	14.88	23.53
P8	23.99	16.92	46.07	45.40	26.17	26.18
P9	44.67	14.00	30.95	47.99	13.97	28.46
P10	22.38	17.29	39.44	34.18	38.91	22.96
P11	34.29	15.36	36.07	42.46	31.18	21.67
P12	38.20	20.39	37.23	45.34	12.99	23.62
P13	44.19	25.52	48.77	54.43	17.69	28.55
P15	29.52	23.60	37.98	43.38	17.70	27.68
P17	34.21	10.17	35.62	39.04	9.47	11.25
P18	19.73	15.09	34.85	31.48	20.27	23.00
P20	18.29	27.94	36.76	25.54	21.08	21.25
P21	46.64	12.19	27.96	46.76	17.80	22.22
P22	15.74	10.08	30.74	27.20	19.33	21.65
P23	17.86	12.06	20.61	18.92	9.55	21.89
P24	26.46	12.80	35.60	33.71	28.81	27.16
P25	73.80	34.97	53.98	89.77	18.55	21.68
P26	45.87	22.30	51.77	63.48	14.67	38.13
P27	19.06	15.61	34.08	31.10	8.65	18.85
P28	31.07	16.55	44.81	26.35	10.79	32.03
P29	24.67	8.90	28.51	16.90	11.03	17.86
P30	36.02	25.81	29.70	39.53	24.42	25.73
Minimum	**15.74**	**8.90**	**20.61**	**16.90**	**8.65**	**11.25**
Maximum	**73.80**	**34.97**	**53.98**	**89.77**	**38.91**	**38.13**
Mean	**33.42**	**17.95**	**36.45**	**40.32**	**19.04**	**23.87**
Stand. deviation	**13.92**	**6.33**	**8.81**	**16.16**	**7.38**	**5.81**

Table A2.21 Magnitude of peak frequency of S1 and L1 spinous processes for all 26 participants during running

Running	Magnitude of peak frequency on S1			Magnitude of peak frequency on L1		
Participants	XX	**XY**	XZ	XX	**XY**	XZ
P1	243.30	46.30	43.52	175.30	44.92	61.68
P2	319.60	63.96	58.82	229.30	61.43	93.16
P3	193.60	46.05	55.61	150.30	35.43	55.01
P4	240.60	54.57	44.57	185.10	50.93	42.20
P5	277.00	28.21	63.13	250.10	34.06	50.66
P6	203.10	50.55	72.75	210.80	30.36	37.86
P8	203.40	48.32	86.17	180.90	52.19	64.04
P9	151.40	42.33	51.61	129.00	30.13	43.23
P10	243.60	74.28	72.82	214.20	47.88	34.60
P11	267.40	48.50	105.10	220.10	37.29	79.60
P12	321.80	74.98	77.76	269.50	32.24	81.95
P13	245.80	83.80	68.45	202.30	54.55	93.89
P15	203.70	50.83	45.95	159.10	56.67	36.61
P17	187.90	23.47	19.59	202.00	21.00	18.45
P18	205.90	73.92	41.62	158.90	62.71	50.87
P20	278.20	114.70	59.59	243.50	49.94	92.72
P21	203.20	36.57	55.91	196.70	37.79	55.09
P22	238.30	54.96	56.17	216.70	34.41	60.21
P23	215.20	40.37	43.18	172.40	38.58	68.86
P24	237.00	57.80	70.61	244.10	77.97	75.45
P25	322.60	64.79	64.48	257.30	53.21	136.00
P26	243.42	49.99	86.62	244.20	44.07	85.16
P27	214.80	55.69	64.59	222.90	44.22	58.97
P28	303.60	41.55	56.46	239.10	67.12	129.90
P29	211.70	63.60	45.28	164.20	28.33	46.42
P30	298.10	26.27	71.38	254.50	39.26	117.90
Minimum	**151.40**	**23.47**	**19.59**	**129.00**	**21.00**	**18.45**
Maximum	**322.60**	**114.70**	**105.10**	**269.50**	**77.97**	**136.00**
Mean	**241.32**	**54.48**	**60.84**	**207.40**	**44.87**	**68.10**
Stand. deviation	**45.69**	**19.51**	**17.58**	**37.95**	**13.47**	**29.58**

A3 Raw results for “Study to monitor spinal posture and motion of desk workers” (Chapter 7)

Physiological movements

Table A3.1 Ranges of flexion for all 18 participants measured before and after 3 hours of desk work activities (bold = main movement plane)

ROM	**Flexion (Before)**			**Flexion (After)**		
Participants	FX	**FY**	FZ	XX	**XY**	XZ
P1	1.0	**42.3**	-1.3	-5.9	**39.1**	-8.0
P3	9.9	**42.2**	-5.9	5.6	**35.0**	2.6
P4	-1.9	**45.0**	-5.2	-5.6	**49.5**	-8.6
P5	2.0	**43.0**	-7.0	2.6	**41.3**	-7.7
P7	7.0	**64.8**	-12.2	12.1	**63.2**	-10.7
P8	2.6	**61.7**	-7.5	0.6	**62.6**	-9.1
P9	1.5	**60.6**	1.7	-3.4	**49.7**	4.0
P10	-8.7	**55.5**	7.0	-4.0	**53.6**	6.5
P12	-5.0	**54.3**	2.1	-4.1	**53.6**	2.1
P13	3.8	**51.7**	-7.1	3.6	**50.5**	4.3
P14	-2.2	**50.7**	-4.9	3.4	**48.4**	-5.7
P15	-4.2	**48.7**	6.0	-3.0	**51.6**	9.5
P16	4.7	**46.7**	0.8	6.8	**43.1**	-7.5
P17	-4.9	**56.4**	-3.9	-2.6	**58.4**	-5.2
P19	2.9	**40.6**	-3.5	2.7	**48.1**	-3.8
P20	4.3	**27.3**	-3.6	4.6	**30.6**	-4.3
P21	3.1	**40.1**	-4.6	2.0	**34.4**	9.3
P22	-1.9	**43.0**	2.2	-4.7	**50.6**	1.5
Minimum	-8.7	**27.3**	-12.2	-5.9	**30.6**	-10.7
Maximum	9.9	**64.8**	7.0	12.1	**63.2**	9.5
Mean	0.8	**48.6**	-2.6	0.6	**48.0**	-1.7
Stand. deviation	4.7	**9.3**	5.0	5.0	**9.2**	6.7

Table A3.2 Ranges of extension for all 18 participants measured before and after 3 hours of desk work activities (bold = main movement plane)

ROM	**Extension (Before)**			**Extension (After)**		
Participants	FX	**FY**	FZ	XX	**XY**	XZ
P1	2.6	**-15.7**	3.4	3.7	**-13.1**	3.9
P3	2.3	**-15.6**	-2.2	2.1	**-13.8**	-3.5
P4	3.3	**-28.9**	1.9	3.9	**-25.6**	0.9
P5	2.8	**-30.5**	-2.0	3.8	**-25.8**	-4.6
P7	4.0	**-21.2**	-3.2	4.3	**-16.6**	-2.3
P8	-3.7	**-31.1**	3.6	-2.2	**-30.5**	6.1
P9	1.2	**-26.5**	1.8	1.1	**-26.8**	0.6
P10	1.8	**-23.5**	3.5	3.0	**-18.0**	1.2
P12	4.7	**-20.1**	-1.7	4.0	**-16.1**	1.2
P13	4.9	**-23.2**	2.5	6.4	**-22.9**	0.4
P14	3.3	**-17.3**	3.7	4.5	**-13.3**	3.0
P15	2.8	**-24.8**	-3.8	1.5	**-16.0**	-3.6
P16	2.3	**-15.0**	2.0	-3.3	**-15.1**	-1.6
P17	-3.0	**-28.6**	-5.9	2.2	**-21.2**	-4.3
P19	3.8	**-34.9**	5.4	1.4	**-31.1**	6.4
P20	-4.1	**-13.8**	2.9	-5.3	**-8.7**	3.9
P21	-3.8	**-23.4**	6.8	-1.8	**-12.1**	1.6
P22	-4.7	**-18.5**	2.4	-3.7	**-17.8**	0.5
Minimum	-4.7	**-34.9**	-5.9	-5.3	**-31.1**	-4.6
Maximum	4.9	**-13.8**	6.8	6.4	**-8.7**	6.4
Mean	1.1	**-22.9**	1.2	1.4	**-19.1**	0.5
Stand. deviation	3.3	**6.3**	3.5	3.3	**6.6**	3.4

Table A3.3 Ranges of right lateral flexion for all 18 participants measured before and after 3 hours of desk work activities (bold = main movement plane)

