THE HONG KONG POLYTECHNIC UNIVERSITY

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EFFECTS OF BACK PAIN ON THE CORRELATION BETWEEN HIP AND LUMBAR SPINE MOVEMENTS

BY

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A thesis submitted in partial fulfillment of the requirements for the Degree of Master of Philosophy

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no materials previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

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Abstract

Abstract of the thesis entitled "Effects of back pain on the correlation of hip and lumbar spine movements" *submitted by* Thomas Ki Tai Wong *for* M.Phil. *at The Hong Kong Polytechnic University in August 2004.*

Aim of study

The aim of this experimental study was to examine the effects of low back pain and limitation in straight leg raise on the kinematics of the lumbar spine and hips.

Methods

A real-time three-dimensional electromagnetic tracking system was used to measure the movements of the lumbar spine and hips during various anatomical movements. Kinematic analysis was performed in asymptomatic subjects (n=20), and back pain subjects with (n=18) and without (n=24) limitation in straight leg raise. Subjects were requested to perform forward, backward and side bending, and twisting of the trunk. One-way analysis of variance, (ANOVA) was used to compare the maximum magnitude of movements among the three groups. Cross-correlation was employed to reveal the relative time lag between lumbar spine and hips and the strength of correlation of the movements.

Results

ANOVA revealed that the ranges of various lumbar spine movements were significantly reduced in back pain subjects ($p<0.05$). During forward bending of trunk, the maximum hip flexion ranges were significantly different among the three groups. However, there were no differences in the hip ranges of movements

in the other directions ($p<0.05$). Back pain subjects required significantly more time to complete all three trunk movements ($P<0.05$).

For forward & backward bending, the contributions of the lumbar spine and hips were approximately equal. During side-bending of the trunk, the magnitude of the lumbar spine movement was more than twice of those of the hips. On the other hand, during trunk twisting, the contribution of the spine was smaller than that of the hips. Back pain and limitation in SLR was found to affect the relative contributions of the lumbar spine and hips during side-bending and twisting of the trunk, but not that for forward and backward bending.

The strength of correlation between the movements of the lumbar spine and hip were high in normal subjects for all trunk movements. The mean peak cross-correlation coefficients were generally smaller in back pain subjects ($p<0.05$). The time lags at peak correlation were not significantly different from zero for all movements ($p>0.05$) in all groups.

Discussion and conclusion

The experimental results suggest that back pain is associated with significant changes in the kinematic characteristics of the trunk. Subjects with limited SLR exhibited further reduction in hip flexion when compared with subjects with back pain only. It is suggested that stiffness of posterior hip tissues may contribute to the limitation in SLR and range of movement.

It is revealed that back pain patients modify their joint coordination strategies in accomplishing trunk movements and take a longer time to complete the movements. These may seriously affect the functional activities and the quality of life of the patients. Clinically, it is important to evaluate the kinematic characteristics of both the lumbar spine and hip for back pain patients. Assessment of lumbar spine motions alone will not be able to reveal how joint coordination is affected by back pain and the potential implications on functional performance. Exercise program should be aimed to restore not only range of movement but also the movement coordination.

Publications arising from the thesis

Full papers (peer-reviewed):

Lee RYW and Wong TKT (2002) Relationship between the movements of the lumbar spine and hip. Human Movement Science. 21(4):481-494.

Wong TKT and Lee RYW (2004) Effects of low back pain on the relationship between the movements of the lumbar spine and hip. Human Movement Science. 23(1):21-34.

Conference abstracts:

Wong TKT and Lee RYW (2002) Relationship between the movements of the lumbar spine and hips, In: Proceedings of the 3rd Pan Pacific Conference of Rehabilitation, Hong Kong, p23.

Wong TKT and Lee RYW (2003) Effects of back pain on the movements of the lumbar spine and hip, In: Proceedings of the 13th International Conference on Mechanics in Medicine and Biology, Taiwan, p61.

Wong TKT and Lee RYW (2004) Effects of back pain on the correlations of the lumbar spine and hip. In: Proceedings of the XVth Congress of the International Society of Electrophysiology and Kinesiology, Boston, p198.

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List of abbreviations

ALL	Anterior longitudinal ligament
ANOVA	Analysis of variance
CMC	Coefficient of Multiple correlation
DVF	Digital videofluoroscopic technique
EMT	Electromagnetic device
ICC	Intraclass correlation coefficient
ISB	International Society of Biomechanics
JCS	Joint coordinate system
LBP	Low back pain
Lx	Lumbar spine
MRI	Magnetic resonance imaging
NPH	Non-painful hip
NPS	Numerical Pain Scale
PH	Painful hip
PLL	Posterior longitudinal ligament
RDQ	Roland-Morris Disability Scale
ROM	Range of movement
SEU	System electronic unit
SLR	Straight leg raise

Chapter 1 Introduction

1.1. Magnitude of the low back pain problem

Low back pain (LBP) is a common health problem in many countries. 70-85% of people have at least an episode of LBP some time in their life (Borenstein, 2001; Svensson & Andersson, 1982). The annual prevalence of LBP was found to be 15-45% in the USA and about 34% in the UK (Lau et al., 1995). In Hong Kong, Lau et al found that the annual prevalence was 22% , which was lower than other western countries (Lau et al., 1995). But it was revealed that the prevalence was as high as 58% among manual lifting workers in Hong Kong (Lau et al., 1995, Yeung 2002).

Back pain continues to be a major occupational and public health problem with substantial economic and social burdens (Williams et al., 1998). Johns et al (1994) showed approximately 10 million employees in the United States suffered from back pain that impaired their performance. LBP was also causing 149 million lost work days annually (Guo et al., 1999). A British research study found that 3% of subjects were absent from work for more than 6 months due to LBP, but this accounted for 33% of the benefits paid during the study period (Watson et al., 1998).

The high incidence rate of LBP has been responsible for the high compensation costs for employers and insurance companies. A cost-of-illness study in the UK estimated that the direct clinical costs of LBP were £1.6 billion in 1998 and the overall costs, including lost work and compensation, varied between £6.6 billion and £12.3 billion (Maniadakis & Gray, 2000). In the United states, Rizzo et al (1998) estimated that the annual productivity loss was approximately US$28 billion based on data from the 1987 National Medical Care Expenditure Survey. The joint study of the Liberty Mutual Insurance Company, the Washington State Department of Labor and Industry, and the Bureau of Labor Statistics (Murphy & Volinn, 1999) revealed that about US$8.8 billion was spent on LBP in 1995.

Clearly, based on the above data, low back disorders is a significant public health problem. The efficiency of clinical management of this problem must be improved to miminise the economic costs. This would require a thorough understanding of the physiological and mechanical mechanisms of LBP, which demands further research into the problem.

1.2. The correlation between the lumbar spine and hip

Recent research has provided large amount of information which provides insights into the mechanisms of LBP. However, they were primarily focused on the lumbar spine, and the mechanical interaction between the lumbar spine and the neighbourhood joints was not fully understood. Experimental investigations would be required to examine such interaction if a thorough understanding of the mechanisms of LBP was to be sought. There was surprisingly little information on the relationship between the lumbar spine and the hips, as many activities of daily living would involve the movements of both regions, for instance, picking up object from floor, lifting and bending of the trunk. The contributions of the lumbar spine and hips might vary from one activity to another, and could also be potentially affected by back pain.

Recent evidence (Goeken & Hof, 1994; Grenier et al., 2003; Halbertsma et al., 2001; Mellin, 1990) showed that dysfunctions of the lumbar spine would affect the mobility of the hip. For instance, the hip flexion range and the flexibility of the hip tissues were found to be decreased in LBP patients (Goeken & Hof, 1994; Grenier et al., 2003; Halbertsma et al., 2001; Mellin, 1990). On the other hand, it was, believed that alteration in the hip mobility would affect the mechanical functions of the lumbar spine (Li et al., 1996).

In fact, clinical examination of low back pain should not be limited to the lumbar region only but also the hips. Symptoms due to mechanical dysfunctions of the lumbar spine might spread to the hips and beyond (Beattie et al., 2000; Jonsson & Stromqvist, 1993; Kortelainen et al., 1985). Likewise, symptoms due to hip dysfunctions could also radiate to the low back region (Swezey, 2003). Clinically, straight leg raising test is widely employed to test the flexibility of posterior hip tissues, primarily the hamstrings, and tensions in the sciatic nerve (Rebain et al., 2002; Rebain et al., 2003). It was suggested that limitation in straight leg raising might be produced by spinal pathologies such as herniated intervertebral disc (Atalay et al., 2003; Xin et al., 1987) and spondylolisthesis (Moller et al., 2000). It is a popular clinical practice to treat low back symptoms by stretching the posterior hip tissues, for instance, the hamstring muscles (Bohannon, 1984; Khalil et al., 1992).

There was ample evidence to show that the lumbar spine and hips work together mechanically and the clinical examination of the two regions could not be separated. Thus there was a strong need to increase our understanding of the mechanical interaction between the lumbar spine and hips. The present study attempted to fill this knowledge gap by examining the kinematic behavior of the two regions.

1.3. Purpose of the study

Specifically, the purpose of this study was:

1. to examine the correlation between the lumbar spine and hip movements in normal subjects in all three anatomical planes, and
2. to examine the effects of back pain and limitation in straight leg raising on the correlation between the lumbar spine and hip movements.

It was hoped that the study would provide fundamental information on the effects of back pain on the lumbar spine and hip movements. With such information in hands, clinical assessment could be made more precise and it would be possible to identify the physical impairments of the patients. Appropriate rehabilitation programs could then be designed according to the patients' impairments for restoring the normal kinematics of lumbar spine-hip complex.

Chapter 2 Review of Literature

This review of related literature has several general purposes. Firstly, the review provides a basic orientation to the relevant anatomy and basic biomechanics of the lumbar spine and hip. Secondly, a review of different measurement and computational methods of the lumbar spine and hip movements are presented, which are central to the materials presented in this thesis. Finally, some preliminary data on three-dimensional movement patterns of lumbar spine and hip in normal and back pain subjects are discussed, providing justification for the needs of this study.

2.1. Biomechanically relevant anatomy of the lumbar spine and hip

This section briefly reviews the anatomy of the lumbar spine and hip relevant to this study. The details can be found elsewhere in many anatomical textbooks (Agur et al., 1999; Bogduk, 1997; Cunningham & Romanes, 1972; Gray et al., 1995). The lumbar vertebral column consists of five vertebrae. There are three intervertebral joints between two consecutive vertebrae. One is formed between two vertebral bodies which are linked by intervertebral disc and the other two, namely the zagapophysial joints, are formed by the articulation of the superior articular processes of one vertebra with the inferior articular processes of the vertebra above.

The intervertebral disc consists of two basic components. They are the nucleus pulposus in the central and annulus fibrosus surrounding the nucleus pulposus. The intervertebral disc in the lumbar region is the thickest among all the spinal regions (Bogduk, 1997). The main mechanical functions of the disc are weight-bearing and allowing movement between vertebral bodies. Collectively the vertebral bodies and discs form a column that provides rigidity and length, and permits movements (White & Panjabi, 1990). During forward bending of the lumbar spine, each intervertebral disc is being compressed slightly, anteriorly, and is resisted by tension developed in the posterior annulus fibrosus (Adams et al., 1980). Extension and lateral flexion are achieved by corresponding events in the opposite direction and in the coronal plane, respectively. Rotation of the lumbar spine is achieved by small degree of twisting at each disc, but the disc alone is not strong enough to resist torsion of the lumbar spine. It requires other additional elements such as the zagapophysial joints and ligaments surrounding the spine (Gunzburg et al., 1991; Markolf, 1972; Taylor & Twomey, 1986).

The zagapophysial joints exhibit the features of synovial joints. The articular facets are covered by articular cartilage, and a synovial membrane connects the margins of the articular cartilages of the two facets. The synovial membrane is surrounded by a joint capsule that links up the two articular processes (Bogduk, 1997). The mechanical functions of the zagapophysial joints are mainly to direct and limit movements. The zagapophysial joints of the lumbar spine can effectively block the movements of axial rotations and forward sliding of the vertebrae (Gunzburg et al., 1991; Markolf, 1972; Taylor & Twomey, 1986) and, as such, the intervertebral discs are protected from excessive torsion.

Many ligaments are attached to the vertebrae. The main mechanical function of these ligaments is to maintain the stability of the spine, but the specifics of individual ligaments are not presented to this review, although, some of the functions of the ligaments, which are essential to the later discussion, are presented here. The ligamentum flavum consists of fibers of elastin which allows large extensibility and without permanent deformation (Evans & Nachemson, 1969). The anterior longitudinal ligament extends along the anterior surface of the vertebral column from the occiput to the sacrum. It becomes taut with extension, slack with flexion, and reinforces the anterior discs. The posterior longitudinal ligament is situated in the spinal canal and covers along the posterior surface of the vertebral bodies and discs. The PLL becomes taut with flexion and slack with extension (Adams et al., 1988; Adams et al., 1980).

The hip joint is defined as a synovial ball-and-socket joint which allows movements in three dimensions. It is formed by the articulation of the hemispherical head of the femur and the cup-shaped acetabulum of the hip bone (Fagerson, 1998; Gray et al., 1995; Snell, 2000). The stability of the hip joint is provided by the capsule and strong ligaments around the joint (Hewitt et al., 2001). Although the high stability of hip joint provides by the strong capsule and its surrounding ligaments, the hip joint still allows for a large degree of mobility. The largest movement at the hip joint is in sagittal plane: flexion and extension. The limitation of flexion movement might be due to the capsular restriction or the apposition of the thigh against the trunk when the knee is flexed (Fagerson, 1998). Hip extension might be limited by the iliofemoral ligament and, when the knee is straightened, stiffness of the rectus femoris muscle. Hip abduction is limited by the tightness of adductor muscles, pubofemoral ligament and the iliofemoral ligament, whereas hip adduction is limited either by the apposition of the opposite extremity or tightness of the tensor fascia latae muscle. Hip medial rotation is limited by the tightness of the hip lateral rotators and the ischiofemoral ligament, whereas the limitation of lateral rotation can be due to the lateral band of the iliofemoral ligament, the pubofemoral ligament, tightness of the hip medial rotator muscles, and the femoral anteversion (Fagerson, 1998; Gray et al., 1995).

2.2. In-vivo measurement methods of the lumbar spine and hip movements

Measurement of lumbar spine and hip movements is commonly employed in clinical assessment of low back pain patients. There are several simple and straightforward methods frequently employed by clinicians for establishing physical diagnosis and evaluation of treatment effectiveness, such as the fingertips-to-floor and the Schöber method (Macrae & Wright, 1969). However, these measurements are unrepresentative of the actual movements of the lumbar spine, and the measurements are limited to one anatomical plane only (Miller et al., 1992; Pearcy, 1986; Portek et al., 1983). Human lumbar spine is very complex and it has six degrees of freedom that allows three-dimensional movements. These methods cannot fulfill clinical and experimental situation when three-dimensional movement data are required. Some methods have the ability to measure the three-dimensional movements of the lumbar spine and hip, such as the three-dimensional radiography, opto-electronic method and electromagnetic tracking method.

A review of in-vivo measurement methods of the lumbar spine and hip is presented in the following section to show the strength and weaknesses of each method. The review is summarized in Table 2.1.

2.2.1. *The inclinometer method*

The inclinometer method was first documented by Loebl (1967) and Troup et al (1968). This technique was previously used to measure the sagittal and

Table 2.1 Comparison of advantages and disadvantages of different in-vivo measurement methods

Measurement methods	Advantages	Disadvantages
Inclinometer method	- Simple and easy to use - Provides a quick reference for clinical assessment - Non-invasive	- Poor intrarater reliability for lumbar extension movement (r=0.15-0.42) - Does not provide three-dimensional movement data - Provides no information about kinematics pattern
Two-dimensional and three-dimensional radiography	- Accurate determination of spinal movements	- Time consuming and complicated - Risk of radiation exposure - Provides no information about kinematics pattern
Interventional open magnetic resonance imaging	- Accurate determination of spinal movements - No ionizing radiation exposure	- Very expensive - Provides no information about kinematics pattern
Opto-electronic method	- Provides three-dimensional information about kinematics pattern - Non-invasive	- Expensive - Too complex and time consuming - Problem in discriminating between closely spaced makers
Potentiometer method	- Provides repeatable three-dimensional movements of lumbar spine	- Great error when measuring trunk extension - Can only measure spinal movements only but not for the hip - Requires an external linkage which may affect the movement
Gyroscopic system	- Provides highly repeatable movement data - Relatively low cost - Provides real-time kinematics information	- Signal tends to drift over an extended period of time - Requires integration to obtain displacement data
Electromagnetic tracking system	- Provides highly repeatable and accurate movement data - Provides real-time kinematics information - Small sensor for easy attachment	- Signals can be adversely influenced by the presence of metals

frontal movement of the spine (Mayer et al., 1984; Ng et al., 2001; Reynolds, 1975). The double inclinometer method is carried out by placing one inclinometer on sacrum and the other over the T12-L1 spinous processes. The lumbar spine motion can be readily obtained by the subtraction of the hip motion from the gross motion. The one inclinometer method can also be used to measure the lumbar spine and hip movement by carrying out the above measurements separately. Lateral flexion of the lumbar spine can also be measured by inclinometer (Dillard et al., 1991; Dopf et al., 1994; Mellin, 1986; Ng et al., 2001; Nitschke et al., 1999; Reynolds, 1975) with high reliability ($r>0.9$).