ROM	Right flexion (Before)			Right flexion (After)		
Participants	FX	FY	**FZ**	XX	XY	**XZ**
P1	-2.2	6.5	**-14.9**	-1.0	9.2	**-14.4**
P3	3.2	3.6	**-13.6**	3.9	8.7	**-15.1**
P4	3.4	5.8	**-21.8**	5.0	3.0	**-22.6**
P5	3.9	3.2	**-27.6**	3.0	6.9	**-25.1**
P7	6.5	15.2	**-26.0**	2.9	10.7	**-25.8**
P8	7.8	4.4	**-17.4**	1.2	6.8	**-19.5**
P9	-3.1	-7.6	**-19.2**	2.7	-2.3	**-19.7**
P10	5.3	16.8	**-20.5**	7.3	29.8	**-23.3**
P12	12.0	9.4	**-19.8**	8.6	12.6	**-21.2**
P13	7.4	15.3	**-24.3**	8.1	15.5	**-22.6**
P14	8.6	15.1	**-21.2**	5.2	12.1	**-19.7**
P15	5.2	11.2	**-18.2**	4.8	15.6	**-17.2**
P16	5.3	9.5	**-21.2**	4.7	8.5	**-21.1**
P17	5.5	8.5	**-26.7**	5.5	12.0	**-25.3**
P19	6.5	11.4	**-22.0**	6.9	14.3	**-21.2**
P20	-4.0	1.8	**-11.0**	-2.1	-2.6	**-12.9**
P21	4.2	21.5	**-22.8**	6.1	16.5	**-22.2**
P22	-5.8	4.8	**-12.7**	-1.5	15.9	**-15.0**
Minimum	-5.8	-7.6	**-27.6**	-2.1	-2.6	**-25.8**
Maximum	12.0	21.5	**-11.0**	8.6	29.8	**-12.9**
Mean	3.9	8.7	**-20.0**	4.0	10.7	**-20.2**
Stand. deviation	4.7	6.8	**4.8**	3.2	7.4	**3.9**

Table A3.4 Ranges of left lateral flexion for all 18 participants measured before and after 3 hours of desk work activities (bold = main movement plane)

ROM	**Left flexion (Before)**			**Left flexion (After)**		
Participants	FX	FY	**FZ**	XX	XY	**XZ**
P1	2.3	6.5	**18.0**	1.5	8.3	**15.4**
P3	0.8	3.8	**16.1**	0.6	5.4	**16.0**
P4	0.6	5.3	**21.0**	-1.7	-4.6	**23.9**
P5	-4.8	13.5	**21.5**	-3.5	9.3	**22.2**
P7	-7.9	13.5	**24.7**	-6.6	11.5	**25.7**
P8	-2.2	-4.8	**17.8**	2.6	-4.6	**17.9**
P9	-2.9	7.1	**21.1**	-2.5	5.9	**22.2**
P10	-9.4	14.2	**33.3**	-9.0	17.7	**30.7**
P12	-5.4	10.3	**23.3**	-4.1	8.6	**22.4**
P13	3.4	11.9	**20.9**	2.3	11.8	**22.8**
P14	-2.2	10.7	**17.4**	-1.8	6.5	**17.4**
P15	-5.3	7.4	**21.4**	-5.7	7.5	**24.3**
P16	-5.6	12.3	**19.5**	-4.0	13.9	**19.9**
P17	-5.9	11.6	**26.3**	-4.8	9.2	**20.4**
P19	-3.4	11.3	**22.3**	-9.0	13.3	**24.4**
P20	-6.0	4.7	**14.9**	-4.6	3.8	**12.6**
P21	-4.2	10.8	**22.3**	-5.4	5.1	**23.6**
P22	-3.5	11.7	**16.5**	-6.6	14.3	**16.0**
Minimum	-9.4	-4.8	**14.9**	-9.0	-4.6	**12.6**
Maximum	3.4	14.2	**33.3**	2.6	17.7	**30.7**
Mean	-3.4	9.0	**21.0**	-3.4	7.9	**21.0**
Stand. deviation	3.4	4.7	**4.3**	3.5	5.9	**4.5**

Table A3.5 Ranges of right axial rotation for all 18 participants measured before and after 3 hours of desk work activities (bold = main movement plane)

ROM	Right axial rotation (Before)			Right axial rotation (After)		
Participants	**FX**	FY	FZ	**XX**	XY	XZ
P1	**-5.5**	-8.4	-3.5	**-2.9**	-7.8	-1.3
P3	**-7.8**	-11.8	-3.7	**-4.4**	-9.3	-2.4
P4	**-8.5**	-8.4	-2.0	**-6.1**	-3.5	-5.0
P5	**-14.0**	-7.2	-2.2	**-11.5**	-7.6	-2.1
P7	**-10.1**	-7.3	4.0	**-9.3**	-11.5	5.6
P8	**-12.3**	-6.1	5.6	**-11.1**	-3.0	7.6
P9	**-8.1**	-4.4	-1.3	**-7.8**	-5.8	1.1
P10	**-9.4**	-4.9	-5.5	**-5.8**	-5.9	2.3
P12	**-14.3**	-6.2	-2.9	**-14.9**	-8.9	-1.6
P13	**-6.5**	-9.5	-7.4	**-5.0**	-12.9	-6.8
P14	**-6.6**	-9.2	3.7	**-4.3**	-8.1	2.2
P15	**-7.4**	-11.0	1.2	**-6.9**	-9.2	0.3
P16	**-16.4**	-11.2	-3.2	**-16.9**	-10.1	6.2
P17	**-13.2**	-4.4	5.3	**-10.4**	-4.2	4.9
P19	**-13.7**	-4.1	5.3	**-13.3**	-10.5	5.5
P20	**-5.6**	-1.8	-1.0	**-5.4**	-2.7	-2.2
P21	**-13.5**	-5.9	-5.1	**-9.8**	-1.9	-4.2
P22	**-16.7**	-9.5	-5.4	**-11.2**	-7.0	-1.3
Minimum	**-16.7**	-11.8	-7.4	**-16.9**	-12.9	-6.8
Maximum	**-5.5**	-1.8	5.6	**-2.9**	-1.9	7.6
Mean	**-10.5**	-7.3	-1.0	**-8.7**	-7.2	0.5
Stand. deviation	**3.7**	2.8	4.2	**3.9**	3.2	4.2

Table A3.6 Ranges of left axial rotation for all 18 participants measured before and after 3 hours of desk work activities (bold = main movement plane)

ROM	**Left axial rotation (Before)**			**Left axial rotation (After)**		
Participants	**FX**	FY	FZ	**XX**	XY	XZ
P1	**5.6**	3.4	5.0	**4.4**	2.1	3.2
P3	**12.1**	-4.2	-1.0	**10.9**	-7.5	-5.8
P4	**11.1**	-5.0	4.4	**9.0**	-10.6	1.1
P5	**11.8**	-8.6	2.7	**9.0**	-3.0	-5.8
P7	**9.0**	-8.7	-3.0	**11.2**	-6.3	-6.1
P8	**12.0**	-2.8	-3.4	**11.2**	-5.0	-6.1
P9	**8.5**	-4.0	-1.3	**9.3**	-4.4	-2.5
P10	**9.7**	4.1	11.1	**10.3**	-7.1	5.3
P12	**13.9**	-4.7	3.3	**12.8**	-4.4	2.6
P13	**8.8**	-4.9	-1.8	**9.1**	-7.7	2.9
P14	**5.3**	-3.9	-1.0	**4.6**	-2.5	-1.9
P15	**10.8**	-12.3	5.8	**10.9**	-7.1	3.0
P16	**17.7**	-9.1	-2.0	**16.5**	-3.8	15.3
P17	**12.2**	-8.2	-2.9	**9.6**	-3.8	-5.4
P19	**15.7**	5.3	-4.6	**15.8**	4.2	2.0
P20	**8.8**	2.5	1.7	**7.7**	2.2	-3.3
P21	**13.8**	-5.1	3.1	**8.8**	-3.5	4.0
P22	**13.1**	-1.7	1.8	**9.0**	-3.8	2.1
Minimum	**5.3**	-12.3	-4.6	**4.4**	-10.6	-6.1
Maximum	**17.7**	5.3	11.1	**16.5**	4.2	15.3
Mean	**11.1**	-3.8	1.0	**10.0**	-4.0	0.3
Stand. deviation	**3.2**	4.9	4.0	**3.1**	3.8	5.5