Although this method is simple and easy to use in clinical practice (Lee, 2002), there are some problems associated with this method. Previous reliability studies showed that the intrarater correlation coefficients ranged from 0.73 to 0.88 for flexion movement (Burdett et al., 1986; Reynolds, 1975; Saur et al., 1996) and 0.9 for lateral flexion (Ng et al., 2001), but, the intrarater reliability for the extension motion of the lumbar spine was found to be poor ($r=0.15$-0.42) (Burdett et al., 1986; Dillard et al., 1991; Saur et al., 1996). The poor reliability might be due to the fact that sustained extension is uncomfortable and the subject is hard to maintain their balance during the measurement (Dillard et al., 1991; Reynolds, 1975).

A high correlation between radiographic and inclinometer measurements of sagittal plane movements of the lumbar spine were demonstrated ($r=0.73$-0.98) (Burdett et al., 1986; Mayer et al., 1984; Saur et al., 1996). However, Portek et al (1983) found that the discrepancy between radiographic and inclinometer methods could be as large as 14 degrees.

In general, this method is easy to apply and can provide a quick reference for clinical assessment. But this method only assesses the measurement in one anatomical plane and cannot provide three-dimensional movement data for more elaborate study. This method also only shows the measurement of the end range of movement providing no information about the kinematics pattern of the movements (Lee, 2002). Moreover, this method does not provide accurate information about the hip movement during forward and backward bending of the trunk.

2.2.2. *Two-dimensional and three-dimensional radiography*

Measurements of spinal movements using single plane radiographs were wildly employed in clinical and research studies (Allbrook, 1957; Dimnet et al., 1978; Dvorak et al., 1991; Hanley et al., 1976; Pennal et al., 1972; Tanz, 1953; Weitz, 1981). A single plane radiographs provide images in two-dimensional manner. To measure flexion and extension, lateral views are required and for lateral flexion, anterior posterior (A-P) views are required. The movements of the lumbar spine are measured by the superimposition of vertebrae on two radiographs (Pearcy, 1986). The details of this technique can be found elsewhere (Pearcy, 1986). As flexion and extension of the lumbar spine occur without significant movements in other two planes (Pearcy, 1985), the results provided by the superimposition technique correlate well with three-dimensional technique (Portek et al., 1983). However, lateral flexion of the lumbar spine is coupled with axial rotation, flexion or extension; plane radiograph cannot provide accurate measurement of these coupled movements. In addition, because of the lumbar lordosis, the A-P radiograph do not view all the vertebrae at the same inclination, and thus such measurements do not provide true angles of lateral flexion (Pearcy, 1986). Axial rotation of the lumbar spine can be measured by the Pedical Shadow Offset technique (Nash & Moe, 1969), which is carried out by assessing the position of the pedicles in relation to the edges of the vertebral body on A-P radiographs (Pearcy, 1986). Although Drerup (1985) has developed an accurate method to determine rotation of the lumbar spine. This technique is not ideal because axial rotation as axial rotation of the vertebrae is coupled with other movements and the method is prone to error. Two-dimensional radiographic technique can provide accurate and reliable measurements providing that the relative positions of the subject and the X-ray equipment are strictly controlled (Pearcy, 1986).

Measurements of the lumbar spine movements using three-dimensional radiographic techniques were described by various authors (Pearcy et al., 1984; Pearcy et al., 1985; Pearcy, 1985; Pearcy & Tibrewal, 1984; Stokes et al., 1981). This is done by using two X-ray sources, where they positioned 90° to each other and two film plates, sited orthogonally (Brown et al., 1976; Frymoyer et al., 1979; Stokes et al., 1981; Suh, 1974). Accurate determination of lumbar spinal movements from radiographs relies on the ability to identify the bony landmarks on each vertebra in the two views (Lee, 2002; Pearcy, 1986). This is the most inaccurate part of these techniques (Pearcy, 1986)and the average error associated with landmark identification was shown to be about 4 mm. The accuracy of these techniques can be greatly improved by employing optimization procedures that adjust the positions of the landmarks to fulfill the constraint that each vertebra is a rigid body (Pearcy & Whittle, 1982). Panjabi et al (1992) showed that the average errors involved in the determination of intervertebral rotation were 1.25 degrees only.

However, these techniques are limited to research application due to the complexity of the landmark identification and three-dimensional reconstruction of the coordinate data (Pearcy, 1986).

Radiography measurements only provide information in the initial and final positions and no kinematics information can be given throughout the range (Lee, 2002; Pearcy, 1986). To record the kinematics information of the lumbar spine, a method that can capture the image of the spine throughout the movements is certainly required. Digital videofluoroscopic technique (DVF) is one the techniques that capable of taking a series of radiographic (Breen et al., 1989ab; 1989ba). 'Digitized videofluoroscopy' generally consists of a fluoroscope, an image intensifier and a video camera, which allows two-dimensional dynamic images of the spine to be captured at low dose of radiation exposure. After capturing the images on a videotape, the image sequences can be digitized into a number of successive frames and the motion patterns can be analyzed on a computer. Due to the low dose of radiation, the images of the lumbar spine are of poor quality and the identification of bony landmarks is very difficult. Initially, all the bony landmarks were marked manually and much effort is required to quantify and improve the accuracy and inter- and intraobserver repeatability. Recently, some works have been done to locate the vertebrae automatically using matching criteria of templates (Muggleton & Allen, 1997) or edge detection using phase congruency and Hough transform (Zheng et al., 2003). These techniques improve the accuracy of detecting the edges of the vertebrae and thus improve the estimation of movements of the lumbar spine. In general, there are several advantages of DVF including the ability to show the intervertebral movements of the lumbar spine dynamically. The dosage of radiation that the patient received, is relatively less when compares with conventional radiographs (Breen et al., 1989b). The disadvantages of this technique are that the accuracy of measurements is highly dependent on the quality of image and the identification of bony landmarks or the edges of vertebrae. However, the quality of image can be easily affected by soft-tissue scattering and distortion of image within the image-intensifier or in digital processing (Breen et al., 1989a). This technique is also time-consuming and complicated due to the laborious works required in identifying bony landmarks. This also limits its use to research studies only instead of routine application on clinical assessment. Although the dosage of radiation is relative less, the inherent health risk of X-ray exposure is not fully understood and this raises ethical questions regarding using this technique on patients. Lastly, due to the size of the intensifier and the X-ray source, this technique can only study the kinematics of few lumbar segments at once, but not the kinematics of the whole lumbar spine and hip (Breen et al., 1989a; Breen et al., 1989b; Muggleton & Allen, 1997; Zheng et al., 2003).

2.2.3. *Interventional open magnetic resonance imaging*

Interventional open magnetic resonance imaging (MRI) is a new imaging technique, where patients do not suffer from ionizing radiation exposure. Conventional MRI allows images of thin sections through the body in lying position; hence images taking in vertical position are impossible. Intervention open MRI has the beauty that images can be taken in sitting position without any restriction. Several authors (Harvey et al., 1998; McGregor et al., 2001; McGregor et al., 2002) applied this imaging technique in the study of flexion and extension of the lumbar spine in lying or sitting positions. The repeatability analysis suggested that the measured values are reliable to within approximately 1° and 0.5 to 1 mm in each position. However, this technique is very expensive and not to be routinely used in clinical assessment. Also patients need to sustain in each position for approximately 5 minutes while a series of sagittal scans are obtained. This may not be possible for patients with low back symptoms.

2.2.4. *Opto-electronic method*

Opto-electronic devices such as the CODA-3 (Charnwood Dynamics Ltd. Loughborough, UK) and VICON (Oxford Metrics Ltd. Oxford, UK) have been used to study the movements of lumbar spine and hip (Esola et al., 1996; Gracovetsky et al., 1995; McClure et al., 1997; Pearcy et al., 1987a; Pearcy et al., 1987b; Schache et al., 2002; Schache et al., 2001a; Vanneuville et al., 1994; Whittle & Levine, 1999). This method basically involves markers, which may be made of retroreflective materials or light emitting diodes, and a camera system. Markers can be attached to the trunk, pelvis and thighs and the movements of the markers are captured by the camera system and the angles are calculated in a computer. The movements of the lumbar spine measured by this system are highly similar to those measured by radiographs (Pearcy et al., 1984; Pearcy, 1985). The maximum error of this system in measuring anatomical movements is ±2 degrees (Pearcy et al., 1987a).

The advantages of this system are that it is noninvasive and it can provide movement data in three dimensions. However, it is not the most ideal method for measuring the lumbar spine and hip movements due to several reasons. In earlier measurement systems, automatic detection of the positions of markers was depended on the brightness of the markers. Therefore, the markers have to be bright enough, so that the camera could recognize it (Ferrigno & Pedotti, 1985). Moreover, this system is poor in the discrimination between closely spaced makers (Pearcy, 1986). It is also too complex and time-consuming to be use in routine clinical assessment (Lee, 2002).

2.2.5. *Potentiometer method*

Potentiometer method has been employed to study the kinematics of the lumbar spine (Mannion & Troke, 1999; McGregor et al., 1997; McGregor et al., 1995; Paquet et al., 1991; Quanbury et al., 1986). There is commercially available system such as the CA6000 Spinal Motion Analyser which is capable of measuring three-dimensional movements of the lumbar spine. This system mainly consists of a link arm incorporating six high-precision potentiometers connected through several external bars. Three of the potentiometers are arranged in sagittal plane to determine flexion and extension, two in the frontal plane to detect lateral flexion, and one in the transverse plane to detect rotation. The changes in voltage of each potentiometer depend on the angular displacement at the linkage in the plane perpendicular to the axis of the given potentiometer. The voltage registered is processed in a computer and interpreted as angular movement. The precision and repeatability of this system were examined by McGregor et al (1995) and this system was shown to be highly accurate and repeatable.

Although this system shows high precision and repeatable results, some technical problems need to be considered. A study by Mannion and Troke (Mannion & Troke, 1999) found that the linkage arm collided with each other when measuring trunk extension in prone-lying position and the results were greatly affected. In fact, the external arms might produce erroneous movements that are not the actual movements of the spine. This system might be ideal for measuring the movements of the lumbar spine, but it cannot measure the hip movements at the same time.

2.2.6. *Gyroscopic system*

Gyroscopic system has been applied on gait analysis to measure angular velocity of body segments (Mayagoitia et al., 2002; Miyazaki, 1997; Tong & Granat, 1999). The application of gyroscopic system to study spinal movements was first mentioned by Lee et al (Lee et al., 2003). The mechanism of gyroscope is that it measures the Coriolis acceleration of a vibrating device (Lee et al., 2003; Mayagoitia et al., 2002; Miyazaki, 1997; Tong & Granat, 1999). The angular orientation can then be determined from the integration of the gyroscopic signals (Lee et al., 2003).

The repeatability of this system for the measurement of spinal movements is high with mean coefficient of multiple coefficients ranging from 0.972 to 0.991. The spinal movements measured by this system were highly comparable with the results of radiography measurements (Lee et al., 2003). Other advantages of this system for the study of the lumbar spine and hip movements include light-weight of the sensors, and relatively low cost for buying the system.

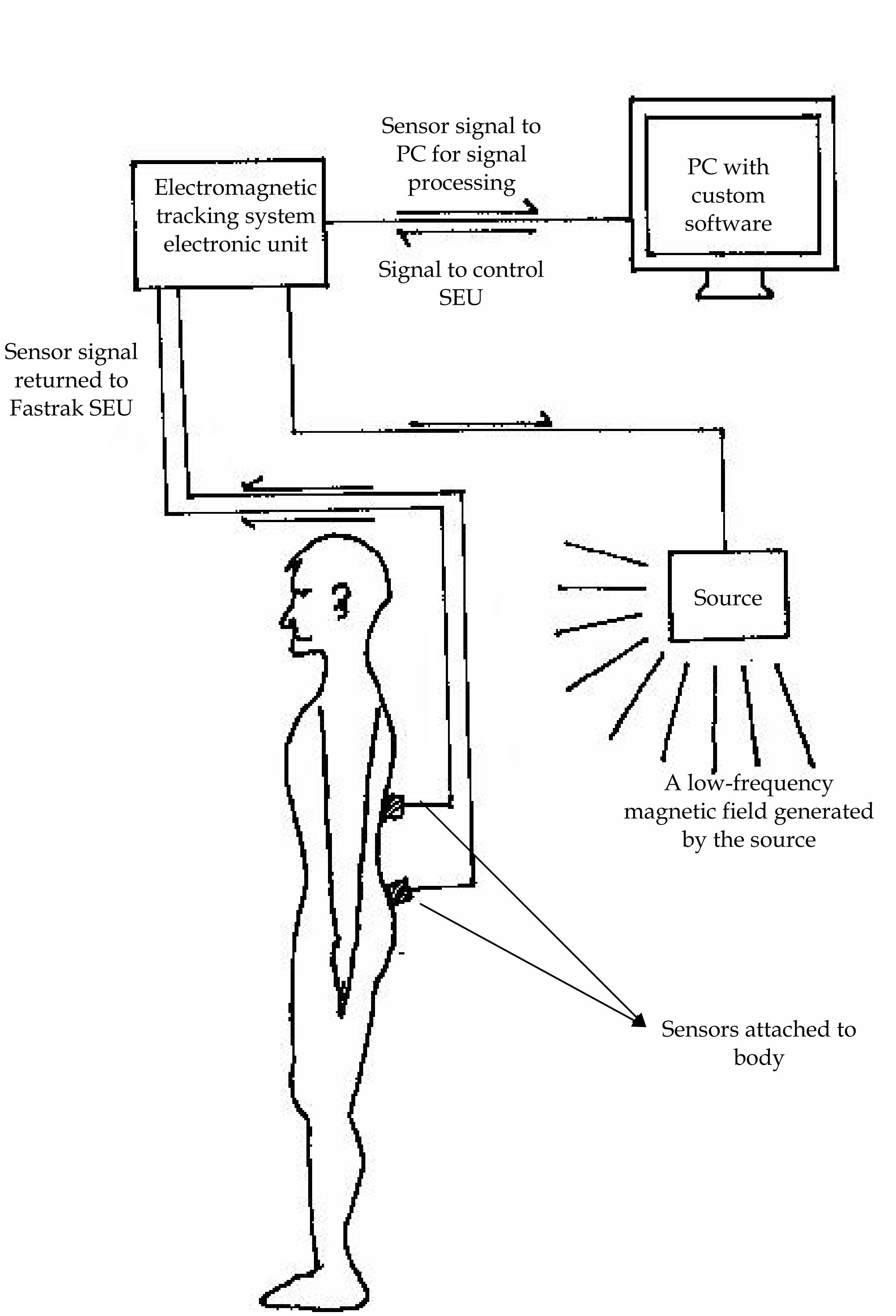
However, the size of the sensor relative to the spinous process is still large and makes it hard to be attached to one particular spinous process. The system could be used to study the relationship between the lumbar spine and hip providing that there are sufficient sensors to be used and smaller sensors are available in the market.

2.2.7. *Electromagnetic tracking system*

The possibility of applying electromagnetic tracking device to study human movements was first examined by An et al (1988). This research found that it was a reliable device for monitoring general spatial rigid body motion. The applications of this device in studying spinal movements have been used by many researchers (Blackburn et al., 2003; Burdett et al., 1986; Hindle et al., 1990; Lee, 2001; Mannion & Troke, 1999; Nelson et al., 1995; Pearcy & Hindle, 1989; Porter & Wilkinson, 1997; Russell et al., 1993; Steffen et al., 1997; Van Herp et al., 2000). Recently, the study of kinematics of the lumbar spine and hip becomes possible with the invention of newer system which consists of more sensors (Blackburn et al., 2003; Nelson et al., 1995; Porter & Wilkinson, 1997). This system consists of three major components: a System Electronic Unit (SEU), a source, and sensors. The source can generate a low-frequency magnetic field which is detected by the sensors. The SEU contains hardware and software to control the analog circuitry, digitize the signals, and perform the calculations to compute the positions and orientations of the sensors relative to the source (An et al., 1988; Lee, 2002) (Figure 2.1).

The accuracy of the device for studying spinal movements was examined by Pearcy and Hindle (1989). They found that the total root-mean-square error was less than 0.2 degrees. It can be considered as highly reliable and accurate for the study of spinal movements. Another beauty of this device is that the size of the sensors is reasonably small, so that the attachments of sensors to the spinous processes are relatively easy. A recent study by Lee (2001) described that this system was able to perform fast serial communication with a computer, enabling

Figure 2.1 A block diagram showing the major components of an electromagnetic tracking system



measurement of movements in real time. All these features allow this system to be conveniently used in clinical assessment.

However, the use of electromagnetic device with the presence of metals could be considered problematic because of the potential interference from metals (Bull & Amis, 1997; Bull et al., 1998; McGill et al., 1997; Milne et al., 1996; Poulin & Amiot, 2002). Milne et al (1996) found that the maximum interference occurred when the offending metal was placed adjacent to the receiver on a line collinear with the centre of the transmitter and sensors. Therefore this device is not suitable for patients with metallic implants in the joint that need to be study. Another precaution is that the equipment used near this device should be made from non-conductive materials (McGill et al., 1997). Equipment that possibly distorts the magnetic field, such as computers and other electrical instrumentations, should be placed away from this device by using long cables. McGill et al (1997) also found that the frequency content of EMG signals could be contaminated by this device at low contraction levels (e.g. 10% MVC).

Electromagnetic tracking device is the most ideal equipment for the purpose of this study. Firstly, this system is highly accurate and reliable providing that the precautions are undertaken during the experiment. For instance, there should be no metallic or conductive materials in the area where the test was carried out. Secondly, the size of the sensors is relatively small. It can be attached to one particular spinous process easily and securely. Finally, it allows three-dimensional movements of the lumbar and hips to be simultaneously measured; fulfilling the aims of the study.