Lumbar curvature angle during standing

Table A3.7 Standing lumbar curvature angles (°) for all 18 participants before and after 3 hour desk work; and lumbar curvature angles (°) between males and females during standing

	Standing lumbar curvature angle (°)		Standing lumbar curvature angle (°)	
Participants	**Before**	**After**	**Male**	**Female**
P1	26.3	25.2		26.3
P3	49.4	49.0		49.4
P4	26.8	27.2		26.8
P5	34.6	33.8		34.6
P7	42.3	41.6		42.3
P8	51.0	49.7		51.0
P9	33.3	28.2		33.3
P10	31.6	32.0		31.6
P12	26.3	26.2		26.3
P13	24.0	23.1	24.0	
P14	20.3	20.9	20.3	
P15	41.2	43.2		41.2
P16	16.0	15.2		16.0
P17	28.3	28.9		28.3
P19	24.2	24.6		24.2
P20	30.8	21.5	30.8	
P21	8.4	7.8	8.4	
P22	32.9	31.6		32.9
Minimum	8.4	7.8	8.4	16.0
Maximum	51.0	49.7	30.8	51.0
Mean	30.4	29.4	20.9	33.2
Standard Deviation	10.9	11.0	9.4	9.9

Desk work activities

Activities duration summary

Table A3.8 Data of 18 participants in duration spent in each dynamic activities (minutes)

	Duration spent in each dynamic activities (minutes)						
Participants	**Drinks**	**Phone**	**Toilet**	**Short walk**	**Stretching**	**Bending**	**Smoking**
P1	2.5	1.4					
P3	3.5					0.9	
P4							9.2
P5	10.9	1.5	3.3	5.4	1.1		
P7	2.2			0.7			
P8	3.6		4.9				
P9							
P10				2.2		1.0	
P12	3.6			3.4		5.7	15.3
P13	4.8		5.6	24.6			
P14	5.1			7.3			
P15	2.8			0.5			
P16				2.2		1.3	
P17							
P19			3.8				
P20	5.0		7.6	1.6			
P21							
P22			3.8	25.5		0.4	
Total duration	**44.0**	**2.8**	**28.9**	**73.5**	**1.1**	**9.3**	**24.6**

Table A3.9 Data of 18 participants in duration spent in each desk work activities (minutes); duration breakdown on total sitting movement (minutes)

	Duration spent in desk work activities (minutes)			Duration breakdown on movement (min)	
Participants	**Dynamic activities**	**Total movement**	**Total static sitting**	**Postural change**	**Postural adjustment**
P1	3.9	67.2	108.8	19.1	48.1
P3	4.4	49.3	125.7	18.2	31.1
P4	9.3	42.3	128.5	19.1	23.2
P5	22.1	50.9	106.6	10.7	40.2
P7	2.9	71.7	104.2	38.7	33.0
P8	8.4	43.7	127.4	21.6	22.1
P9	0.0	30.7	148.8	1.4	29.3
P10	3.2	69.8	107.0	40.6	29.1
P12	28.1	45.7	104.3	30.2	15.5
P13	35.0	27.4	122.9	14.3	13.1
P14	12.4	32.9	135.0	10.9	21.9
P15	3.4	9.0	167.6	1.2	7.8
P16	3.5	58.5	117.8	33.0	25.5
P17	0.0	74.0	105.3	33.1	40.7
P19	3.8	45.4	132.8	24.9	20.5
P20	14.2	24.9	140.3	6.4	18.5
P21	0.0	36.4	142.6	12.9	23.4
P22	29.7	35.7	114.2	14.6	21.1

Movement

Table A3.10 Data of 18 participants showing the number of occurrences of postural change/dynamic activities at S1, L1 spinous processes and the whole lumbar spine; and total duration spent in postural change/dynamic activities of the whole lumbar spine

	Postural change/dynamic activities			
	Number of occurrences			Duration spent (min)
Participants	**S1**	**L1**	**Lumbar**	**Lumbar**
P1	74	109	92	23.01
P3	94	158	151	22.62
P4	164	257	65	28.36
P5	147	249	47	32.81
P7	412	475	407	41.59
P8	134	274	259	30.06
P9	15	39	12	1.36
P10	388	457	477	43.88
P12	376	462	411	58.28
P13	132	230	214	49.26
P14	86	206	181	23.30
P15	11	8	19	4.62
P16	347	439	360	36.44
P17	309	342	214	33.05
P19	162	431	397	28.78
P20	75	176	123	20.57
P21	129	209	175	12.93
P22	304	303	197	44.29

Table A3.11 Data of 18 participants showing the number of occurrences of postural adjustment movements at S1, L1 spinous processes and the whole lumbar spine; and total duration spent in postural adjustment movement for the whole lumbar spine

	Postural adjustment movements			
	Number of occurrences			Duration spent (min)
Participants	**S1**	**L1**	**Lumbar**	**Lumbar**
P1	380	426	443	48.09
P3	313	373	380	31.11
P4	205	244	436	23.23
P5	736	876	1078	40.20
P7	503	446	514	33.04
P8	342	343	358	22.07
P9	430	541	568	29.34
P10	406	497	477	29.11
P12	368	238	289	15.55
P13	215	261	277	13.14
P14	259	500	525	21.94
P15	110	258	247	7.80
P16	394	376	455	25.54
P17	595	622	750	40.68
P19	387	452	486	20.50
P20	315	308	361	18.50
P21	297	431	465	23.42
P22	229	334	440	21.08

Table A3.12 Data of 18 participants showing the number of occurrences of gross movements at S1, L1 spinous processes and the whole lumbar spine

	Number of occurrences of gross movements		
Participants	**S1**	**L1**	**Lumbar**
P1	21	34	24
P3	37	54	30
P4	41	68	38
P5	25	38	28
P7	104	156	107
P8	45	118	97
P9	2	2	0
P10	131	212	149
P12	200	270	216
P13	64	108	92
P14	18	70	54
P15	4	6	4
P16	87	194	108
P17	91	127	75
P19	29	127	117
P20	13	28	17
P21	64	79	39
P22	92	97	48

Table A3.13 Data of 18 participants for mean duration spent in postural change/dynamic activities (seconds) and postural adjustment movements (seconds) at S1, L1 spinous processes and the whole lumbar spine

	Mean duration spent in each group of movements (seconds)					
	Postural change/dynamic activities (seconds)			Postural adjustment movements (seconds)		
Participants	**S1**	**L1**	**Lumbar**	**S1**	**L1**	**Lumbar**
P1	21.1	18.6	18.9	5.8	6.0	6.3
P3	12.7	10.3	10.6	4.7	4.5	4.6
P4	11.8	9.7	10.6	4.0	3.6	4.1
P5	15.6	11.5	17.3	2.2	2.3	2.4
P7	6.5	7.2	7.7	2.3	3.2	3.3
P8	11.3	8.5	8.6	2.4	3.0	3.3
P9	5.5	9.3	10.2	3.0	2.9	3.1
P10	6.2	6.2	6.4	2.4	2.9	3.2
P12	9.7	9.2	9.9	2.5	2.4	2.7
P13	22.9	15.4	16.2	2.7	2.3	2.6
P14	14.9	9.4	9.9	2.2	2.2	2.3
P15	25.8	14.4	18.5	2.4	1.9	1.9
P16	5.7	6.4	7.2	2.6	2.9	3.0
P17	6.5	8.9	10.5	2.3	2.7	3.2
P19	7.0	5.5	5.5	2.3	2.1	2.2
P20	20.0	10.5	13.4	2.4	2.7	2.8
P21	4.4	5.9	5.9	2.6	2.5	2.8
P22	11.2	12.3	17.7	1.9	2.3	2.6

Table A3.14 Data of 18 participants for mean angle change (°) in postural change/dynamic activities (seconds) and postural adjustment movements at S1, L1 spinous processes and the whole lumbar spine

	Mean angle change (°) during movements					
	Postural change/dynamic activities			Postural adjustment movements		
Participants	**S1**	**L1**	**Lumbar**	**S1**	**L1**	**Lumbar**
P1	4.4	4.9	4.0	0.5	0.4	0.5
P3	8.9	6.8	3.9	0.5	0.5	0.5
P4	4.8	3.7	3.6	0.7	0.7	0.6
P5	3.6	3.1	3.6	0.5	0.5	0.4
P7	5.3	5.0	4.9	0.8	0.7	0.7
P8	6.4	6.3	5.8	0.5	0.6	0.7
P9	2.8	2.9	1.8	0.3	0.4	0.3
P10	5.5	5.2	5.0	0.7	0.8	0.7
P12	4.6	6.7	6.5	0.6	0.6	0.7
P13	13.3	11.0	6.4	0.5	0.6	0.6
P14	3.9	5.2	4.7	0.5	0.6	0.6
P15	6.9	5.8	4.8	0.3	0.4	0.4
P16	3.6	5.4	4.7	0.7	0.5	0.6
P17	5.0	4.5	6.6	0.6	0.6	0.4
P19	3.7	4.2	4.5	0.6	0.7	0.7
P20	3.8	3.6	3.0	0.5	0.7	0.6
P21	8.6	7.6	3.9	0.4	0.5	0.5
P22	5.1	5.2	5.5	0.8	0.7	0.7