2.3. Computational methods of three-dimensional movements

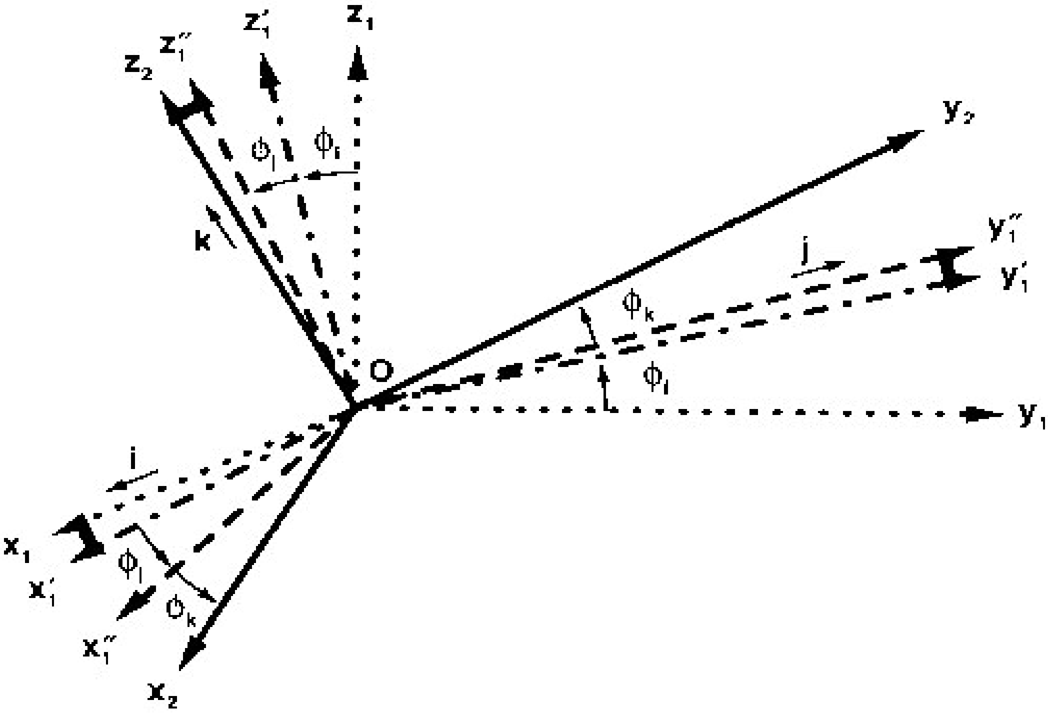
To understand the three-dimensional kinematics of the lumbar spine and hip, the first step is to calculate all the anatomical movements from the data which is captured by different systems using mathematical methods. However, it is a major challenge to the biomechanists and bioengineers to choose the most ideal method for mathematical analysis of three-dimensional movements of joint. It is also a great challenge for the clinicians to understand all these mathematical methods and their meanings in clinical terms. In this section, a review of computational methods of three-dimensional movements is provided.

2.3.1. *Euler's method*

Euler's method is one of the most common method for kinematics analysis. The three-dimensional movements of a joint are described by a sequence of three rotations about three different axe where they are orthogonal to each other (Figure 2.2). The advantage of this method is that the three Euler angles and the displacement vector together can completely describe the movement of a body in three dimensions using only six parameters. The compact nature of the Euler representation can be easily expressed by using matrix techniques. However, it has been shown that different rotational sequences can result in different angle calculations and final positions. Crawford et al (1996) and Schache et al (2001b) showed that different sequence determinations of the same Euler angles began to diverge significantly when relatively large isolated movements of the spine are performed (angles>30°). Therefore, it is important to describe the rotational

Figure 2.2 Euler angle

In the Euler angle representation of three-dimensional orientation, the rotation matrix is parameterized in terms of three independent angles, resulting from an ordered sequence of rotations about the axes (i, j, k), of a selected coordinate system (x_1, y_1, z_1) to obtain the attitude of a second coordinate system (Nigg & Herzog, 1999).



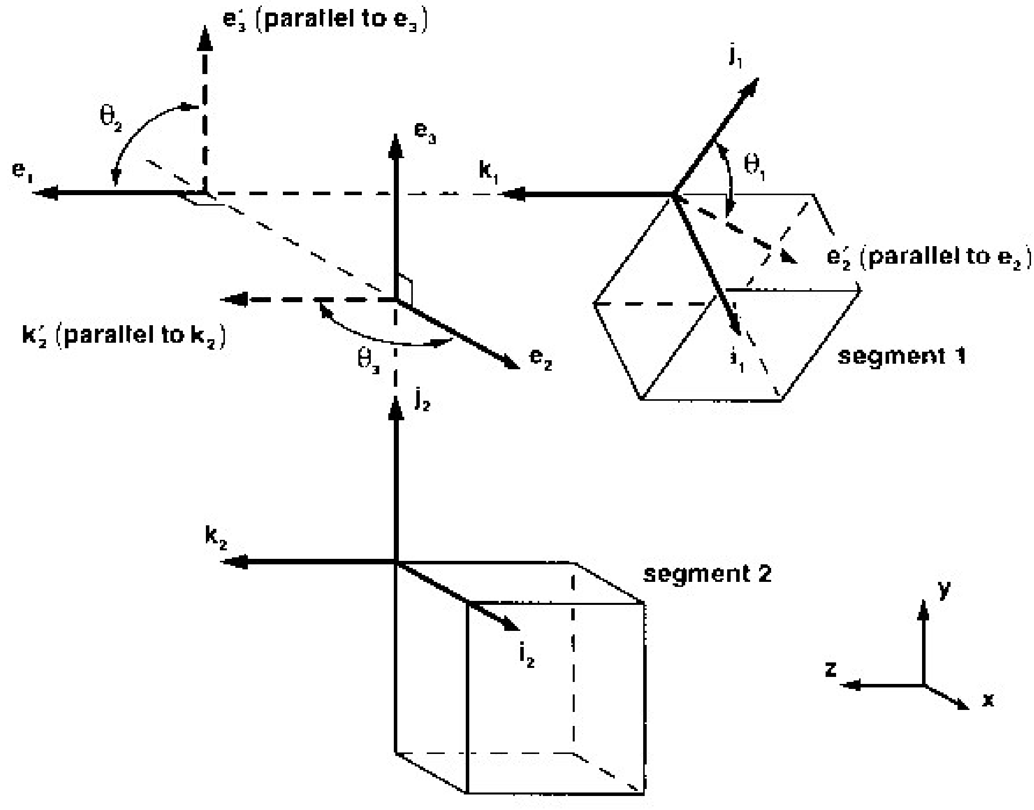
sequence when Euler angles are used to express the three-dimensional movements. This allows comparisons of different results gathered from different studies to be made. Moreover, the sequence dependent nature of the method does not physiologically explain natural spinal movements, because spinal movements occur about the three anatomical axes simultaneously and not in a particular sequence (Lee, 2002).

2.3.2. *Joint coordinate system (JCS) or the floating axis method*

The joint coordinate system or the floating axis method has been used to study the three-dimensional movements of different body joints included the knee joint and the lumbar spine (Burnett et al., 1998; Grood & Suntay, 1983; Lee, 2001) (Figure 2.3). The first axis is the first fixed body axis and is perpendicular to the sagittal plane of the proximal segment. The third axis is the long axis of the distal segment. The second axis is the floating axis which is the cross product of the first and third axes. (Crawford et al., 1996; Grood & Suntay, 1983; Zatsiorsky, 1998). The advantage of this method is that the JCS angles are not sequence dependent and the angles are anatomically meaningful as the first and third axes are aligned with body segments directly. As a result, the angles derived from this method are anatomically meaningful. Therefore this method imposes fewer problems for motion analysis. Besides, this method is also recommended by the International Society of Biomechanics to study human movements. However, the JCS angles cannot be defined for some joint positions when the longitudinal axis of a distal segment is collinear with the frontal axis of the proximal segment, because the cross product of the two vectors cannot be calculated when the two fixed axes are collinear. The nonorthogonality of the axes actually imposes a sequence effect

Figure 2.3 **Joint coordinate system**

Three-dimensional joint orientation is interpreted as a set of three rotations that occur about the axes of a "Joint Coordinate System". One axis, e_1, is selected to be the medio-lateral (z) axis of the proximal segment coordinate system. This is the rotational axis for flexion-extension of the joint. Another axis, e_3, is selected to be the longitudinal axis of the distal segment. Axial rotation is measured about this axis. These two segment-fixed axes defined the remaining axis, with mutually-perpendicular vector, e_2. This is the cross-product of the two segment-fixed axes, and it defines the axis of rotation for lateral bending (or adduction/abduction) of the joint (Nigg & Herzog, 1999).



geometrically (Woltring, 1994) and presents a serious problem when joint forces and moments need to be determined (Zatsiorsky, 1998). These issues must be considered when this method is adopted for three-dimensional movement analysis.

2.3.3. *Helical method or screw method*

The helical method had been discussed by different people for the analysis of human kinematics (Kinzel et al., 1972; Ramakrishnan & Kadaba, 1991; Woltring, 1991). This method permits a description of body attitude by referring to a single rotation about an axis called the helical axis (Figure 2.4). At any instance, the translation and rotation occur along and around this axis. If the location and direction of the helical axis is known, then the position of the body can be described in relation to this axis. Six parameters are required to define a body position. The first two parameters are the two coordinates of the piercing point of the screw axis with any one of the three coordinated planes. The third and fourth parameters are the direction cosines of the helical axis. The last two are the translation along and the rotation about the helical axis (Woltring, 1991; Zatsiorsky, 1998). This method again is sequence independent. Therefore, the mathematics calculations are unambiguous and the results are very unique. However, this method is extremely sensitive to noise when reconstructed from capturing equipment (Woltring, 1991). The clinical interpretation of the helical angle is very difficult for clinicians who do not have the mathematics training (Lee, 2002).

2.3.4. *Spherical rotation coordinate system*

The spherical rotation coordinate system was first proposed by Cheng (2000). This method describe the movement of a body segment in a three-dimensional space using longitude, latitude, radial rotation in a spherical rotation

Figure 2.4 **Helical or screw method**

The movement of the object is visualised as translation along the screw axis (*l*) from point s_1 to point s_2, and the rotation about this axis at angle α. The position of a point on the helical axis can be defined by a vector S. The direction vector of the screw axis should also be given. (Zatsiorsky, 1998).

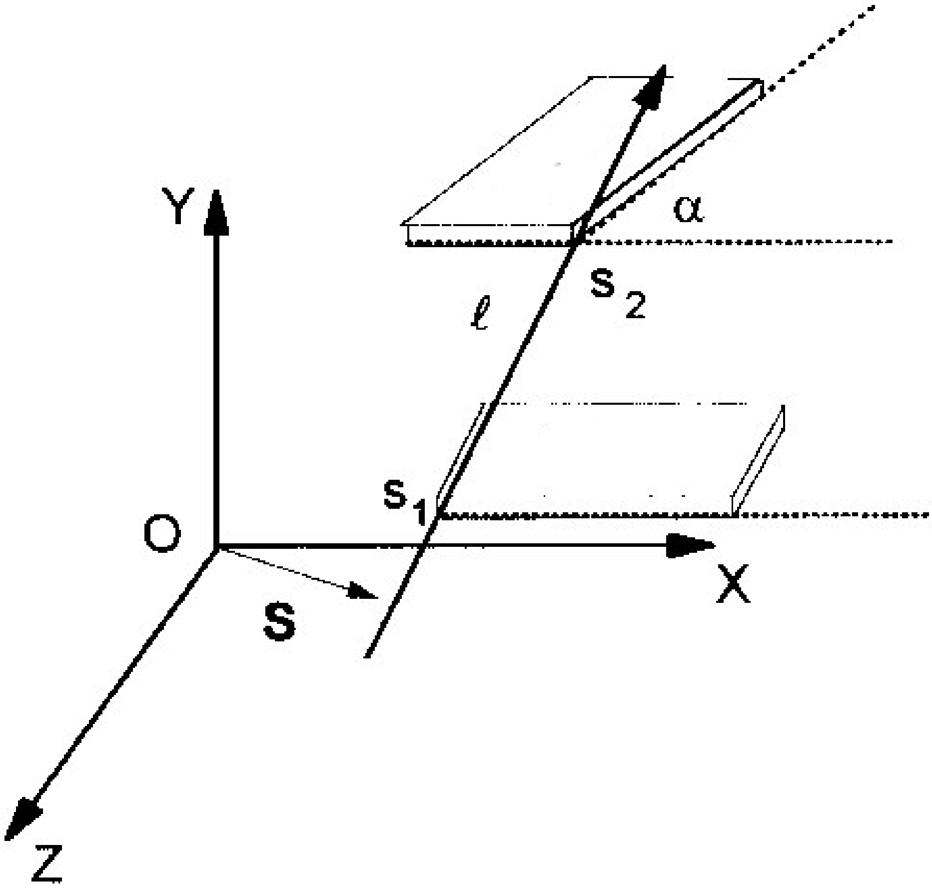
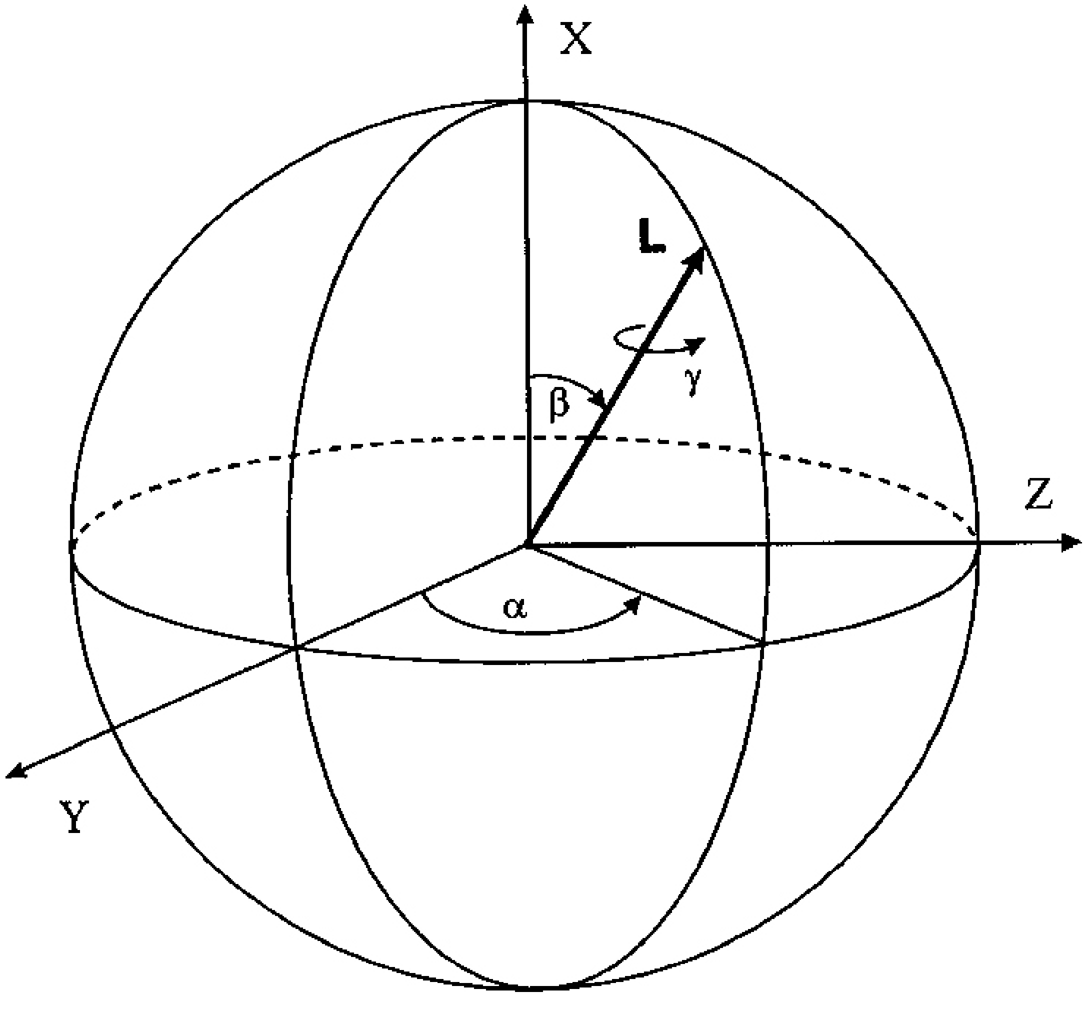


Figure 2.5 Spherical rotation coordinate system

A spherical rotation coordinate system includes three angles: longitude α, latitude β, and the radial rotation angle γ. L is a unit vector of the long axis of a limb segment. Longitude α and latitude β are used to describe long axis rotation. Radial rotation angle γ is used to describe a pure axial rotation about the long axis L of the limb segment (Cheng, 2000).



coordinate system (Cheng, 2000) (Figure 2.5). This coordinate system differs from the classical spherical coordinate system in that the radial rotation angle is used instead of radial displacement. Another difference is that Cheng's system is used to describe the three-dimensional rotations of the limb segment instead of the movement of a point. When describing body segment movement, the longitude and latitude in the spherical coordinate system are used to describe the long axis rotation of the limb segment. Since the long axis is always in the radial direction, the axial rotation about the long axis is defined as the third rotation angle (Cheng, 2000). According to this system, the movement of the limb segment from one attitude to another can be described by a two-step rotation. The first step is the rotation of the long axis of the limb segment about a specific axis passing through the proximal joint and perpendicular to the long axis of the limb. The second step is the axial rotation about the long axis. This two-step rotation is showed to be a sequence independent rotation (Cheng et al., 2000) and it can describe the three-dimensional rotation of a limb segment from one attitude to another. So far, this method has been successfully used to describe the movements of glenohumeral joint only. The applicability of this system to study spinal motion needs to be investigated. The physiological meanings of the spherical rotations can be problematic as human movements do not exist as two-step rotations (Lee, 2002).