Static sitting

Table A3.15 Data of 18 participants for mean angles adopted in the X, Y, and Z axes, and lumbar curvature angles during static sitting (°); X refers to rotation angle, Y refers to sagittal angle; and the Z axis refers to the lateral flexion angle, positive values indicate flexed, left lateral flexed and left rotated postures, while negative values indicate the opposite postures

	Mean angle adopted during static sitting (°)			
Participants	**X**	**Y**	**Z**	**Lumbar curvature**
P1	-4.3	19.6	-2.7	4.6
P3	3.8	31.7	1.8	18.1
P4	-3.4	29.6	0.0	-2.7
P5	-2.1	31.0	1.8	3.0
P7	-3.6	29.6	-2.7	11.4
P8	-2.6	25.4	2.6	25.7
P9	-2.2	27.2	0.9	5.7
P10	4.3	32.8	2.9	-3.0
P12	1.3	27.8	1.1	-1.7
P13	2.2	19.4	1.2	4.0
P14	0.7	28.9	1.5	-8.1
P15	-3.2	24.0	-3.2	17.5
P16	-4.2	18.1	-0.2	-3.4
P17	-1.0	46.7	0.5	-17.1
P19	4.3	25.0	6.2	-1.2
P20	-4.5	34.0	-0.2	-1.9
P21	3.0	14.8	1.2	-5.9
P22	-1.9	14.8	-1.7	16.3

Relationship between changes in range of physiological movements and 3 hour desk work activities

Table A3.16 Multiple regression analysis between changes in extension and standing lumbar curvature angle, mean lumbar curvature angle during static sitting, mean changes in lumbar curvature angle between standing and sitting and total dynamic activities duration

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate	Change Statistics				
					Sig. F Change	R^2 Change	F Change	df1	df2
Summary	.560(a)	0.313	0.102	12.890	0.313	1.483	4	13	0.264

Model		Sum of Squares	df	Mean Square	F	Sig.
ANOVA(b)	Regression	985.770	4	246.443	1.483	.264(a)
	Residual	2160.079	13	166.160		
	Total	3145.849	17			

Model		Unstandardized Coefficients		Standardized Coefficients, Beta	t	Sig.	95% Confidence Interval for B	
		B	Std. Error				B	Std. Error
Coefficients(a)	(Constant)	30.622	14.978		2.044	0.062	-1.736	62.981
	Standing lumbar curvature angle	-5.729	3.668	-4.571	-1.562	0.142	-13.653	2.196
	Mean lumbar curvature angle during static sitting	5.398	3.714	4.292	1.453	0.170	-2.626	13.423
	Total dynamic activities duration	-0.302	0.290	-0.246	-1.039	0.318	-0.929	0.326
	Mean changes in lumbar curvature between standing and static sitting	5.450	3.485	3.115	1.564	0.142	-2.079	12.979

Table A3.17 Multiple regression analysis between changes in right axial rotation and total dynamic activities duration and total number of occurrences of gross movement

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate	Change Statistics				
					Sig. F Change	R^2 Change	F Change	df1	df2
Summary	.447(a)	0.200	0.093	14.613	0.200	1.871	2	15	0.188

Model		Sum of Squares	df	Mean Square	F	Sig.
ANOVA(b)	Regression	799.067	2	399.533	1.871	.188(a)
	Residual	3203.293	15	213.553		
	Total	4002.360	17			

Model		Unstandardized Coefficients		Standardized Coefficients, Beta	t	Sig.	95% Confidence Interval for B	
		B	Std. Error				B	Std. Error
Coefficients(a)	(Constant)	7.126	11.344		0.628	0.539	-17.052	31.305
	Total dynamic activities duration	0.597	0.354	0.396	1.689	0.112	-0.156	1.351
	Total number of occurrences of gross movement	-0.040	0.064	-0.148	-0.629	0.539	-0.176	0.096

Table A3.18 Multiple regression analysis between changes in left axial rotation and standing lumbar curvature angle, total postural adjustment duration, total number of occurrences of postural adjustment duration and number of occurrences of gross movements

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate	Change Statistics				
					Sig. F Change	R^2 Change	F Change	df1	df2
Summary	.586(a)	0.344	0.142	9.612	0.344	1.704	4	13	0.209

Model		Sum of Squares	df	Mean Square	F	Sig.
ANOVA(b)	Regression	629.640	4	157.410	1.704	.209(a)
	Residual	1201.150	13	92.396		
	Total	1830.789	17			

Model		Unstandardized Coefficients		Standardized Coefficients, Beta	t	Sig.	95% Confidence Interval for B	
		B	Std. Error				B	Std. Error
Coefficients(a)	(Constant)	12.335	10.896		1.132	0.278	-11.203	35.873
	Standing lumbar curvature angle	-0.263	0.219	-0.275	-1.203	0.250	-0.736	0.210
	Total number of occurrences of gross movement	-0.045	0.042	-0.247	-1.075	0.302	-0.137	0.046
	Total postural adjustment duration	0.341	0.315	0.335	1.083	0.298	-0.339	1.021
	Total number of occurrences of postural adjustment	0.008	0.018	0.141	0.462	0.652	-0.030	0.047

A4 Example MATLAB codes used to express the relative angles between 2 sensors

```
%First clean up workspace
clear all, close all hidden
finame1=input('Please enter name of Xsens 046 datafile. ','s');
finame2=input('Please enter name of Xsens 047 datafile. ','s');
S46=load(finame1,'ascii');
S47=load(finame2,'ascii');
S46_R=S46(:,2:10);
S47_R=S47(:,2:10);
% express 047 with respect to 046: take into neutral position
zer=input('Please enter the sample number when the zero location is selected. ');
for i=1:size(S46_R,1);
[a,b,c]=ROTXYZ((reshape(S46_R(i,:),3,3)'*reshape(S47_R(i,:),3,3))*(reshape(S46_R(
zer,:),3,3)'*reshape(S47_R(zer,:),3,3))');
Diff47_46(i,1:3)=[a,b,c];end;
figure(1),plot(Diff47_46*180/pi); title(' Relative angles of S47 with respect to
S46')
disp('X = frontal axis, Y = lateral axis to the left, Z = vertical axis');
for n=1:size(S46,1);
sam(n)= S46(n,1);
end
sam=sam';
angname = input('Please enter a filename to save the data. ', 's');
fod = fopen(angname, 'w');
for n=1:size(S46_R,1);
fprintf(fod, '%7.4f\t', sam(n));
fprintf(fod, '%7.4f\t',Diff47_46(n,1)*180/pi);
fprintf(fod, '%7.4f\t',Diff47_46(n,2)*180/pi);
fprintf(fod, '%7.4f\n',Diff47_46(n,3)*180/pi);
end

function [x,y,z] = rotxyz(R)
y1 = asin(R(1,3));
sz = -R(1,2)/cos(y1);
cz =  R(1,1)/cos(y1);
z1 = atan2(sz,cz);
sx = -R(2,3)/cos(y1);
cx =  R(3,3)/cos(y1);
x1 = atan2(sx,cx);
if y1>=0
  y2 = pi - y1;
else
  y2 = -pi -y1;
end
sz = -R(1,2)/cos(y2);
cz =  R(1,1)/cos(y2);
z2 = atan2(sz,cz);
sx = -R(2,3)/cos(y2);
cx =  R(3,3)/cos(y2);
x2 = atan2(sx,cx);
if ((abs(y1)+abs(z1)+abs(x1)) <= (abs(y2)+abs(z2)+abs(x2)))
  y=y1;
  z=z1;
  x=x1;
else
  y=y2;
  z=z2;
  x=x2;
end
```

A5 Applied anatomy of the lumbar spine

The adult vertebral column normally consists of 33 vertebrae. Out of the 33 vertebrae, 24 of them are separate mobile vertebrae; from the skull down, there are 7 cervical vertebrae (C1 to C7) in the neck, 12 thoracic vertebrae (T1 to T12) that support the rib cage followed by 5 lumbar vertebrae (L1 to L5) in the low back area. The other 9 vertebrae are immobile, they are the 5 fused vertebrae (S1 to S5) that form the sacrum and 4 fused vertebrae that form the coccyx (Agur and Lee 1999; Standring et al. 2005).