2.4. Analysis of the correlation between the lumbar spine and hip movements

The measurements of ranges of movements of the lumbar spine and hip provide basic angle-time information for us. Previous studies either compared the absolute values of the maximum ranges of movements of the lumbar spine and hip between control subjects and back pain subjects or calculated the ratio of the lumbar spine to hip movements in certain ranges, e.g. 0°-30°, 30°-60° etc. to reveal the relative contributions from the lumbar spine and hip. However, it does not provide a continuous description of movement correlation across the time history. It is very important to understand the effects of back pain and limited straight leg raising on the correlation of the lumbar spine and hip movements dynamically. In this section, a detail review of different methods for the analysis of movement correlation is provided.

2.4.1. *The cross correlation function*

Cross correlation function is widely used in signal processing and statistics. In the field of signal processing, it can be used to transform one or more signals so that they can be viewed in time or frequency domains. In the area of statistics, it provides a measure of association between signals. If two time series data sets are cross-correlated, a measure of temporal similarity is achieved because it can detect the common periodicities between two signals. Two parameters are provided by cross correlation function, namely the coefficient correlation which assesses the strength of correlation and the time shift of one signal with respect to the other. The following equation is used to calculate the coefficient of cross correlation of two time series *x* and *y*, each with *N* data points.

$$r_{xy}(k) = \frac{c_{xy}(k)}{\sqrt{c_{xx}(0)c_{yy}(0)}} \tag{2.1}$$

where

$$c_{xy}(k) = \sum_{t=1}^{N}(x_t - \bar{x})(y_t - \bar{y}) \tag{2.2}$$

if $k = 0$

$$c_{xx}(0) = \sum_{t=1}^{N} (x_t - \bar{x})^2 \tag{2.3}$$

$$c_{yy}(0) = \sum_{t=1}^{N} (y_t - \bar{y})^2 \tag{2.4}$$

In this equation, the coefficient of cross correlation, $r_{xy}(k)$, indicates the pattern similarity between the two sets of data and k indicates a phase shift of one signal with respect to the other. If there was a phase shift between two time series that have similar patterns, the coefficient of this shift could be found by assessing $r_{xy}(k)$ at different values of k where r_{xy} is maximized (Chatfield, 2004; Li & Caldwell, 1999; Stergiou, 2004).

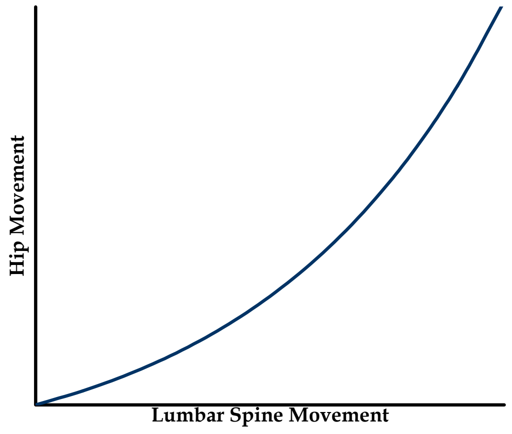
In the practical application of this method in analysing the movements of the lumbar spine and hip, the coefficient of cross correlation indicates the similarity of these two joints movements and the phase shift indicates whether these two movements are synchronised or not. The major advantage of this method is that the analysis is based on the entire profile of the time series instead of just calculating the ratio which only indicates the relative contributions of the lumbar spine and hip. The ratio can not sufficiently describe the correlation of the lumbar spine and hip movements throughout the entire profile.

2.4.2. *Angle-angle diagram*

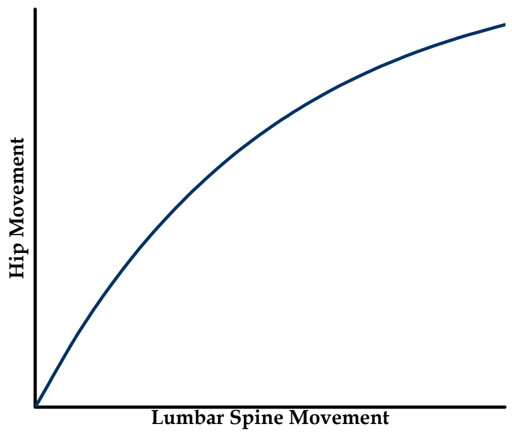
Angle-angle diagram is another useful tool to describe intersegmental movements and coordination (Barker et al., 1996). It is constructed by plotting one angular variable versus another angular variable. This method was previously

Figure 2.6 Different patterns of angle-angle diagrams

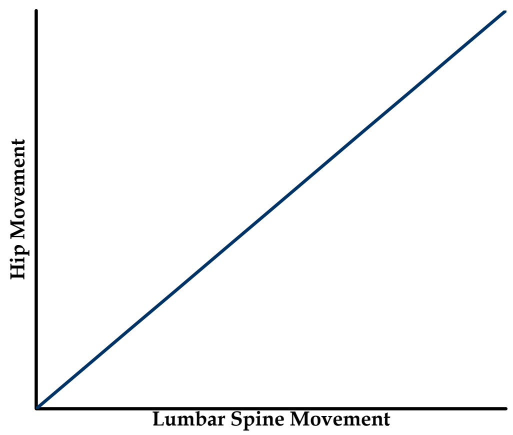
Pattern A



Pattern B



Pattern C



applied on the analysis of abnormal limbs movements during gait cycle and interjoint coordination during upper limb movements (Barker et al., 1996).

However no previous study adopted this method for the analysis of the lumbar spine and hip. Theoretically, the angle-angle curves can be classified into three patterns as shown in Figure 2.6 and qualitative description of interjoint movements can be done by assessing the shape of the curve. Using lumbar spine and hip as an example, pattern A shows that the lumbar spine movement occurred at a greater rate than the hip in the initial stage of the trunk movement. Pattern B indicates that the hip movement occurred at a greater rate in the initial stage. Pattern C shows the hip and spine movements varied at similar rate throughout the trunk movement.

2.5. Three-dimensional movement patterns of the lumbar spine and hip in normal subjects

Numerous studies were conducted to examine the patterns of the lumbar spine both in vitro and in vivo.

2.5.1. *In vitro measurements*

In vitro kinematics studies are generally more accurate than in vivo studies. However it deviates from the clinical situation and the load applied on the specimens is not the same as the load acting on the lumbar spine in vivo. Therefore, the results of in vitro studies are very different from those in vivo studies (Panjabi et al., 1994).

Yamamoto et al (1989) studied the three dimensional kinematics of ten cadaveric whole lumbar spine using four different loads (2.5 Nm, 5 Nm, 7.5 Nm and 10 Nm). They found that 10 Nm was sufficient to produce maximum physiologic motions, but small enough not to injure the specimen. For flexion movement, they found that the average range of motion from L1 to S1 was 38.7°±3.4 whereas, for extension movement, the average range of motion was 25.9°±2.2. The coupled movements in other planes were minimal (Panjabi et al., 1994). For lateral bending, the average range of motion was 28.9°±2.3. Lateral bending of the lumbar spine was coupled with flexion movement in all the lumbar intervertebral joints and axial rotation towards the opposite side to the applied moment in all lumbar levels. For axial rotation, the average range of motion was 11.1°±1.9. Axial rotation of the lumbar spine was coupled with flexion movement in all lumbar levels, lateral bending towards the opposite side to the applied moment in the upper three lumbar intervertebral joints (L1/2; L2/3; L3/4), and lateral bending towards the same side to the applied moment in L4/5 and L5/S1 levels (Panjabi et al., 1994).

In vitro testing of kinematics of the lumbar spine and hip is very difficult due to the complexity of setting up the experiment and most of the literatures were focused on the kinematics of either the single spinal unit or the whole lumbar spine only. Therefore, the in vitro testing of movements of both the lumbar spine and hip are lacking in the literature.

2.5.2. *In vivo testing results*

2.5.2.1. Kinematics of the lumbar spine

Radiographic technique was one of the most popular methods used to measure the movements of the lumbar spine. Several authors employed this method to investigate the kinematics of the lumbar spine (Dvorak et al., 1991;

Hayes et al., 1989; Pearcy et al., 1984; Pearcy, 1985; Pearcy & Tibrewal, 1984; Putto & Tallroth, 1990; Tanz, 1953). Most of the authors only reported the gross range of motion of flexion-extension. The range of motion ranged from 42.2° to 76.9°. Pearcy (1985) reported the flexion and extension range separately, in which he found that the average flexion range was 52° and the average extension range was 16°. There were minimal coupled rotations in other planes of movements. The only significant coupled movement was anterior translation. The discrepancies in these studies were large. The possible reasons were due to the individual variations in spinal mobility and due to the differences in experimental methodologies.

Several authors also investigated lateral bending and axial rotation of the lumbar spine using radiography technique (Dvorak et al., 1991; Pearcy, 1985). There were no significant differences between movements to the right or to the left in either lateral bending or axial rotation. Miles and Sullivan (1961) and Dvorak et al (1991) employed anteroposterior radiographs to measure lateral bending. The average range of motion for lateral bending reported by Miles and Sullivan was 15.3. Dvorak et al (1991) only reported the gross range for left and right lateral bending and it was 49.8°. It should be emphasized that lateral bending was inherently accompanied by axial rotation and such out-of-plane motion would introduce errors in the measurements. Pearcy and Tibrewal (1984) employed biplanar radiographs to study these movements. The average range for lateral bending to left or right side was found to be 17.5° and the average coupled axial rotation was 5.5°. Biplanar radiographic technique could reveal the coupling patterns during lateral bending and axial rotation (Pearcy, 1985; Pearcy & Tibrewal, 1984). For axial rotation, the coupling movements were grossly lateral bending towards the opposite side of the primary movement. However, there was no consistent pattern of coupled flexion and extension during axial rotation (Pearcy, 1985; Pearcy & Tibrewal, 1984). It is very important to note that the observation of these coupled movement patterns is not always consistent and sometimes the coupled movements might deviate from these general observations.

Apart from using radiographic technique, which is rather an invasive method, many authors employed other non-invasive technique to study the movement patterns of the lumbar spine, such as the inclinometer method (Mayer et al., 1984), electromagnetic tracking device (Hindle et al., 1990; Peach et al., 1998; Pearcy & Hindle, 1989; Russell et al., 1993; Van Herp et al., 2000)and most recently, gyroscopic method (Lee et al., 2003). A detail comparison of the range of movements of the lumbar spine of these studies is showed in table 2.2. It is obvious that most of the studies using electromagnetic tracking device have very similar results except for the study by Van Herp et al (2000). The flexion range reported in this was about 20° less than other studies. However, this figure is in good agreement with the studies using radiographic technique (Pearcy, 1985). The possible explanation for this discrepancy is that Pearcy and Hindle and Hindle et al. and presumably Russell et al. applied a 'calibration correction factor' to their measurements on the basis of their calibration experiment. This correction inflated the true values by approximately 10%. This might explains why there was a discrepancy (Van Herp et al., 2000). The difference in the methodology could be another possible explanation to this discrepancy. The same discrepancy happened in the study of Lee et al (2003). All the lumbar spinal movements measured by the gyroscope were smaller than the other studies. In fact, the size of

Table 2.2. Comparisons of the lumbar ranges (degrees) of movements for seven studies in the literature.

	Mayer et al (1984)[a]	Pearcy and Hindle (1989)[b]	Hindle et al (1990)[b]	Peach et al (1998)[c]	Russell et al (1993)[d]	Van Herp et al (2000)[b]	Lee et al (2003)[e]
Method	Inclinometer	EMT	EMT	EMT	EMT	EMT	Gyroscopic
Movement							
Flexion	55	75.6	74.6	71.6	75.1	56.4	48.6
Extension	27	23	26.8	*	25.8	22.5	18.7
Left side bending	*	27.9	29	29.7	28	25.8	16.3
Right side bending	*	28.5	29	30.8	28	26.2	16.3
Left axial rotation	*	16	15	16.6	16.4	14.4	8.9
Right axial rotation	*	15.4	15	15.6	16.4	12.8	8.4

EMT- Electromagnetic Tracking device; * not studied; [a] Ten male subjects, 19-51 years old; [b] Ten male subjects, 20-30 years old; [c] Seventeen male subjects and seven female subjects, 20-30 years old; [d] twenty male subjects, 20-30 years old; [e] 15 male subjects and four female subjects, 20-30 years old.

the gyroscopes were very large and making it difficult to be placed over a single spinous process. The gyroscopes might be placed over L1 or L2 so that the movements of L1/2 were not fully recorded and led to an underestimation of the gross movements of the lumbar spine (Lee et al., 2003). In general, all these non-invasive or skin mounted measurement methods suffered from the same problems that are the movements between the sensors and the skin, as well as the error due to the false locations of spinous processes by palpation. Although all the authors had tried their best to avoid this from happening, these errors were really unavoidable.

2.5.2.2. Kinematics of the lumbar spine and hip during physiological movements

Many authors had particularly looked at the kinematics of the lumbar spine and hip and the relationships between these two regions during forward bending of the trunk (Esola et al., 1996; Lariviere et al., 2000; Lee & Wong, 2002; Mayer et al., 1984; McClure et al., 1997; Nelson et al., 1995; Paquet et al., 1994; Porter & Wilkinson, 1997). Mayer et al (1984)used the two inclinometer technique to measure the movements of hip and lumbar spine. They found that the mean gross flexion range of the lumbar spine and hip was 122°. The mean lumbar flexion and the mean pelvis flexion were 55°and 66° respectively. They also analysed the differential mobility of pelvis and lumbar spine through the flexion arc and suggested that lumbar spine contributes to the gross motion in difference extent at difference stages of flexion.

Paquet et al (1994) employed electrogoniometric recordings to study the lumbar spine and hip movements. They found that the maximum flexion range of the hip-lumbar complex was 126°. The maximum lumbar flexion was 77°and the maximum hip flexion was 49°. These findings were quite different from those of Mayer et al. More lumbar flexion and less hip flexion were found in Paquet's study when compared to the study of Mayer et al. Despite these discrepancies which were likely due to differences in research methodologies, the movement patterns detected in the two studies were similar. Both studies found that the movement of the lumbar spine was greater during the first 75% of total flexion, whereas the hip movement predominated during the last 25% of total flexion.

Esola et al (1996) had investigated the hip-lumbar correlation using opto-electric motion analysis system. They reported that the total forward bending of hip-lumbar complex was 113° with a contribution of 40° from the lumbar spine and 69° from the hips. They analysed the movement pattern by calculating the ratios of lumbar-to-hip flexion (L/H ratio) at 30°intervals of forward bending motion. They have found that the early motion (0°-30°) had approximately a L/H ratio of 2:1. Middle range of motion (30°-60°) had approximately a L/H ratio of 1:1 and in the last 30°(60°-90°) the ratio was approximately 1:2. These findings were in agreement with previous studies that the lumbar spine contributes to a larger extent in the early phase of forward bending.

The most recent study of Porter & Wilkinson (1997) further supported those of Paquet et al (1994). They employed the electromagnetic tracking device to investigate this relationship. They reported the mean values of maximum lumbar flexion and maximum hip flexion were 68°and 58°respectively. They observed that the lumbar spine had an even more significant contribution to total forward bending when compared to the results of Paquet et al (1994)study.

Nelson et al (1995) also used the electromagnetic tracking system to study the relative contributions of the lumbar spine and pelvis during forward bending while a load was carried. They found that both the lumbar spine and pelvis moved simultaneously during loaded forward bending, despite the contribution of the lumbar spine was larger than the pelvis during the initial 50% of the total movement. However, this was not the case for trunk extension. They found that trunk extension was initiated by posterior pelvis rotation first and followed by the extension of the lumbar spine. McClure et al (1997) further supported this observation. They analysed the lumbopelvis rhythm during trunk extension from fully flexed posture to neutral standing posture. They found that extension of the trunk was initially accomplished by hip motion with an increasing contribution from the lumbar spine in the midrange. The lumbar spine becomes the predominate source of motion at the end of extension.

The above review shows that the interaction between the lumbar spine and hip has only been studied in the sagittal plane. The interaction of the two body parts during lateral bending and twisting of trunk has not been studies.

2.5.2.3. Kinematics of the lumbar spine, pelvis and hip during functional activities

Some researchers investigated the coordination of movements between the lumbar spine and pelvis during normal gait (Crosbie et al., 1997; Rowe & White, 1996; Schache et al., 2002; Schache et al., 2001a; Whittle & Levine, 1999). Crosbie et al studied the pattern of spinal movements during walking in 50 males and 58 females aged between 20 to 82 years. They used video-based system to record the movements of the lower thoracic spine, the lumbar spine and the pelvis. For sagittal plane movements, the pelvis was found to rotate posteriorly (posterior tilt) at heel strike and followed by anterior tilting in the early single support phase. The pelvis then reversed its tilt to the next heel strike. The lumbar spine movement complemented those of the pelvis. During heel strike, the lumbar spine was maximally flexed and followed by a rapid extension to neutral until the beginning of single support. Then the lumbar spine was slowly flexed and reached maximum at another heel strike (Crosbie et al., 1997). However, the studies of Whittle and Levine (1999) and Rowe and White (1996) yielded different results. The magnitude of pelvis tilting was relatively consistent between subjects, but there was a great individual variation particularly for the lumbar lordosis. The patterns ranged from spinal movements being in phase with pelvis tilt to completely out-of-phase. Rowe and White (1996) also found that the intra-subject variability was greater in sagittal plane than the other two planes. These discrepancies might due to different methodologies among various studies (Whittle & Levine, 1999).

For frontal plane movements, there were general agreements among these three studies (Crosbie et al., 1997; Rowe & White, 1996; Whittle & Levine, 1999). Whittle and Levine (1999) using angle-angle diagram to illustrate that during right initial contact, the pelvis was approximately level and the lumbar spine was almost straight in the frontal plane. From right initial contact to left toe off, the pelvis tilted upward on the right side gradually and it was accompanied by the right lateral bending of the lumbar spine. During right mid-stance, the pelvis was level again and the lumbar spine followed this movement. The lumbar spine had a brief side bending to the right, while the pelvis continued to dip on the left side. Finally the lumbar spine straightened again before the next left initial contact. The cycle repeated with subsequent gait cycles (Whittle & Levine, 1999). The movements between the lumbar spine and pelvis in this plane were very much in-phase for the whole gait cycle.

For transverse plane movements, the coordination between the lumbar spine and pelvis was again demonstrated using angle-angle diagram by Whittle and Levine (1999). At right initial contact, the pelvis was twisted forward at the right side and the lumbar spine had a corresponding rotation to the right side. There was a 90° phase lag between these movements with the lumbar spine moved earlier than the pelvis. This phase lag was further supported by the findings of Crosbie et al (1997).

Schache et al (2002; 2001a)investigated the relationship between the lumbar spine and pelvis and the lumbo-pelvis-hip complex during running. They recruited 20 male runners with average age of 32.7 years old. The movements of the lumbar spine and pelvis were captured by optoelectronic method. For sagittal plane movements, the average amplitudes of the rotations for the lumbar spine were 13.3°±3.8° and 7.6°±2.0° for the pelvis. The average angular positions for the lumbar spine were -22.9°±6.2° and 16.4°±3.3° for the pelvis. The lumbar spine flexed slightly and the pelvis posteriorly tilted during early stance. During mid-stance, these movements reversed so that the lumbar spine extended and the pelvis anteriorly tilted. Right toe off followed the peak extension of the lumbar spine and anterior tilt of the pelvis. This movement cycle for the lumbar spine and pelvis was repeated following initial contact of the contralateral lower limb. There were great variations in the flexion-extension cycle of the lumbar spine across subjects. This is consistent with the results of Whittle and Levine (1999) for walking. The great variability might possibly due to the differences in the lumbar lordosis among subjects. Angle-angle diagram showed that flexion-extension of the lumbar spine and anterior-posterior tilt of the pelvis were coordinated during running (Schache et al., 2002). In another study conducted by the same research group, they also found that the hip movement was highly coordinated with the movements of the lumbar spine and pelvis (Schache et al., 1999). The mean pelvis anterior-posterior tilt angle has been shown to have significant negative correlation with maximum hip extension range of movement during running. More anterior tilting was found in runner who has reduced hip extension during terminal stance. This might be a compensatory mechanism for those runners who have restriction in hip extension movement.

The average amplitudes of rotations in frontal plane were 18.5°±3.9° and 10.6°±3.0° for the lumbar spine and pelvis respectively. Right lumbar lateral bending was observed at right initial contact and the pelvis was lower on the left side (Schache et al., 2002) and the hip was in adducted position (Novacheck, 1998). These movements continued to increase until loading response (initial contact). Both the lumbar spine and the pelvis movements attained to their peak almost at the same time. The lumbar spine then started to laterally bend towards the left as the pelvis began to elevate on the left side. The lumbar spine was laterally bent to the left and the pelvis was lower on the right during left initial contact. From mid stance to toe off, the hip was abducted slightly and reached its maximum during mid swing to assist the foot clearance at this phase. From mid swing to terminal swing, the hip adducted again to prepare the next initial contact (Novacheck, 1998). The same movement manner just repeated again on the contra-lateral side. The movements of the lumbar spine and pelvis in frontal plane again were very coordinated during running as revealed by the angle-angle diagram. There was an almost perfect linear relationship during early and mid stance of the running cycle. However, right after toe off to initial contact of the contralateral lower extremity, the lumbar spine maintained a relatively neutral position whereas the pelvis dropped slightly to the side that the foot was having the initial contact (Schache et al., 2002).

For transverse plane movements, axial rotation of the lumbar spine was coordinated well with the axial rotation of the pelvis. However their relationships were out of phase by 21% of the running cycle where the lumbar spine attained its peak rotation earlier than the pelvis. The peak axial rotation to the left of the lumbar spine was found to occur just after right toe off. At this moment, the right hip would approach its maximal extension whilst the left hip would pass the maximal flexion (Schache et al., 1999). The movement pattern of axial rotation of the pelvis during running is different to that during walking. The major difference was that at right initial contact during walking, the pelvis was shown to rotate to the left (Whittle & Levine, 1999) whereas the pelvis was rotated slightly to the right during running. It was suggested that this was important for minimizing the horizontal braking forces as initial contact and avoid potential loss of speed (Novacheck, 1998; Schache et al., 1999).

2.6. Three-dimensional movement patterns of the lumbar spine and hip in subjects with low back disorders

Numerous studies had shown that low back pain affects the mobility of the lumbar spine and its adjacent joints (Dolan & Adams, 1993; Ellison et al., 1990; Fairbank et al., 1984; Mellin, 1990). Dolan & Adams (1993)found that the reduction in hip mobility was greater than the spine in subjects with history of low back pain and the mobility of hip became an important determinant of the bending moment acting on the spine in these subjects. Fairbank et al (1984) also found that the femoral rotations were significantly less in back pain subjects. All the above evidence suggests that back pain can adversely affect the kinematics of the lumbar spine and hip.

Pacquet et al (1994) specifically studied the effects of back pain on the movements of the lumbar spine and hip. They found that the mean maximum magnitude of flexion in low back pain patients was approximately 20% smaller than that of normal subjects. They also reported that back pain patients attained their maximum flexion of the lumbar spine at a later part of the range when compared to normal subjects. Angle-angle diagram also showed that the contribution of the lumbar spine relative to the hip was reduced, particularly during flexion.

Esola et al (1996) compared the total amounts of forward bending motion and velocity between low back pain patients with normal subjects. They found that there was no significant difference in these variables. These findings conflict with the finding of Burton et al (1989) who noted that low back pain patients tended to exhibit more lumbar spine movement during the early phase of movement. The discrepancy could be explained by the different clinical conditions of the patients and the recruitment criteria employed in these studies. In regard to the patterns of movement during flexion, Esola et al (1996) calculated the L/H ratio for 30° interval from 0° to 90°. They found the subjects with history of low back pain had an L/H ratio during the middle phase (30°-60°) of 0.72 as compared to 1.06 for normal subjects. It was evident that this group of subjects tended to move less in the lumbar spine in the early phase of movement. Another finding in this study was that the correlation of hamstring flexibility to total hip and total forward bending motions was much higher in subjects with history of low back pain than those normal subjects. They hypothesized that the hamstrings were used to control forward bending in subjects with low back disorders but not for normal subjects.

However, Porter and Wilkinson (1997) found that there was generally significant reduction of lumbar spine contribution in subjects with chronic low back pain, although one third of back patients had great reductions in hip flexion during forward bending. They also found that one third of chronic low back subjects had a range of hip flexion less than 43°, but only 2 out of 17 normal subjects had this presentation. This finding agreed the results of Dolan & Adams (1993).

Vogt et al (2001) examined the influences of nonspecific chronic low back pain on three-dimensional lumbar spine kinematics in locomotion. They found that the temporal patterns of the pelvis and thoracic curves were similar in both normal and back pain groups. However, there was increased inter-subject variability in back pain subjects. This might indicate that patients might have individual adaptations and adjustments in walking behavior.

2.7. Summary

The above review shows that the lumbar spine and hip have different contribution to spinal movements in different activities, although there are significant shortcomings in the previous in vivo studies. For instance, all previous in vivo studies on physiological movements examined the sagittal movements only.

There was no information on the contribution of lumbar spine on movements of in anatomical planes. Furthermore, although preliminary evidence showed that back pain may affect the correlation between hip and lumbar spine during normal physiological movements, the precise effects are not fully understood. This is largely because there is no ideal methodology for investigating the movement correlation. Previous studies only used movement ratios to study the correlation of hip and lumbar spine movements. This was rather preliminary and the phase relationship between the hip and lumbar spine movements was not studied in any of the previous work. The effects of back pain on the phase relationship between hip and lumbar spine movements and the three-dimensional kinematic patterns remain unknown. Finally, back pain is often accompanied by limitation in SLR. There was evidence that stiffness of posterior hip tissues or limited SLR could affect spine and hip kinematics. But no previous research had examined such effects. It is hoped the present study could address the above limitations of previous research and provide fundamental information on the effects of back pain on hip and spine movement coordination.

Chapter 3 Methodology

3.1 Subjects

Sixty-two male subjects were recruited from a local university (The Hong Kong Polytechnic University) and outpatient physiotherapy clinic of a local hospital (The United Christian Hospital) by posters. Subjects had to fulfill all the inclusion criteria before they were tested. They were divided into three groups: Group 1 (control) - twenty normal subjects who were in good health with no history of back pain or leg pain that might be attributed to the back within the last 12 months. Group 2 (back pain only) – twenty-four subjects with current low back pain due to mechanical causes for lasted for 6 to 12 weeks (sub-acute). Their pain should be over the L1-sacrum region without any radiation to areas distal to the gluteal crease and no limitation in straight leg raise (SLR). Twelve of these subjects had pain over the left side of the back and the remaining subjects had pain over the right side. Group 3 (back pain + SLR) – eighteen subjects with sub-acute back pain and limitation in SLR (i.e. SLR with a pain free range of less than 55°). Ten of group 3 subjects had pain over the left side of the back accompanied by limitation in SLR with the left leg, and the remaining subjects had pain and limitation in SLR with the right side. The low back pain subjects were also asked to fill in the Roland-Morris Disability Scale (RDQ), the Chinese Version (Leung et al., 2003) to assess their level of disability. They had a mean score of 11±4 for the RDQ. The pain intensity of groups 2 and 3 subjects was measured using a numerical rating scale (NRS) ranging from 0 to 10, where zero represented no pain and ten represented extremely intense pain. They had a mean NRS of 6±2 representing a group of patients with mild pain in the sub-acute stage. The demographic data, mean RMS and mean NRS are summarized in table 3.1.

Subjects were excluded if they had

- inflammatory joint disease
- past history of fracture, dislocation and spinal surgery
- neurological signs or unable to perform trunk movements due to unbearable pain

Ethics approval for this study was obtained from the Departmental Research Committee of the Hong Kong Polytechnic University. Subjects were informed about the experimental procedure and any potential risks prior to the attainment of written consent

3.2 Methods

3.2.1 *Apparatus*

The 3SPACE Fastrak (Polhemus Inc., Colchester, VT 05446, USA) (Fig 3.1) was used to measure movements of the lumbar spine and hips. It had a source that generated a low-frequency magnetic field which was detected by the sensors. It provides real-time six degrees of freedom measurement by using the electromagnetic field to detect the three-dimensional position and orientations of the sensors relative to the stationary source. The source was placed in a fixed position close to the subject (within 0.7m) (Biryukova et al., 2000; Harryman et al., 1990; Pearcy & Hindle, 1989). The global coordinate reference system X_g, Y_g, Z_g was designated by the source (Fig 3.2). The positive axes were defined as follows: X_g axis – horizontal pointing anteriorly, the Y_g-axis horizontal point to the left of the subject and Z_g-axis pointing superiorly and aligned with the cardinal planes of the body. The four local coordinate reference systems of L1, S2 and the thighs are defined in Table 3.2 and are illustrated in Figure 3.3. The local coordinate reference

systems for the lumbar spine and hip followed the International Society of Biomechanics (ISB) protocol. The right hand rule was used to determine positive rotation in all calculations.

Two sensors of the system were employed to measure the movements of the lumbar spine - one sensor was placed over the L1 spinous process and the second sensor over the sacrum (Figure 3.4). Two other sensors were used to measure the movements of the hips by placing them over the posterior aspect of the left and right thighs (Figure 3.5). Each sensor was attached to a small, mouldable plastic plate with plastic screws. The plate was rectangular in shape which measured 3cm * 3.5cm. A Velcro band was threaded through the plate and tightly wrapped around the subject's trunk or leg so as to minimise the movement between the sensor and the underlying skin. The cables of the sensors were attached to the skin on the side of the trunk so that they did not move the sensor erroneously during the movement. Initial testing showed that the above arrangement provided the most secure sensor attachments. Fastrak accuracy is affected by the presence of metallic object, whether nearby or between the source and the sensors. Therefore no metallic object was placed around the measuring area.

The Fastrak had an electronic unit that calculated the three-dimensional positions and orientations of the sensors relative to the source. The unit was linked

Table 3.1 Demographic data, mean RMS and mean NRS of groups

Group	Number of subjects	Age	Height (cm)	Weight (kg)	NPS	RMS
1	20	42 (8)	170 (6)	71(11)	NA	NA
2	24	41 (11)	172 (4)	69 (6)	6 (2)	10 (4)
3	18	34 (10)	174 (4)	71 (5)	6 (2)	12 (4)

Group mean values (SD) are presented in this table
NPS=Numerical Pain Scale; RMS=Roland-Morris Disability Scale, NA=Not applicable

Table 3.2 Definition of the local co-ordinate reference systems

Anatomical landmarks	Local coordinate reference system
Lumbar vertebrae 1	Origin: the centroid of the vertebral body (half way between the centers of the two endplates). Y_L axis: passes through the centers of the upper and lower endplates. Z_L axis: parallel to a line joining bases of the right and left pedicles. X_L axis: points forward
Sacrum	Origin: Midpoint between right and left anterior superior iliac spine (ASIS). Z_S axis: points from the origin to the right ASIS. Y_S axis: perpendicular to both X and Z, positive cranially (superiorly in the erect standing position) X_S axis: lies in the plane defined by the ASISs and the midpoint of the posterior superior iliac spines (PSISs) and points ventrally (anterior, in the direction of progression) orthogonal to the Z axis.
Femur	Z_F axis: perpendicular to the Y axis, located in the plane defined by the hip center and both femoral epicondyles, pointing laterally to the right side of the body. Y_F axis: along the line joining the hip center and the midpoint of the medial and lateral femoral epicondyles, pointing proximally. X_F axis: perpendicular to both, pointing ventrally (anteriorly).

Figure 3.1 The 3SPACE Fastrak (Polhemus Inc., Colchester, VT 05446, USA)