The shape of an adult's vertebral column is formed of 4 curvatures, the cervical, thoracic, lumbar and the sacrococcygeal curves (Agur and Lee 1999). The cervical curve is concave posteriorly from C1 to T2. The thoracic curve lies between T2 to T12, and is convex posteriorly. The lumbar curve is concave posteriorly between T12 and the lumbosacral joint. From the lumbosacral joint to the tip of the coccyx, lies the sacrococcygeal curve that is convex posteriorly (Agur and Lee 1999; Standring et al. 2005). These curves serve as shock absorbers against vertical compressive loads and assist the tendons of the spinal muscles, spinal ligaments and intervertebral discs in absorbing energy due to locomotion movements (Adams et al. 2002; Standring et al. 2005).

The lumbar vertebral column consists of 5 separate bony vertebrae that provide rigidity and allow mobility. The height of the vertebrae and intervertebral discs provide separation of the thoracic spine from the pelvis, and such separation is necessary to enable movement of the thoracic spine relative to the pelvis (Adams et al. 2002). Movement of the lumbar vertebral column is achieved by compressing the intervertebral discs and excessive movements are resisted by tension developed in the annulus fibrosus of the intervertebral discs (Adams et al. 2002), the detailed components of the intervertebral discs will be discussed in the following page. The lumbar vertebral column is also built to withstand axial compression loads that are produced by the weight of the upper body, head and any load carried in the upper limbs (Adams and Dolan 1995; Adams et al. 2002;

Bogduk 2005). To achieve this function, the vertebral body is made up of an outer cortical bone and reinforced internally by trabeculae that are arranged vertically and horizontally (Adams et al. 2002; Bogduk 2005), as shown in Figure A5.1. Both the vertical and horizontal trabeculae work together to transmit compression loads and to prevent buckling of the vertical trabeculae (Adams et al. 2002).

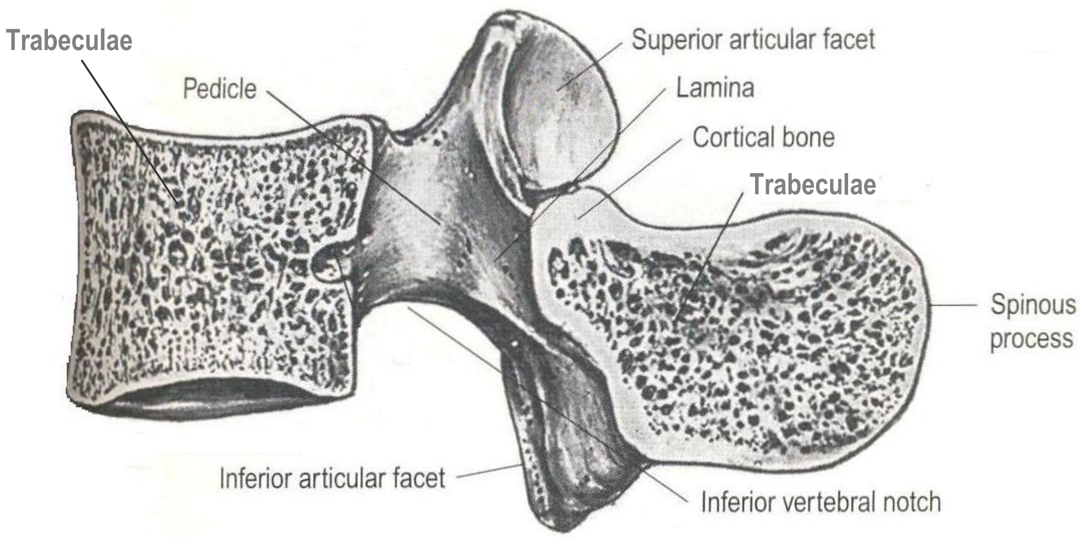
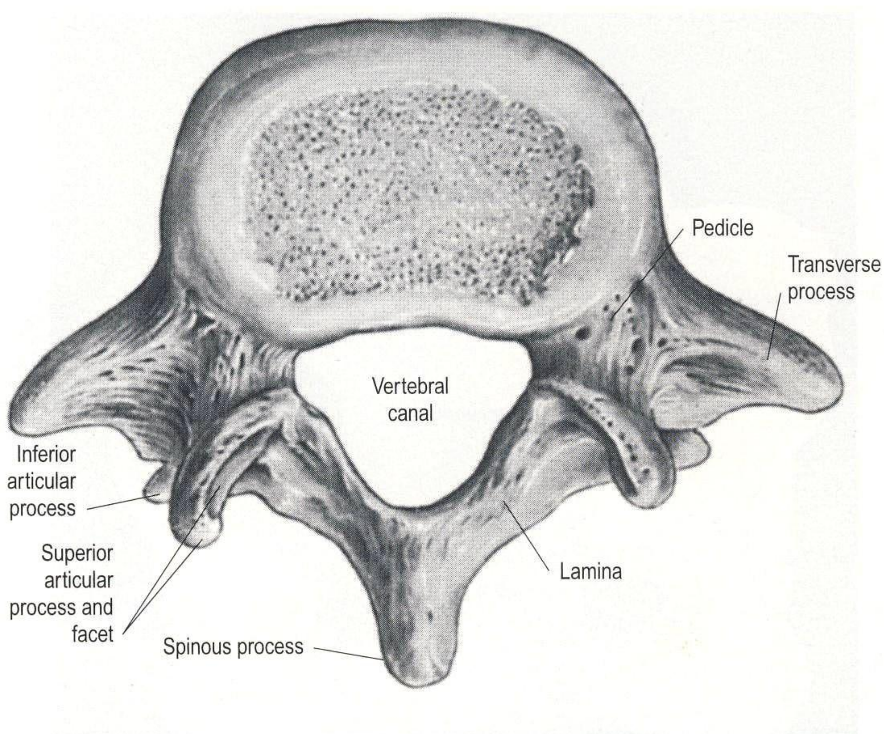


Figure A5.1: Illustration of vertical and horizontal trabeculae of a lumbar vertebral body (from Standring et al. 2005 Gray's Anatomy, 39th Edition, with permission of Elsevier, Churchill Livingstone)

The vertebral body loses its bone density with age, with the trabeculae affected more than the cortical bone and thus the vertebral body loses its strength in bearing compressive loading. Trabeculae do not thin uniformly and therefore the horizontal and vertical trabeculae may not connect and orientate the way they used to, this further weakens the resistance to deformation (Adams et al. 2002; Bogduk 2005). Women after menopause are usually affected the most due to a reduced level of sex hormones and in addition a low level of physical activity also has an influence on bone deterioration (Adams et al. 2002).

The posterior elements of the lumbar vertebrae provide stability and control of movements (Adams et al. 2002; Bogduk 2005). The posterior elements of a vertebra include the pedicles, laminae, the articular processes, the spinous processes and the transverse processes, and are shown in Figure A5.2. The pedicles work as support in the posterior elements of the vertebrae and transmit forces sustained by the posterior elements to the vertebral bodies, and vice-versa (Adams et al. 2002; Bogduk 2005). The laminae on the other hand receive forces that act on the spinous processes and the articular processes (Bogduk 2005).