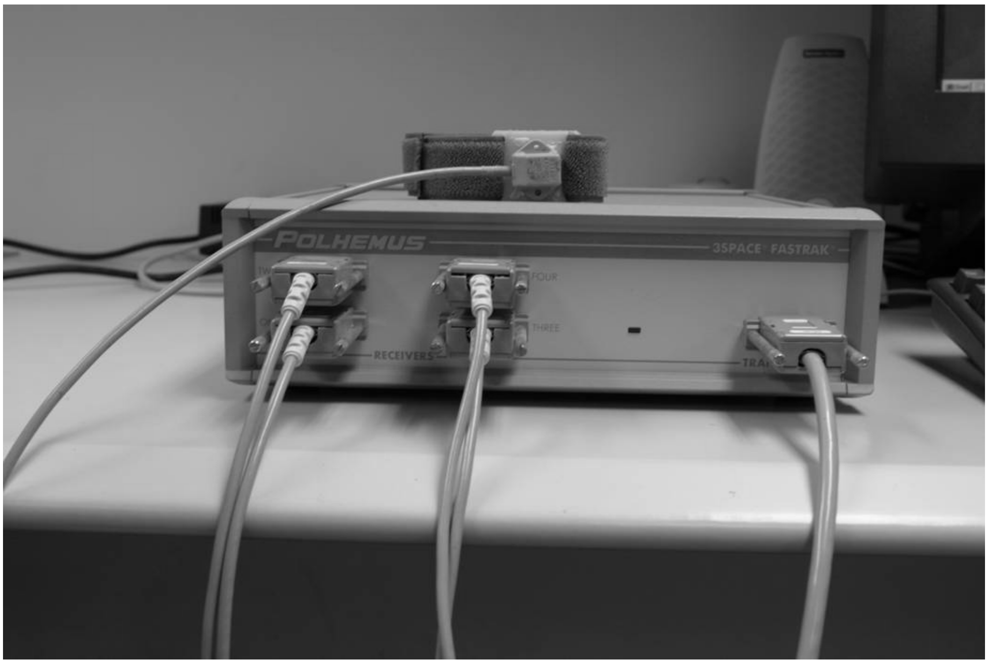


Figure 3.2 Global co-ordinate reference system

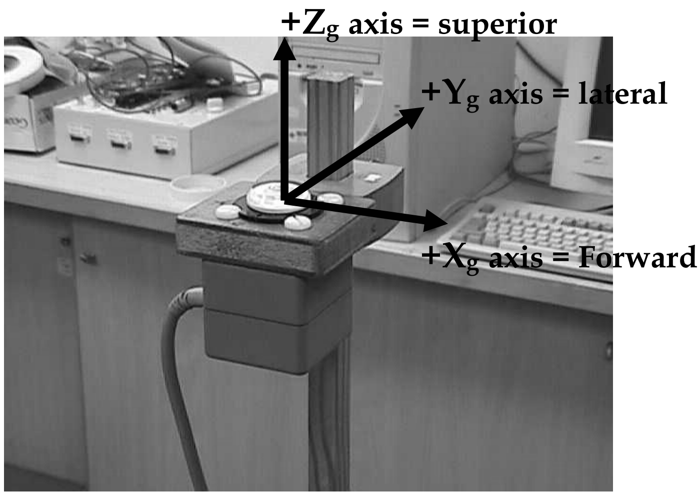


Figure 3.3 Local co-ordinate reference systems

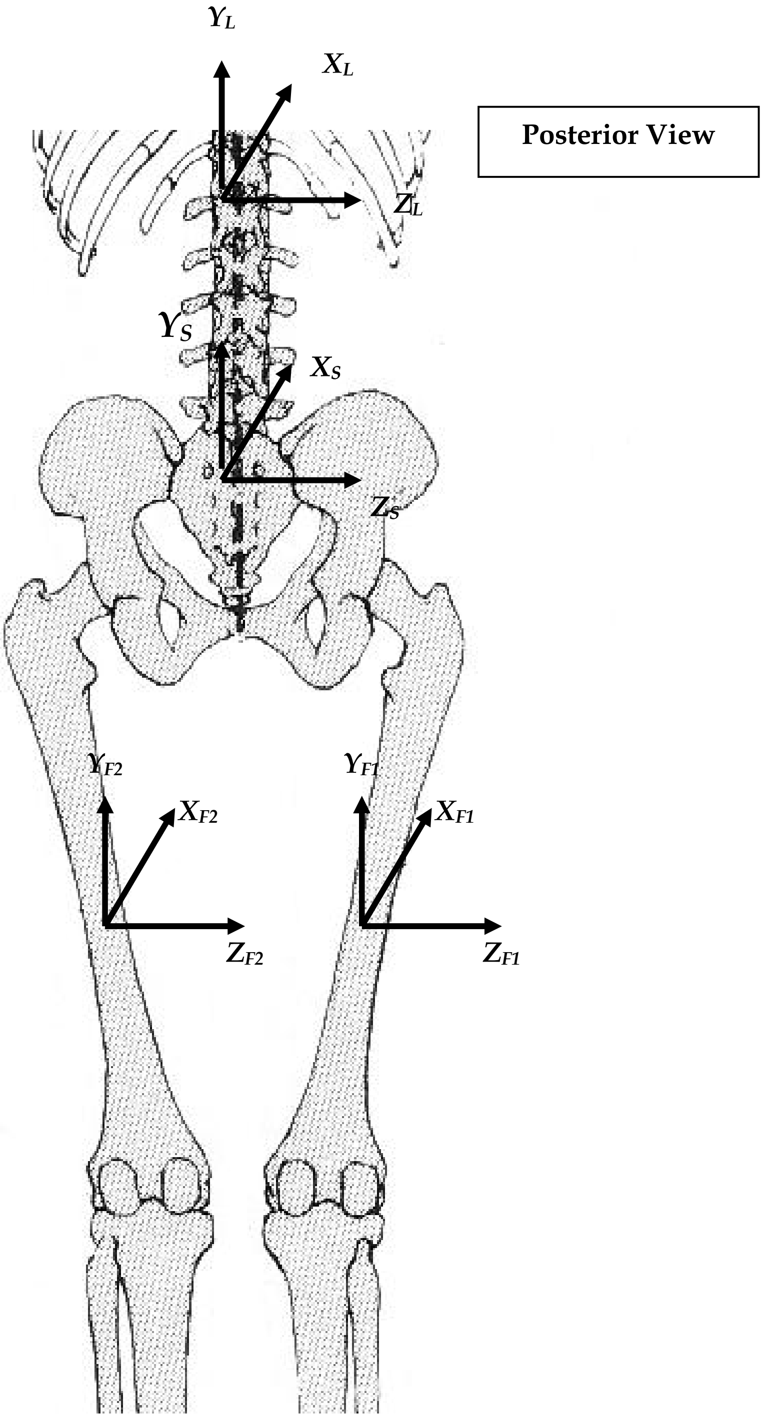


Figure 3.4 Placement of sensors over L1 spinous process and sacrum

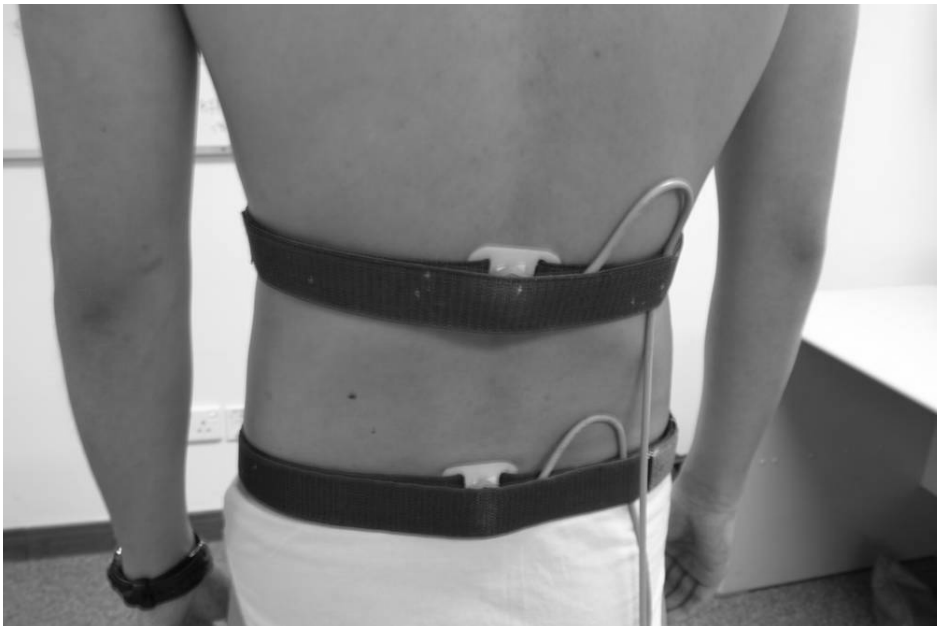


Figure 3.5 Placement of sensor over the posterior aspect of thigh

to a personal computer via an RS232C serial interface. Specifically developed custom software was used to control the Fastrak operation, data acquisition and display the results in real time. The software developed in this study was able to perform fast serial communication at 115.2 kBaud allowing a data update rate of 120Hz. As four sensors were used in this experiment, the sampling rate was 30Hz per sensor. The data was then saved and analysed in later stage.

3.2.2 *Procedure*

All subjects were asked to read and signed the Informed Consent Form (appendix I) upon arrival. Routine clinical examination of the subjects was conducted by a qualified physiotherapist prior to data collection. This included history taking and clinical examination including palpation, passive SLR test and screening tests to exclude subjects with pathologies that would prevent them from participating in this study. The method of passive SLR test followed the procedure described by Magee (2002). A Myrin goniometer (Parir, 746 24 Balsta, Sweden) was attached to the thigh of the tested leg to measure the range of hip flexion during the SLR test. Subject was asked to relax and lay down in the supine position, the hip medially rotated and adducted, and the knee fully extended. The therapist flexed the hip until the subject complained of pain or tightness in the back and back of the leg and the range of hip flexion was noted.

After completion of the clinical examinations, subjects were asked to perform warm up exercise which included forward, backward and side bending, and twisting of the trunk to end of range for 10 repetitions to each direction. This was to "precondition" the spine and hip, ensuring the consistency of measurements during the real data collection. The attachment of sensors to the subject followed a strict procedure in order to place the sensors onto the appropriate bony landmarks. The spinous processes of L1 and S2 were located by palpation. Subjects were asked to prone-lying on a plinth. The posterior superior iliac spines were located by palpating downward and posteriorly from the iliac crests of the hip bones. The S2 level was taken to be the intersection of an imaginary line connecting the posterior superior iliac spines. The L1 level will then be located by counting 6 spinous processes from S2 (Gray et al., 1995). The thigh sensors were placed over the posterior aspects of the mid-thighs and tightly wrapped around the thighs by Velcro strips. After the sensors were attached onto the body, subjects were asked to bend their back to see if there were any restrictions of the movements or loosening of sensors.

The transmitter was situated at the posteriolateral side of the subject. The subject was positioned such that all sensors were within 0.7m from the transmitter, which was the working range of the transmitter for optimal accuracy. The transmitter was attached to a wooden pedestal and placed 1.3m above the ground. A spirit level attached to the top of the transmitter was checked before the data collection to make sure it was centred.

The subjects were then requested to stand upright in their most comfortable posture with feet shoulder-width apart and palms facing inwards. The positions of the lumbar spine and hips in this posture were recorded by the Fastrak and taken as the zero reference positions. Standing posture was chosen as it is a functional position and clinically, it is more convenient to carry out the assessment in standing. The movements of the lumbar spine and hips were calculated with respect to these reference positions. Each subject performed three continuous cycles of each of the following movements of the trunk: (1) maximal forward and then backward bending with knees kept in extended positions, (2) maximal side bending towards the left and right in extended knees positions, and (3) maximal twisting towards the left and right with both feet firmly stand on the ground. Subjects were asked to perform all the movements in pure sagittal, frontal and horizontal planes. Demonstrations of pure movements were given by the physiotherapist and trial runs of movements were performed by subjects prior to the data capturing. Post-hoc analysis of the movement data confirmed that there were unacceptable movements in the unwanted planes. The three movement trials of the trunk were tested in a random order. Each trial was performed over a 30 second period at a speed that was most comfortable for the subject. There was a rest period of 5 minutes after each movement trial. In order to examine the repeatability of the movement data, each movement was repeated three times.

3.2.3 *Data Analysis*

3.2.3.1 Calculation of three-dimensional movements

The Fastrak output comprised the 3x3 matrices of direction cosines that described the orientations of the sensors relative to the source. Lumbar spine movements, which were described by the relative orientation between the L1 and sacral sensors, and hip movements from that between the thigh and sacral sensors, were derived from these matrices. The method of computation was based on the mathematical techniques proposed by earlier authors (Cole et al., 1993; Grood & Suntay, 1983; Lee, 2001; Pearcy et al., 1987b). Using the lumbar sensor and hip sensor as an example, the relative orientation of the L1 vertebra and the sacrum represented the posture or movement of the lumbar spine. The orientation may be described by a matrix $[R]$ which expressed the orthogonal base vector set of the L1 vertebra $[A_L]$ in terms of that of the sacrum $[A_S]$ (Fig 3.3).

$$\begin{bmatrix} A_{L1x} & A_{L1y} & A_{L1z} \\ A_{L2x} & A_{L2y} & A_{L2z} \\ A_{L3x} & A_{L3y} & A_{L3z} \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \times \begin{bmatrix} A_{S1x} & A_{S1y} & A_{S1z} \\ A_{S2x} & A_{S2y} & A_{S2z} \\ A_{S3x} & A_{S3y} & A_{S3z} \end{bmatrix} \quad (3.1)$$

or

$$[A_L] = [R][A_S], \quad (3.2)$$

$$[R] = [A_L][A_S]^{-1} = [A_L][A_S]^T, \quad (3.3)$$

where x, y and z are the axes of the global reference system (ground), and $[A_S]^T$ is the transpose of $[A_S]$.

The anatomical base vector sets $[A_L]$ and $[A_S]$ are unknown, but the Fastrak provides information on the orientation or base vector sets of the sensors attached to L1 and the sacrum $[S_L]$ and $[S_S]$. As the sensors are rigidly attached to the body, the anatomical and sensor axes will have fixed spatial relationships.

$$[S_L] = [M_L]\,[A_L], \quad (3.4)$$

$$[S_S] = [M_S]\,[A_S], \quad (3.5)$$

where $[M_L]$ and $[M_S]$ are matrices which defined the spatial relationships.

If the upright standing posture is taken as the zero reference position, then

$$[A_L]_{\text{upright}} = [A_S]_{\text{upright}} = [I], \quad (3.6)$$

where $[I]$ is the unit matrix.

Thus,

$$[M_L] = [S_L]_{\text{upright}}, \quad (3.7)$$

$$[M_S] = [S_S]_{\text{upright}}, \quad (3.8)$$

It is then possible to express $[R]_{lumbar}$ in terms of the base vector sets of the sensors.

$$[R]_{lumbar} = [A_L]\,[A_S]^T, \quad (3.9)$$

$$[R]_{lumbar} = [S_L]\,[M_L]^T\,[S_S]^T\,[M_S], \quad (3.10)$$

$$[R]_{lumbar} = [S_L]\,[S_L]^T_{upright}\,[S_S]^T\,[S_S]_{upright} \quad (3.11)$$

The three anatomical angles (α, β and γ) can be computed from $[R]$ using the method suggested by various authors (Cole et al., 1993; Grood & Suntay, 1983; Lee, 2001; Pearcy et al., 1987b). For the case of hip joint, the anatomical base vector set $[A_H]$ is also unknown. The thighs sensors provide the base vector sets for both thighs. Similar calculations of hip movements can be carried using Fastrak information about the relative orientation of hip and sacral sensors.

$$[R]_{hip} = [S_h]\,[S_h]^T_{upright}\,[S_S]^T\,[S_S]_{upright} \quad (3.12)$$

where $[R]_{hip}$ expressed the orthogonal base vector set of the thigh $[A_H]$ in terms of that of the sacrum $[A_S]$. $[S_h]$ and $[S_S]$ are the orientation or base vector sets of the sensors attached to the thigh and the sacrum respectively.

The following sign convention was adopted during the calculations of different movements: (a) the lumbar spine: flexion, left lateral flexion and left axial rotation were considered to be positive, and (b) the hip: flexion, abduction and lateral rotation were positive. Movements in the opposite directions were represented by negative values.

3.2.3.2 Repeatability of movement data

Based on the above calculations, the range of movements of the lumbar spine and hip were obtained and they were plotted against time. In order to examine the repeatability of measurements of each joint movement, the angle-time curves obtained in the various movement cycles were first normalised with respect to time to a uniform length. The normalization was done by dividing the whole movement into four different phases and each phase of movement constituted 25% of the whole normalized curve. The first 25% was from the starting point to the peak of the first movement. The second 25% was from the first peak to the following zero degree point. The third 25% was from the zero degree point to the peak of the second movement. The last 25% was from the second peak to the end of the second movement, which denoted by the second zero degree point.

In order to investigate the repeatability of each movement of the lumbar spine and hip, the coefficient of multiple correlation (CMC) (Kadaba et al., 1989; Yu et al., 1997) was calculated to determine the degree of similarity of the movement-time curves obtained in the three trials. This method was employed because all the normalized curves are all waveform data. Unfortunately, statistical measures, such as Intraclass correlation coefficient (ICC) or Pearson product-moment correlation coefficient (Portney & Watkins, 2000) are limited to assess the repeatability of measurements of a single sample point in the waveforms, such as the maximum joint angle in this case. Measurements of a single sample point may be repeatable even though the waveforms are inconsistent. CMC is a ideal measure to examine the repeatability of waveform data (Kadaba et al., 1989) and it was previously employed in some gait studies (Kadaba et al., 1989; Yu et al., 1997). After the normalization, the data sets have a uniform length of n sample points.

The coefficient of multiple correlation (Kadaba et al., 1989; Yu et al., 1997) is given by

$$CMC = \sqrt{1 - \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}(Y_{ij} - \overline{Y}_j)^2 / n(m-1)}{\sum_{i=1}^{m}\sum_{j=1}^{n}(Y_{ij} - \overline{Y})^2 /(mn-1)}} \qquad (3.13)$$

where Y_{ij} is the *j*th sample point of *i*th set of measurement, $\overline{Y}_j$ is the mean at the *j*th sample point over the *m* data sets, and $\overline{Y}$ is the grand mean over the *n* sample points and the *m* data sets. The ratio on the right hand size of the equation (3.2) is referred to as the variance ratio. The numerator of the ratio is the variance of the waveform data about a 'running' mean ($\overline{Y}_j$) or the ensemble mean curve across the various data sets, and the denominator is the variance about the grand mean. Therefore, CMC provides a value approaching 1 when the waveforms of every data set are similar to each other, while dissimilar waveforms give rise to a value approaching 0. Portney and Watkins (2000) suggest that there is good correlation if the coefficient is above 0.75. Coefficients from 0.5 to 0.75 suggest moderate reliability, and values below 0.5 represent poor reliability. To study the errors of this calculation, the root means square error was also determined to show the errors involved in measuring the joint movement. It was done by calculating the root mean square error of each movement curve from that of the mean curve which was obtained by averaging the three movement curves.

3.2.3.3 Maximum ranges of movements and the ratios of the lumbar spine to hip movements

Descriptive statistics were computed from the angle-time curves. The means and standard deviations of the maximum range of each direction of movement of the lumbar spine and hip were determined. Movements in the sagittal plane of the lumbar spine and hip could be compared directly as all the movements were symmetrical. However, movements in the frontal and horizontal planes of the lumbar spine and hip were classified according to the side where pain was felt. This was not applicable, however, for asymptomatic subjects in Group 1, and in this case, movements of the two sides of the body were pooled together. This was acceptable because t-tests revealed that there were no significant differences in the magnitude of movements towards the two sides ($p>0.05$) in normal subjects group. The overall means of the movements were used for comparisons with the magnitude of movements of the painful subjects.

The ratios of the magnitude of the movement of the hips to those of the lumbar spine were computed for each direction of movements. This ratio revealed the relative contribution of the lumbar spine and hip to the whole movement. As the sign convention was different for different directions, the ratio might have different sign for different movements. To eliminate any confusion associated with the use of sign, all the ranges were converted to absolute values in determining the ratio. For group 1 subjects, the following ratios were calculated.