Superior view



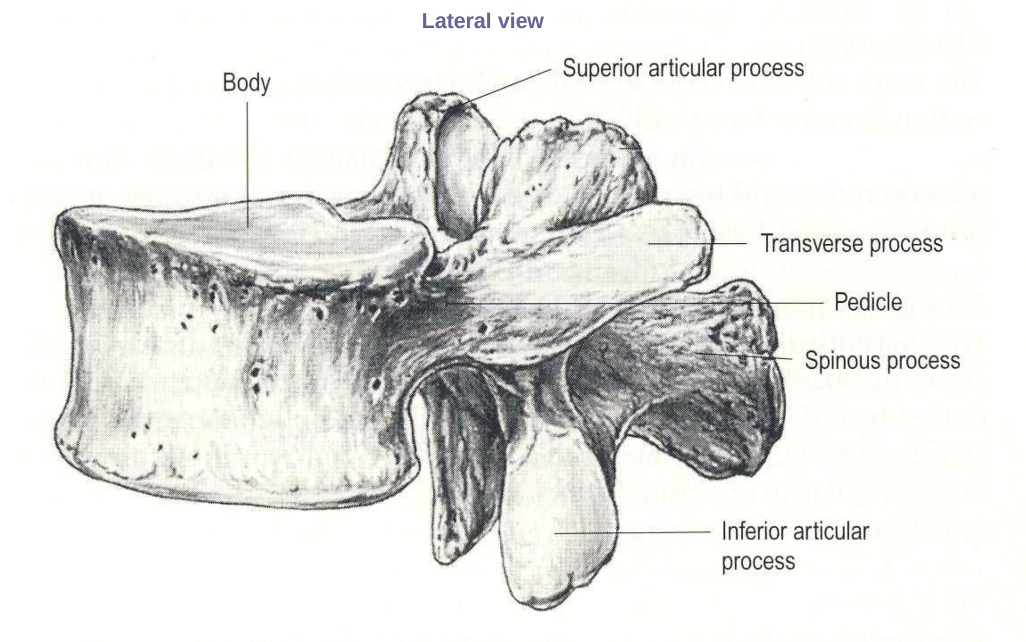


Figure A5.2: Illustration of the posterior elements of the lumbar vertebra (from Standring et al. 2005 Gray's Anatomy, 39th Edition, with permission of Elsevier, Churchill Livingstone)

Between each vertebra, there lies an intervertebral disc. The intervertebral discs are made up of 2 components, the outer part is the annulus fibrosus; and the inner part the nucleus pulposus (Adams et al. 2002; Bogduk 2005; Standring et al. 2005). The main functions of the intervertebral discs are to transmit loads and to allow movement to occur between the vertebral bodies (Adams et al. 2002; Bogduk 2005).

The annulus fibrosus consists of layers of tightly packed collagen, called the lamellae. These lamellae are stiff and strong so the annulus fibrosus is able to transmit compression loads between the vertebrae; they are also deformable in order to allow movements between vertebrae (Adams et al. 2002; Bogduk 2005). As shown in Figure A5.3, the annulus fibres are arranged in parallel and are orientated in the opposite direction between the adjacent lamellae (Adams et al. 2002; Bogduk 2005; Standring et al. 2005). This arrangement enables the annulus fibrosus to resist tension in different directions (Adams et al. 2002; Bogduk 2005).

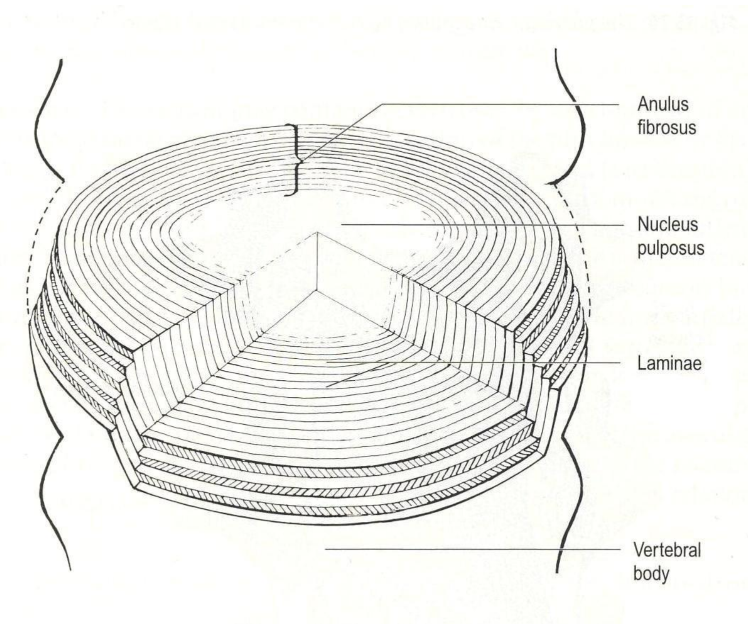


Figure A5.3: Illustration of the basic structures of a lumbar intervertebral disc (from Standring et al. 2005 Gray's Anatomy, 39th Edition, with permission of Elsevier, Churchill Livingstone)

At the centre of the intervertebral disc is a semi-fluid gel component called the nucleus pulposus. This prevents the annulus fibrosus from buckling inward during sustained compressive loads and hence maintains the stiffness of the intervertebral discs (Adams et al. 2002; Bogduk 2005).

Each lumbar intervertebral disc is approximately 10mm in height; during daily upright activities, the disc height will reduce due to fluid expelled from the intervertebral disc caused by compressive loads (Adams et al. 2002). This phenomenon is referred to as creep and is further discussed in Section 2.3. Intervertebral disc height does not decrease with age; in fact it maintains or even increases in height (Adams et al. 2002; Bogduk 2005; Sether et al. 1990; Twomey and Taylor 1985). The process of aging of the intervertebral discs starts as early as birth (Adams et al. 2002; Boos et al. 2002). As the intervertebral discs age, the collagen contents increase and thus intervertebral discs become more fibrous and the distinction between the nucleus pulposus and the annulus fibrosus becomes unclear (Adams et al. 1977; Bogduk 2005; Sether et al. 1990). The nucleus pulposus dehydrates gradually and becomes stiffer and more granular (Adams et al. 2002; Bogduk 2005; Sether et al. 1990). As the nucleus pulposus loses fluid content to collagen, it decreases in volume and hydrostatic pressure thus shifting the role of compressive load resistance to the annulus pulposus, this could subject the annulus pulposus to a higher risk of injury (Adams et al. 2002; Bogduk 2005).

There are two vertebral endplates in each intervertebral disc covering the nucleus pulposus and partially covering the annulus fibrosus. The other side of these cartilaginous endplates covers the area of the vertebral body by an apophyseal ring. Vertebral endplates enable nutrient diffusion to the nucleus pulposus (Bogduk 2005). Vertebral endplates start to experience thinning and cell death in the superficial layers of the cartilage between the ages of 20 to 65; calcification occurs and this compromises nutrition supply to the intervertebral discs; also the strength of endplates decreases with age (Adams et al. 2002; Ariga et al. 2001; Bogduk 2005).

The zygapophyseal joints, also known as the apophyseal joints or facet joints are synovial joints between the superior articular processes of the lower vertebrae and the inferior articular processes of the upper vertebrae (Adams et al. 2002; Bogduk 2005; Standring et al. 2005). The functions of the zygapophyseal joints in the lumbar spine are to limit axial rotation and to resist forward displacement of the vertebrae in order to protect intervertebral discs from excessive torsion and to prevent the vertebrae from dislocating (Adams and Dolan 1995; Adams et al. 2002; Bogduk 2005; Standring et al. 2005).

The ligament that interconnects the anterior portions of the lumbar vertebral bodies and intervertebral discs is the anterior longitudinal ligament (Adams et al. 2002; Bogduk 2005; Standring et al. 2005). The main function of the anterior longitudinal ligament is to prevent anterior separation of the vertebral bodies during extension (Bogduk 2005; Standring et al. 2005). Posteriorly, the posterior longitudinal ligament covers the vertebral bodies and intervertebral discs within the vertebral canal (Adams et al. 2002; Standring et al. 2005) and works to prevent posterior separation of the vertebral bodies during flexion (Bogduk 2005; Standring et al. 2005). Figure A5.4 shows the location of the ligaments of the lumbar vertebral column.