- Sagittal plane: Hip flexion/Lumbar flexion, Hip extension/Lumbar extension.
- Frontal plane: Ilpsilateral Hip abduction/Lumbar side flexion, Contralateral Hip adduction /Lumbar side flexion.
- Horizontal plane: Ilpsilateral Hip medial rotation/Lumbar axial rotation and Contralateral Hip lateral rotation/Lumbar axial rotation.

For group 2 & 3 subjects, as mentioned earlier, the hips had been classified into painful and non-painful side according to the side where pain was felt in the lumbar spine region for back pain only group (group 2) and limitation in straight leg raising group (group3). The ratios were calculated in the following manners.

- Sagittal plane: Hip flexion of painful side/Lumbar flexion, Hip flexion of non-painful side/Lumbar flexion, Hip extension of painful side/Lumbar extension, Hip extension of non-painful side/Lumbar extension.
- Frontal plane: Hip abduction of painful side/Lumbar side flexion towards painful side, Hip adduction of non-painful side/Lumbar side flexion towards painful side, Hip adduction of painful side/Lumbar side flexion towards non-painful side, Hip abduction of non-painful side/Lumbar side flexion towards non-painful side.
- Horizontal plane: Hip medial rotation of painful side/Lumbar axial rotation towards painful side, Hip lateral rotation of non-painful side/Lumbar axial rotation towards painful side, Hip lateral rotation of painful side/Lumbar axial rotation towards non-painful side, Hip medial rotation of non-painful side/Lumbar axial rotation towards non-painful side.

The overall means of the ratios were compared among the three groups, to test the effect of location of pain and also used for comparison between different groups to test the effects of back pain and limitation in straight leg raising on the ratios.

3.2.3.4 Time duration of movement cycle

The time duration of one complete cycle of each trunk movement was determined for groups in achieving different movements. It was done by marking the starting point and the finishing point of each movement cycle e.g. Flexion-Extension, in the angle time curve graphically. The initial data were fitted with horizontal lines, and the starting points were visually identified on the curves when the values deviated from the horizontal lines. Similarly, the finishing points were marked when the angle-time curves went back to the original levels after the movement cycles. The duration between these two points was determined and the mean of three trials was also calculated for further comparison between different groups.

3.2.3.5 Cross correlation

Cross correlation (Chatfield, 2004; Li & Caldwell, 1999; Stergiou, 2004), as discussed in literature review (please see section 2.4.1.), is a measure of temporal similarity by detecting the common periodicities between two signals. Cross-correlation analysis was done on the angle-time data over the three consecutive movement cycles of the trunk between the movements of the lumbar spine and hips. The peak correlation coefficient would show the strength of correlation of the movements of the lumbar spine and hip. The phase relationship between the lumbar spine and hip movements was examined on the angle-time curves by determining the time lag at which the absolute value of the correlation coefficient was maximal. Movement of the lumbar spine was used as a reference for establishing the correlation. A positive time lag implied that the lumbar spine moved earlier than the hip in the movement cycle. The signs of the lumbar spine movement and the accompanying hip movement were made the same in the cross-correlation analysis so that the phase difference could be properly detected. For instance, in analyzing between left lateral flexion of the spine and the accompanying right hip adduction, the right hip adduction would have to be made positive so that it would not appear to be half cycle out of phase. Similarly, the left hip medial rotation that accompanied left axial rotation was made positive in the cross-correlation analysis of these two movements.

3.2.3.6 Angle-angle diagram and curve fitting

Angle-angle diagram was employed to illustrate the contribution of the lumbar spine and hip in all six directions of movements graphically. The signs of the movements were made positive. For sagittal plane movements, we plotted the lumbar spine movements (flexion/extension) against the averaged hip movements (flexion/extension). The range of movements for left and right hip in sagittal plane were pooled together as t-test revealed that there were no difference between the left and right hip movements. For the movements in frontal and horizontal planes, the lumbar lateral flexion/axial rotation movements were plotted against the hip abduction/medial rotation and adduction/lateral rotation.

As mentioned in the literature review (please see section 2.4.2.), there are three major patterns of movements. In order to differentiate the curve into one of these patterns, the curve could be fitted using two functions.

- linear polynomial function,

$$h = ml + c \qquad (3.14)$$

where h= hip movement, m=the slope of the fitted linear curve, l=lumbar spine movement and c=the y-intercept.

- an exponential function

$$h = a * exp(b * l) \qquad (3.15)$$

where *h*= hip movement, *l*=lumbar spine movement, *a*=constant and *b*=constant.

All the curves were plotted using the curve fitting toolbox in MatLab version 6.5 (The Mathwork Inc). A decision was then made which would be the most appropriate function according to the goodness of fit of each function. According to Portney & Watkins (2000), the curve is considered to be moderately reliable if the correlation coefficient is equal to 0.7 or above (Portney & Watkins, 2000). Hence if the correlation coefficient was less than 0.7, the curve was considered not to follow any pattern. Otherwise, the curve was considered either to be linear or exponential depending on which function has a higher correlation coefficient.

3.2.3.7 Statistical analysis

One-way analysis of variance (ANOVA) was performed using the software SPSS Version 11.5.0 (SPSS Inc., Illinois 60606) to compare the difference among the three groups, the mean magnitude of the movements of the lumbar spine and hip, the relative ratio of various movements, time durations of movements, the cross-correlation coefficients and the time lag among the three groups of subjects. Statistical significance was accepted at the 5% level. Post-hoc analysis was carried out using the Tukey procedure if any significant difference was revealed among the three groups. In order to test the symmetry of movements in the frontal and horizontal planes of the lumbar spine, paired t-tests were used to reveal any significant differences between movements towards the painful and non-painful sides.

The effects of back pain on the shape of the angle-angle curves. Chi-square test was employed to determine if the number of subjects in each shape of the curve was different in the three groups.

Chapter 4 Results

4.1. Reliability of measurement

The coefficient of multiple correlation (CMC) was employed to measure the repeatability of movement data. The advantage of the CMC in evaluating repeatability is that it measures the repeatability of the movement-time profile. The mathematical formulation of CMC is thoroughly explained in the methodology (Chapter 3, section 3.2.3.2.). The results of this analysis for various physiological movements are shown in Table 4.1. The mean CMC for the three physiological movements for the lumbar spine, the left hip and right hip were 0.97±0.05, 0.98±0.02 and 0.98±0.02 respectively. The respective mean root-mean-square errors were 1.1±0.5°, 1.6±0.8° and 1.6±0.9°. These results indicated that the measurements of different physiological movements were highly repeatable in terms of the shapes of the movement curves and the maximum range of movements. The measurement system was considered to be able to provide sufficiently reliable data for the purpose of this study.

4.2. Maximum ranges of movements of the lumbar spine and hips and the ratios of lumbar spine to hips

4.2.1. *Forward and backward bending*

The results of the maximum ranges of movements of the lumbar spine and hips, and the relative ratios for forward and backward bending are summarised in Table 4.2. Diagrammatic presentations of the movements of the lumbar spine and hips during forward and backward bending are also illustrated in Figure 4.1 & Figure 4.2 respectively. During forward bending of the trunk, both

Table 4.1 Coefficient of multiple correlation (CMC) & root-mean-square errors (RMSE) for the movement-time curves of the lumbar spine and hips

		Flexion-Extension		Lateral Bending		Axial Rotation	
	Group	CMC	RMSE (°)	CMC	RMSE (°)	CMC	RMSE (°)
Lumbar Spine	1	0.99 (0.00)	1.4 (0.4)	0.99 (0.01)	1.0 (0.6)	0.97 (0.03)	0.9 (0.5)
	2	0.99 (0.01)	1.6 (0.6)	0.98 (0.01)	0.9 (0.5)	0.92 (0.17)	0.9 (0.9)
	3	0.96 (0.10)	1.6 (0.7)	0.99 (0.01)	0.9 (0.3)	0.95 (0.08)	0.9 (0.4)
Left Hip	1	0.99 (0.01)	2.0 (0.9)	0.98 (0.02)	0.8 (0.3)	0.99 (0.01)	1.0 (0.5)
	2	0.98 (0.02)	2.6 (1.4)	0.96 (0.06)	1.2 (0.8)	0.99 (0.01)	1.4 (0.6)
	3	0.98 (0.03)	2.3 (1.3)	0.95 (0.04)	1.1 (0.7)	0.98 (0.01)	1.7 (0.6)
Right Hip	1	0.99 (0.01)	2.1 (1.0)	0.98 (0.01)	0.8 (0.3)	0.99 (0.01)	1.1 (0.6)
	2	0.98 (0.03)	2.7 (1.4)	0.96 (0.04)	1.2 (0.7)	0.98 (0.03)	1.7 (1.2)
	3	0.98 (0.01)	2.3 (0.9)	0.95 (0.04)	1.2 (0.8)	0.98 (0.01)	1.7 (0.6)

Note: All RMSE measurements in degrees; Group mean values (SD) are presented in this table.

the lumbar spine and hip exhibited flexion movement. The magnitude of the lumbar spine movement was generally similar to that of the hips, as shown by the hip to lumbar spine ratios. It was shown that back pain and limitation SLR were associated with significant decreases in the ranges of both the lumbar spine and hip flexion ($p<0.05$). The decrease in hip flexion was significantly larger in subjects with limitation in SLR than in subjects with back pain only ($p<0.05$). The relative ratios of hip to lumbar spine was not significantly affected in subjects of groups 2 and 3 ($p>0.05$), as back pain and limitation in SLR affected the ranges of movements in both the lumbar spine and hips.

During backward bending of the trunk, both the lumbar spine and hip demonstrated extension movement (Figure 4.2). Back pain and limitation in SLR were associated with the decreases in the ranges of lumbar spine and hips, but such decreases were found to be statistically significant only for hip extension in subjects with limitation in SLR ($p<0.05$).

The average relative ratio of hip extension to lumbar spine extension was about 0.7. Although there were decreases in the ranges of lumbar spine and hips, the relative ratio was not affected significantly in subjects of groups 2 and 3 ($p>0.05$).

4.2.2. *Lateral bending towards painful and non-painful sides*

The results of the maximum ranges of movements and the relative ratios of lumbar spine to hip during lateral bending are summarised in Table 4.3. Diagrammatic presentations of the movements of the lumbar spine and hips are also shown in Figures 4.3 and 4.4. During lateral bending of the trunk, side flexion of the lumbar

Table 4.2 Maximum ranges of movements and the relative ratios of the lumbar spine and hip during forward and backward bending

Group	1	2	3
Forward bending			
Mean Lx flexion ROM (°)[a, b]	**61.9 (2.2)**	**33.2 (1.8)**	**29.8 (2.9)**
Mean PH flexion ROM (°)[a, b, c]	**72.1 (3.6)[d]**	**54.2 (3.9)**	**41.1 (3.4)**
Mean NPH flexion ROM (°)[a, b, c]		**53.9 (3.4)**	**42.1 (3.6)**
Ratio of PH/Lx movements[d]	**1.09 (0.05)[d]**	**1.43 (0.06)**	**1.18 (0.13)**
Ratio of NPH/Lx movements[d]		**1.43 (0.06)**	**1.19 (0.13)**
Backward bending			
Mean Lx extension ROM (°)[e]	**15.5 (1.8)**	**14.9 (1.6)**	**12.7 (1.4)**
Mean PH extension ROM (°)[b]	**16.0 (1.5)[d]**	**13.5 (1.0)**	**11.1 (1.4)**
Mean NPH extension ROM (°)[b]		**13.7 (1.2)**	**11.1 (1.6)**
Ratio of PH /Lx movements[d]	**0.74 (0.34)[d]**	**0.69 (0.31)**	**0.79 (0.19)**
Ratio of NPH/Lx movements[d]		**0.73 (1.10)**	**0.72 (0.21)**

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side; ROM= range of movement

Group mean values (SEM) are presented in this table.

[a] Significant difference between groups 1 and 2 ($p<0.05$)

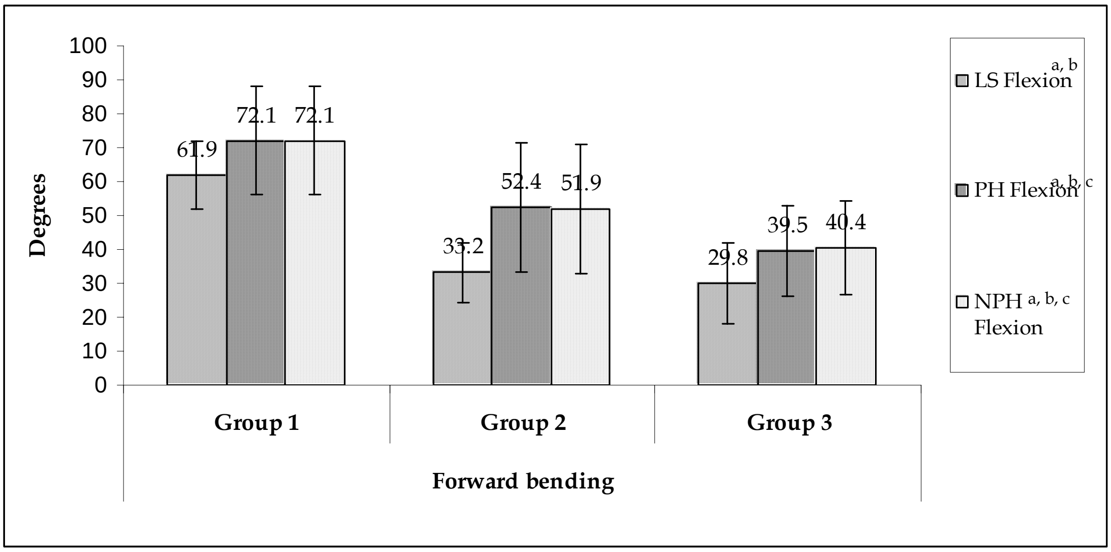
[b] Significant difference between groups 1 and 3 ($p<0.05$)

[c] Significant difference between groups 2 and 3 ($p<0.05$)

[d] For non-painful subjects in Group 1, movements of the two sides of the body were pooled together. The overall means of the movements were used for comparison with movements in the painful subjects in groups 2 and 3.

[e] No significant difference among the three groups ($p>0.05$)

Figure 4.1 Means and standard deviations of the maximum ranges of movements during forward bending.

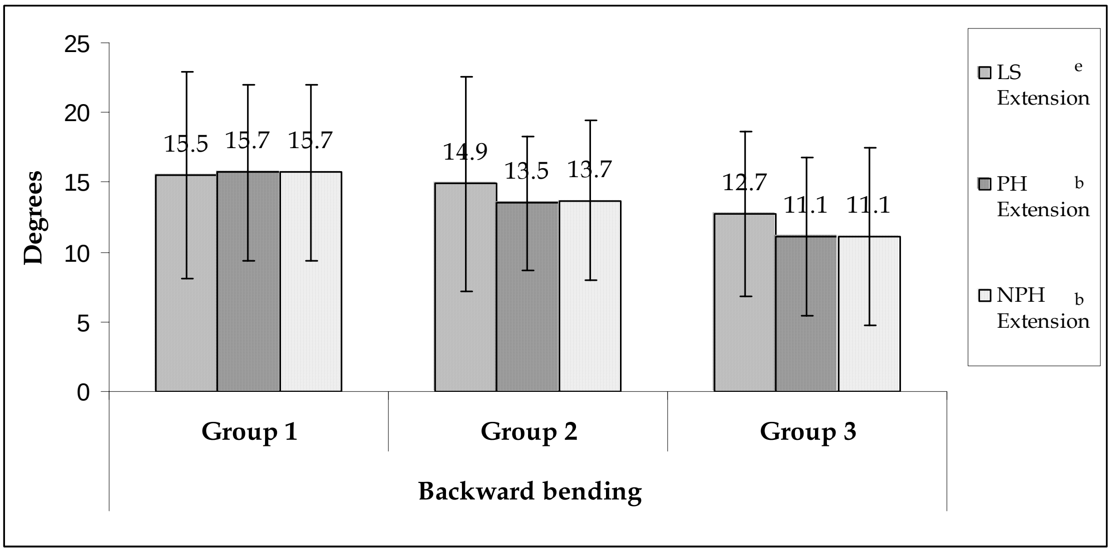


[a] Significant difference between groups 1 and 2 ($p<0.05$)

[b] Significant difference between groups 1 and 3 ($p<0.05$)

[c] Significant difference between groups 2 and 3 ($p<0.05$)

Figure 4.2 **Means and standard deviations of the maximum ranges of movements during backward bending**



[b] Significant difference between groups 1 and 3 ($p<0.05$)

[e] No significant difference among the three groups ($p>0.05$)

spine was found to be accompanied by abduction of the ilpsilateral hip and adduction of the contralateral hip. The magnitude of the lumbar spine movement was generally more than twice of those of the hips for normal subjects, as shown by the hip to lumbar spine movement ratios. Subjects with back pain and limitation in SLR showed significant reduction in the movement of the lumbar spine ($p<0.05$). However there were no significant differences in the ranges of hip abduction and adduction among the three groups ($p>0.05$). Since back pain affected the movements of the lumbar spine only but not those of the hips, the ratios of the hip to lumbar spine movements were significantly increased in subjects of groups 2 and 3. The above results were found in both lateral bending towards the painful side and the non-painful side. Paired t-test revealed that for group 2, the 95% confidence interval of the difference –0.8 to 1.1. There was no significant difference for side flexion between movements towards painful and non-painful sides ($p>0.05$). For group 3, the 95% confidence interval of the difference –0.2 to 1.2, there was no significant difference for side flexion between movements towards painful and non-painful sides ($p>0.05$).