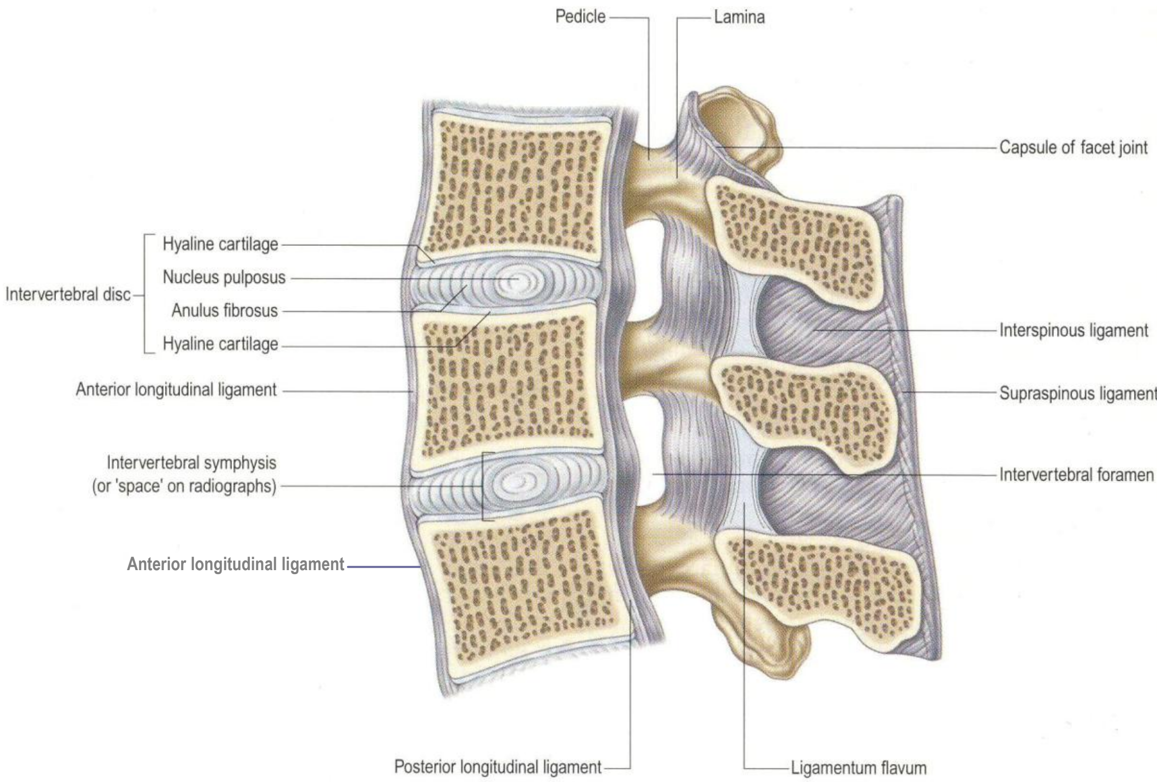


Figure A5.4: Illustration of the ligaments of the lumbar spine (from Standring et al. 2005 Gray's Anatomy, 39th Edition, with permission of Elsevier, Churchill Livingstone)

Within the posterior elements of the lumbar vertebral column, lie the ligamentum flavum, interspinous and supraspinous ligaments. The ligamentum flavum connects adjacent laminae; these ligaments contain a large proportion of elastin fibres that enable the ligamentum flavum to stretch during flexion and recoil when the neutral position is resumed (Adams et al. 2002; Bogduk 2005; Standring et al. 2005). The adjacent spinous processes are connected by interspinous ligaments; while the supraspinous ligament links the posterior tip of the consecutive spinous processes, and usually ends at L4 (Adams et al. 2002; Bogduk 2005; Standring et al. 2005).

The muscles surrounding the lumbar vertebral column may be categorised into 3 groups; the intertransverse muscles, the anterolateral muscles and the posterior muscles (Adams et al. 2002; Bogduk 2005). The intertransverse muscles connect the transverse processes; while the anterolateral muscles cover the anterolateral aspects of the lumbar spine; and the posterior muscles are attached to the posterior elements of the lumbar vertebral column (Adams et al. 2002; Bogduk 2005). Each of these groups of muscles function in a different manner and also work co-operatively to stabilise and control movement in the lumbar vertebral column (Adams et al. 2002; Bogduk 2005; Standring et al. 2005). As muscle ages, it becomes weaker by losing mass and strength; stiffer due to increase in collagen content; and slower in reaction and control as the proprioceptive ability is impaired (Adams et al. 2002).

A6 Inertial measurement systems

A6.1 Gyroscope theory

There are 3 main types of gyroscopes, the spinning mass gyroscopes, optical gyroscopes and vibratory gyroscopes. The spinning mass gyroscope or the conventional gyroscope consists of a mass spinning in movable gimbals; when the gyroscope is tilted, it produces precession or a change in rotational direction on the rotating mass axis and the rotating angle can then be measured (Titterton and Weston 2004). Optical gyroscopes work by emitting 2 laser beams in opposite directions in the enclosure and measure the rate of rotation by detecting the phase shift between the two beams (Nebot 1999). There are a variety of vibratory gyroscopes available, such as tuning fork gyroscopes (Eichholz et al. 2000; Hashimoto et al. 1995; Prasad et al. 2005) and vibrating ring gyroscopes (Ayazi et al. 2000; Ayazi and Najafi 2001). MEMS gyroscopes usually work in vibratory mode (Park and Horowitz 2003; Prasad et al. 2005). The materials and structure of different vibratory gyroscopes are dependent on the specific design, though all vibratory gyroscopes are based on the same concept, which is the Coriolis coupling principle (Nebot 1999). The basic operation of a vibratory gyroscope can be described as a proof mass, typically silicon; that is suspended in 2 perpendicular directions, one is the driving or vibrating axis and the other is the sensing axis, as shown in Figure A6.1. The silicon is excited by an electrostatic force to vibrate in the driving axis at constant amplitude. When there is a change in rotation of the driving axis, the Coriolis force will transfer the energy and cause a vibration perpendicular to the driving axis, in the sensing axis (Alper and Akin 2002; Aminian and Najafi 2004; Nebot 1999; Park and Horowitz 2003; Park and Horowitz 2004).

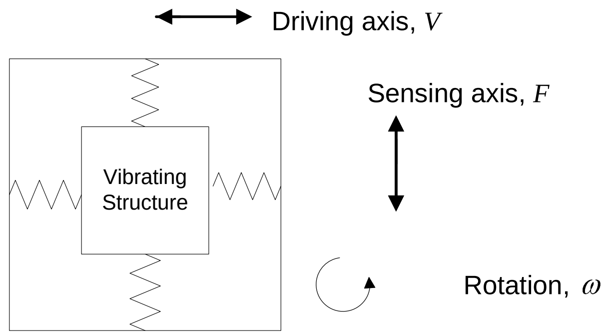


Figure A6.1: Basic vibratory gyroscope configuration

The Coriolis force that causes vibration in the sensing axis is proportional to the angular velocity of the rotation. The Coriolis force is also dependent on the mass of the vibrating silicon, m, and the velocity of the vibrating silicon, V. Therefore, Coriolis force, F can be expressed as (Aminian and Najafi 2004; Prasad et al. 2005; Xie and Fedder 2003)

$$F = -2m\omega V \quad \text{E A6.1}$$

The electronic detection components embedded in the system measure the Coriolis force, in terms of deformation of the silicon supporting bars or springs in the sensing axis. This Coriolis force is proportional to the rate of rotation acting on the driving axis. As the mass and the velocity of the vibrating silicon are known, the angular velocity of the driving axis can be derived from the Coriolis force and converted into voltage at the output of the sensor.

The computation of the rotation angles from angular velocities can theoretically be achieved by integrating the data measured by the gyroscopes, however in 3 dimensional strapdown inertial measurements, the computation of 3 dimensional rotational angles require a more complex set of mathematical functions as the 3 axes are orthogonal to each other and individual rotational angle depends on the rotations in all 3 axes.

There are many different mathematical algorithms for describing the orientations of rotating axes. The direction cosine matrix (also known as the rotation matrix) is a 3x3 matrix, with its columns representing the unit vectors in the body axes projected onto the reference axes (Titterton and Weston 2004; Zatsiorsky 1998). A direction cosine matrix with the body axes projected onto the reference axes, R_b^r can be expressed as followed.

$$R_b^r = \underbrace{\begin{pmatrix} Cos_{Xx} & Cos_{Xy} & Cos_{Xz} \\ Cos_{Yx} & Cos_{Yy} & Cos_{Yz} \\ Cos_{Zx} & Cos_{Zy} & Cos_{Zz} \end{pmatrix}}_{\text{Body axes (columns)}} \Big\} \text{Reference axes (rows)} \qquad \text{E A6.2}$$

Where the upper case letters refer to the axes of the reference frame and lower case letters refer to the axes of the body frame. In other word, Cos_{Yz} represent the cosine of the angle between the Y axis of the reference frame and Z axis of the body frame.

Direction cosine matrix can be used to transform vectors in the body frame to the reference frame by multiplying the vectors, in this case, the angular velocities, $\underline{\omega}$ of the gyroscopes, by the direction cosine matrix, $\underline{R}$, as shown below.

$$\dot{\underline{R}} = \underline{R}\underline{\omega} \qquad \text{E A6.3}$$

Where $\underline{\omega}$ is expressed in the form of 3x3 identity matrix.

$$\underline{\omega} = \begin{pmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{pmatrix} \qquad \text{E A6.4}$$

However the direction cosine matrix is represented by 9 elements which does not lend itself readily to be interpreted as rotational angles with respect to anatomical representations (Craig 1986). The use of Euler angles on the other hand is a more popular method in rotational angle representation, as it is easy to interpret as the angles are directly associated to anatomical movements. Euler angles transform a coordinate frame to another by using 3 rotation angles about 3 different axes (Craig 1986; Titterton and Weston 2004). The 3 Euler angles are ϕ, rotates about $\underline{X}$ axis; θ, rotates about $\underline{Y}$ axis; and ψ, rotates about the $\underline{Z}$ axis, as shown in Figure A6.2.

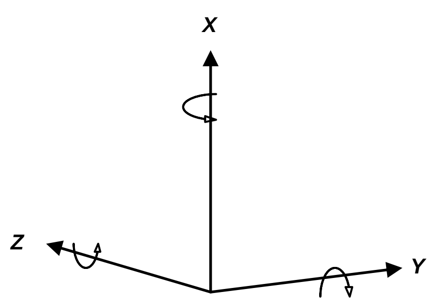


Figure A6.2: Three dimensional axes rotation

When there is a rotation of ϕ, about $\underline{X}$ axis, the location of $\underline{Y}$ and $\underline{Z}$ axes are displaced by an angle of ϕ. Similarly when $\underline{Y}$ axis is rotated an angle of θ, $\underline{X}$ and $\underline{Z}$ axis are displaced by θ; and when $\underline{Z}$ axis is rotated with ψ, $\underline{X}$ and $\underline{Y}$ axes will displace by an angle of ψ. Therefore, the 3 rotations about each individual axis could be mathematically defined as follows.

$$\underline{Rx}(\phi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix} \qquad \text{E A6.5}$$

$$\underline{Ry}(\theta) = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix} \qquad \text{E A6.6}$$

$$\underline{Rz}(\psi) = \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \text{E A6.7}$$

In order to transform the body frame to the reference frame, the Euler angles may be expressed as a product of the 3 individual rotations (Craig 1986; Titterton and Weston 2004), as shown below.

$$\underline{[Rzyx]_b^n} = \underline{[Rz]^T}\,\underline{[Ry]^T}\,\underline{[Rx]^T} \qquad \text{E A6.8}$$

And the product of the Euler angles transformation is expressed in terms of direction cosine matrix as shown in equation E A6.9.

$$\underline{[Rzyx]_b^n} = \begin{pmatrix} \cos\theta\cos\psi & -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{pmatrix} \qquad \text{E A6.9}$$

Which can be simplified to

$$\underline{[Rzyx]_b^n} = \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{pmatrix} \qquad \text{E A6.10}$$

From the matrix, the Euler angles of the body frame with respect to the reference frame can be obtained by using the following equations.

$$\phi = \tan^{-1}\left(\frac{R_{32}}{R_{33}}\right) \quad \text{E A6.11}$$

$$\theta = \sin^{-1}\left(R_{31}\right) \quad \text{E A6.12}$$

$$\psi = \tan^{-1}\left(\frac{R_{21}}{R_{11}}\right) \quad \text{E A6.13}$$

Euler angles however will encounter problems when θ is approaching ±90^o, the solution for ϕ and ψ will become indeterminent as R_{33} and R_{11} (the denominators) approach zero. This phenomenon is known as gimbal lock (Craig 1986; Mital and King 1979; Titterton and Weston 2004; Zatsiorsky 1998). Consequently as θ approaches ±90^o other solutions need to be sought using other elements of the direction cosine matrix (Craig 1986; Titterton and Weston 2004; Zatsiorsky 1998).

Gyroscopes often suffer from drift over time and it is essential to incorporate a drift correction algorithm in order to minimise errors in orientation estimation especially during integration of the results complete with the drift component (Dejnabadi et al. 2006; Luinge and Veltink 2005).

A6.2 Accelerometer theory

When there is no acceleration due to body movement or the acceleration due to body movement is relatively small when compared to the gravitational component (Mathie et al. 2004b; Veltink et al. 1996; Zheng et al. 2005), accelerometers can be used to measure tilt angle.

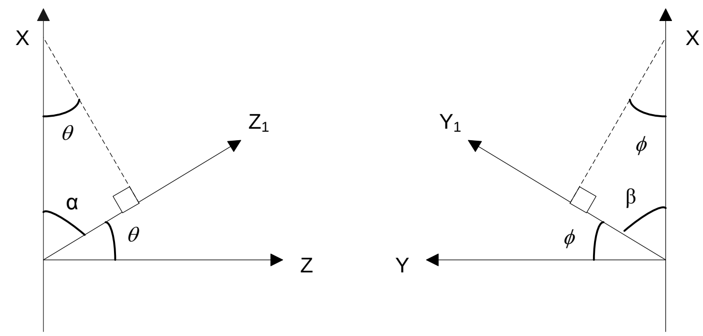


Figure A6.3: Illustration of tilt angle calculation

Figure A6.3 shows the tilt angles of the respective axes, tilt angle for Z_1 axis, θ with respect to the ground can be calculated by

$$Z_1 = X \sin\theta \qquad \text{E A6.14}$$

Where X is the vertical axis or the negative gravitational component, $-g$, where g is equal to 1. Equation E A6.14 can be rewritten as

$$Z_1 = -g \sin\theta \qquad \text{E A6.15}$$

$$\theta = -\sin^{-1}(Z_1 / g) \qquad \text{E A6.16}$$

$$\theta = -\sin^{-1}(Z_1) \qquad \text{E A6.17}$$

Similarly the tilt angle for Y_1 axis, ϕ with respect to ground can be calculated by a similar equation as shown below (Clifford and Gomez 2005; Kionix 2006; Luinge et al. 1999) as

$$\phi = -\sin^{-1}(Y_1) \quad \text{E A6.18}$$

To calculate the tilt angle for Z_1 axis, α with respect to the vertical axis,

$$Z_1 = X\cos\alpha \quad \text{E A6.19}$$

$$\alpha = -\cos^{-1}(Z_1) \quad \text{E A6.20}$$

And the tilt angle for Y_1 axis, β with respect to vertical axis can be calculated by

$$\beta = -\cos^{-1}(Y_1) \quad \text{E A6.21}$$

However, when the acceleration due to body movement is large, for example during measurement of spinal movement, the acceleration measured will include components due to body movement and gravitational acceleration. This then presents a challenge to subtract the gravitational component from the accelerometer signals without knowing the direction of the sensor. In this case, inclination information may need to be obtained from other sensors such as gyroscopes.

MEMS (micro-electromechanical systems) accelerometers operate based on a 'damped mass' principle. A single axis accelerometer can be described as a system comprising a proof mass that is suspended by beams in one direction in an enclosure, as shown in Figure A6.4. When there is a change in acceleration in the sensing direction, it will cause the proof mass to displace and the consequent change in the mechanical force of the beams will produce changes in the electrical response of the electronic detection components (Aminian and Najafi 2004; Mathie et al. 2004b; Veltink et al. 1996). The displacement of the proof mass is proportional to acceleration experienced by the accelerometer.

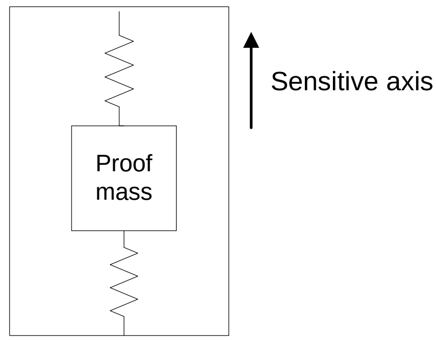


Figure A6.4: Basic operational principles of accelerometers

The mechanical force, f of the displacement is expressed as followed.

$$f = ma \quad \text{E A6.22}$$

Where m is the mass of the proof mass and a is the acceleration experienced by the enclosure. Since f and m are known, acceleration a can be converted to voltage as the output of the MEMS accelerometer.

List of publications/presentations related to this thesis

Ha, T.H., R. Lee and M.P. Jones. Measurement of Spinal Motion Using Inertial Sensors – Comparison of Different Computation Methods. *8th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering CMBBE 2008* 27 February-1 March 2008, Porto, Portugal (Poster presentation)

Ha, T.H., R. Lee and M.P. Jones. Measurement of Spinal Motion Using Inertial Sensors. *The Health Technologies KTN/University of Brighton Conference* 3 April 2008, Brighton, UK (Oral presentation)

Ha, T.H., A.P. Moore, R. Lee, K. Saber-Sheikh and M.P. Jones. Measurement of Spinal Motion Using Inertial Sensors. *The 10th International Symposium on 3D Analysis of Human Movement,* 28-31 October 2008, Santpoort/Amsterdam, The Netherlands (Interactive presentation)

Ha, T.H., R. Lee and M.P. Jones. 2009. Measurement of Spinal Motion Using Inertial Sensors – Comparison of Different Computation Methods. *Proceedings of the 8th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering CMBBE 2008,* 27 February-1 March 2008, Porto, Portugal