4.2.3. *Twisting towards painful and non-painful sides*

The results of the maximum range of movements and the relative ratios of lumbar spine to hips during twisting are summarised in Table 4.4. Diagrammatic presentations of the movements of the lumbar spine and hips are shown in Figures 4.5 and 4.6. During twisting of the trunk, the lumbar spine rotated to the same side, the ilpsilateral hip rotated medially and the contralateral hip rotated laterally. The

Table 4.3 Maximum ranges of movements and the relative ratios of the lumbar spine and hip during lateral bending of the trunk

Group	1	2	3
Lateral bending towards painful side			
Mean Lx side flexion ROM (°)[a, b]	23.7 (1.2)[d]	11.6 (0.9)	12.8 (4.7)
Mean PH abduction ROM (°)[e]	11.9 (1.4)[d]	11.6 (1.1)	10.1 (1.2)
Mean NPH adduction ROM (°)[e]	11.5 (1.6)[d]	9.3 (1.0)	8.4 (1.3)
Ratio of PH/Lx movements [a,b]	0.42 (0.18)[d]	0.72 (0.25)	0.66 (0.20)
Ratio of NPH/Lx movements [a,b]	0.37 (0.32)[d]	0.51 (0.37)	0.44 (0.44)
Lateral bending towards non-painful side			
Mean Lx side flexion ROM (°)[a, b]	23.7 (1.2)[d]	11.2 (0.8)	12.5 (1.1)
Mean PH adduction ROM (°)[e]	11.5 (1.6)[d]	9.0 (1.3)	6.8 (1.4)
Mean NPH abduction ROM (°)[e]	11.9 (1.4)[d]	11.3 (1.4)	8.4 (1.4)
Ratio of PH/Lx movements [a,b]	0.37 (0.32)[d]	0.54 (0.29)	0.39 (0.44)
Ratio of NPH/Lx movements [a,b]	0.42 (0.18)[d]	0.63 (0.29)	0.59 (0.24)

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side; ROM= range of movement

Group mean values (SEM) are presented in this table.

[a] Significant difference between groups 1 and 2 ($p<0.05$)

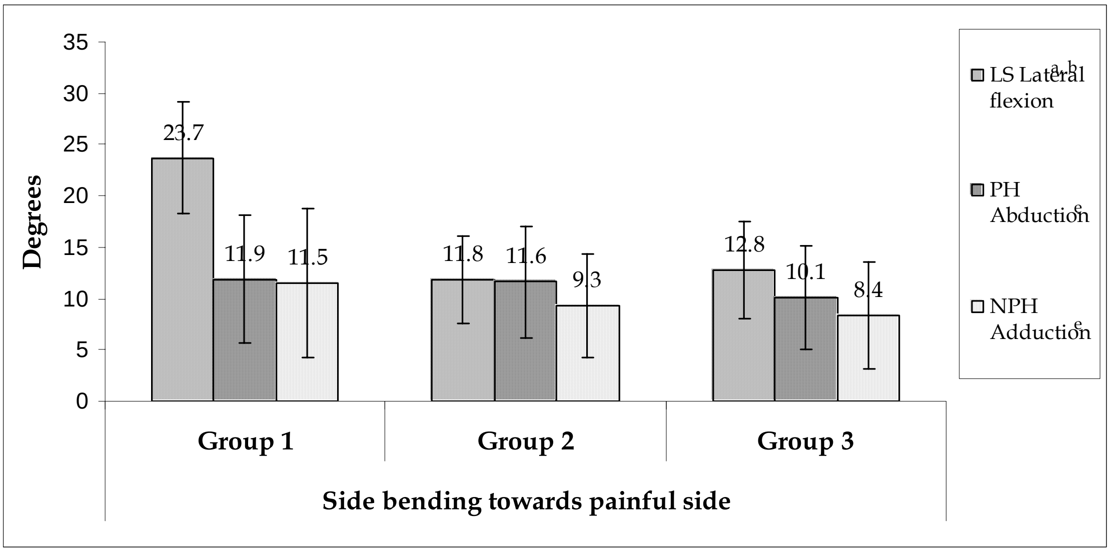
[b] Significant difference between groups 1 and 3 ($p<0.05$)

[c] Significant difference between groups 2 and 3 ($p<0.05$)

[d] For non-painful subjects in Group 1, movements of the two sides of the body were pooled together. The overall means of the movements were used for comparison with movements in the painful subjects in groups 2 and 3.

[e] No significant difference among the three groups ($p>0.05$)

Figure 4.3 **Means and standard deviations of the maximum ranges of movements during lateral bending towards painful side**

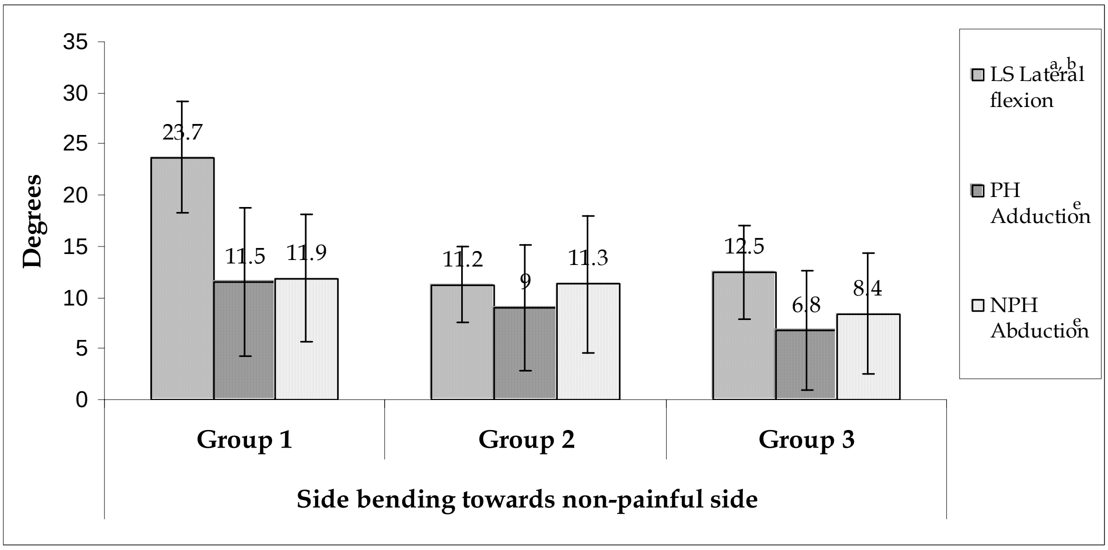


[a] Significant difference between groups 1 and 2 ($p<0.05$)

[b] Significant difference between groups 1 and 3 ($p<0.05$)

[e] No significant difference among the three groups ($p>0.05$)

Figure 4.4 Means and standard deviations of the maximum ranges of movements during lateral bending towards non-painful side.



[a] Significant difference between groups 1 and 2 ($p<0.05$)

[b] Significant difference between groups 1 and 3 ($p<0.05$)

[e] No significant difference among the three groups ($p>0.05$)

Table 4.4 Maximum ranges of movements and the relative ratios of the lumbar spine and hip during twisting of the trunk

Group	1	2	3
Twisting towards painful side			
Mean Lx axial rotation ROM (°)[a, b]	**12.2 (1.0)[d]**	**7.3 (0.8)**	**9.0 (0.8)**
Mean PH medial rotation ROM (°)[e]	**20.5 (1.0)[d]**	**22.3 (1.2)**	**18.4 (1.6)**
Mean NPH lateral rotation ROM (°)[e]	**17.5 (1.2)[d]**	**20.8 (1.1)**	**18.9 (1.7)**
Ratio of PH/Lx movements [a,b]	**1.56 (0.07)[d]**	**2.78 (0.04)**	**1.72 (0.09)**
Ratio of NPH/Lx movements [a,b]	**1.18 (0.09)[d]**	**2.63 (0.04)**	**1.79 (0.07)**
Twisting towards non-painful side			
Mean Lx axial rotation ROM (°)[a, b]	**12.2 (1.0)[d]**	**6.7 (0.6)**	**8.0 (0.7)**
Mean PH lateral rotation ROM (°)[e]	**17.5 (1.2)[d]**	**17.3 (0.6)**	**20.8 (1.2)**
Mean NPH medial rotation ROM (°)[e]	**20.5 (1.0)[d]**	**19.7 (1.0)**	**18.2 (1.4)**
Ratio of PH/Lx movements [a,b]	**1.18 (0.09)[d]**	**2.44 (0.04)**	**2.63 (0.04)**
Ratio of NPH/Lx movements [a,b]	**1.56 (0.07)[d]**	**2.70 (0.04)**	**2.08 (0.05)**

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side; ROM= range of movement

Group mean values (SEM) are presented in this table.

[a] Significant difference between groups 1 and 2 ($p<0.05$)

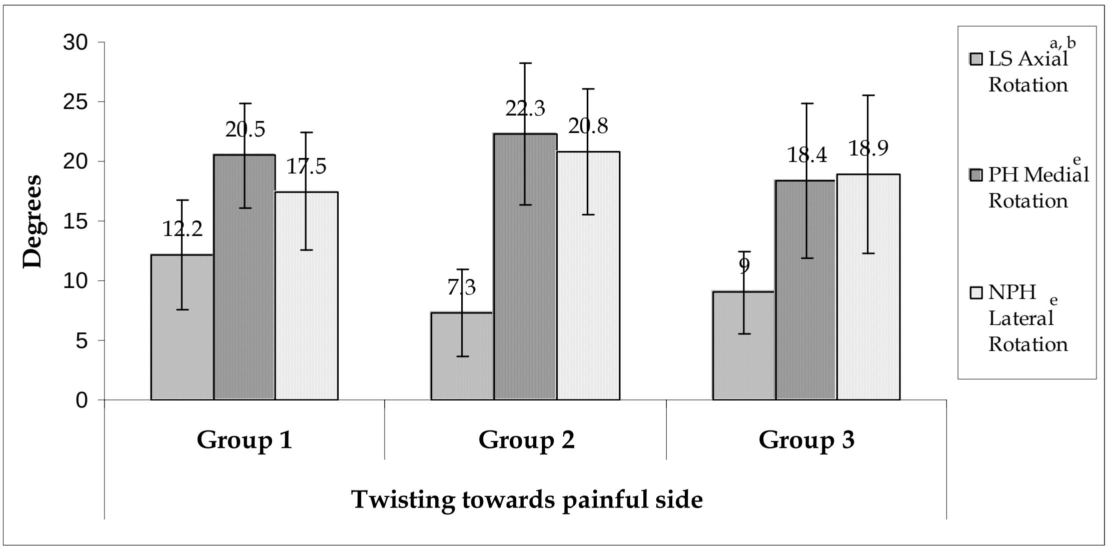
[b] Significant difference between groups 1 and 3 ($p<0.05$)

[c] Significant difference between groups 2 and 3 ($p<0.05$)

[d] For non-painful subjects in Group 1, movements of the two sides of the body were pooled together. The overall means of the movements were used for comparison with movements in the painful subjects in groups 2 and 3.

[e] No significant difference among the three groups ($p>0.05$)

Figure 4.5 Means and standard deviations of the maximum ranges of movements during twisting towards painful side

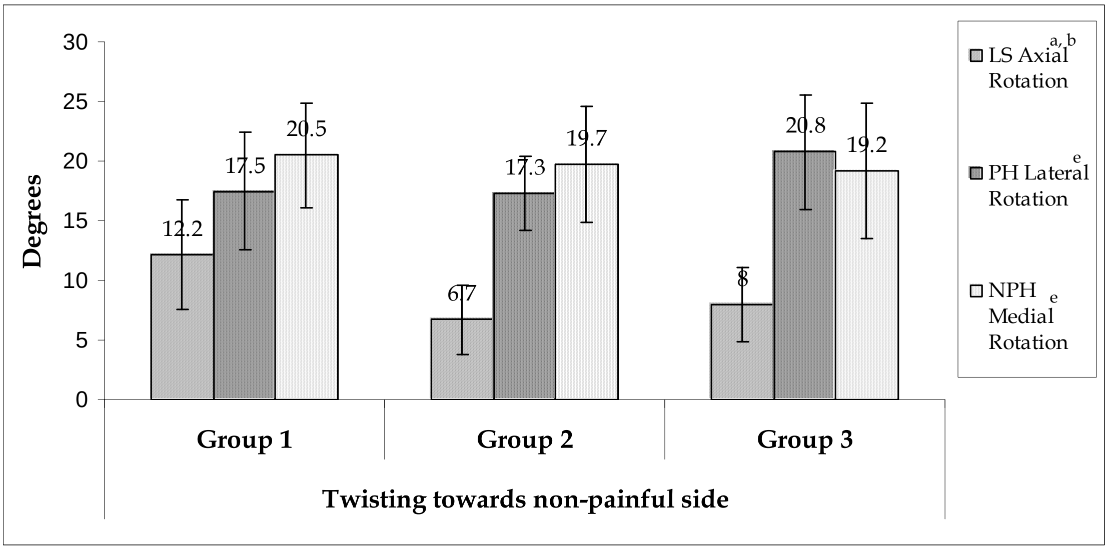


[a] Significant difference between groups 1 and 2 (p<0.05)

[b] Significant difference between groups 1 and 3 (p<0.05)

[e] No significant difference among the three groups (p>0.05)

Figure 4.6 **Means and standard deviations of the maximum ranges of movements during twisting towards non-painful side**



[a] Significant difference between groups 1 and 2 ($p<0.05$)

[b] Significant difference between groups 1 and 3 ($p<0.05$)

[e] No significant difference among the three groups ($p>0.05$)

ratios of hip to lumbar spine movements in all groups were more than 1, indicating that the contribution of the lumbar spine was smaller than that of the hips in accomplishing the movement. Subjects with back pain and limitation in SLR exhibited significantly less movement in lumbar rotation towards both sides ($p<0.05$), but there were no significant changes in hip medial and lateral rotation during these movements ($p>0.05$). As a results, significant increases in the ratios of ratios of hip to lumbar spine movements in all groups were more than 1, indicating hip to lumbar spine movements were obtained in both painful groups ($p<0.05$). Paired t-test revealed that for group 2, the 95% confidence interval of the difference –0.1 to 1.5. There was no significant difference for axial rotation between movements towards painful and non-painful sides ($p>0.05$). For group 3, the 95% confidence interval of the difference –0.7 to 0.6, there was no significant difference for axial rotation between movements towards painful and non-painful sides ($p>0.05$).

4.3. Cross-correlation analysis and the time duration of movement cycles

The mean peak cross-correlation coefficient, the mean time lags of the hip relative to the lumbar spine and the time duration of forward and backward bending, lateral bending, and twisting of the trunk are presented in Table 4.5.

4.3.1. *Forward and backward bending*

The mean peak cross-correlation coefficients for forward and backward bending were high (0.89-0.96). Thus, the shapes of the movement-time curves of the lumbar spine and hip were very similar. The time lags at peak correlation were negligible, and t-tests showed that these values were not significantly different

Table 4.5 Cross-correlation analysis

Group	1	2	3
Forward & backward bending			
Mean peak correlation coefficient – Lx and PH[e]	**0.96 (0.01)[d]**	**0.93 (0.02)**	**0.90 (0.03)**
Mean peak correlation coefficient – Lx and NPH[e]	**0.96 (0.01)[d]**	**0.93 (0.09)**	**0.89 (0.13)**
Mean time lag between Lx and PH (s)[e]	**-0.02 (0.01)**	**-0.03 (0.02)**	**0.002 (0.02)**
Mean time lag between Lx and NPH (s)[e]	**-0.02 (0.01)**	**-0.02 (0.02)**	**0.003 (0.02)**
Mean duration of one cycle of forward and backward bending (s)[a,b]	**4.44 (0.20)**	**8.30 (0.49)**	**9.33 (0.60)**
Lateral bending			
Mean peak correlation coefficient – Lx and PH[e]	**0.84 (0.04)[d]**	**0.76 (0.04)**	**0.77 (0.05)**
Mean peak correlation coefficient – Lx and NPH[e]	**0.84 (0.04)[d]**	**0.78 (0.04)**	**0.80 (0.05)**
Mean time lag between Lx and PH (s)[e]	**0.07 (0.06)**	**-0.56 (0.52)**	**0.28 (0.57)**
Mean time lag between Lx and NPH (s)[e]	**0.07 (0.06)**	**-0.06 (0.46)**	**0.30 (0.18)**
Mean duration of one cycle of side bending towards the left and right side (s)[a,b,c]	**3.66 (0.16)**	**6.36 (0.31)**	**7.29 (0.36)**
Twisting			
Mean peak correlation coefficient – Lx and PH[a, c]	**0.87 (0.02)[d]**	**0.71 (0.06)**	**0.85 (0.03)**
Mean peak correlation coefficient – Lx and NPH[a]	**0.87 (0.02)[d]**	**0.73 (0.04)**	**0.83 (0.03)**
Mean time lag between Lx and PH (s)[e]	**-0.06 (0.03)**	**-0.55 (0.31)**	**0.15 (0.19)**
Mean time lag between Lx and NPH (s)[e]	**-0.06 (0.03)**	**-0.60 (0.24)**	**0.15 (0.19)**
Mean duration of one cycle of twisting towards the left and right side (s)[a,b]	**3.51 (0.14)**	**5.92 (0.34)**	**6.23 (0.36)**

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side; ROM= range of movement

Group mean values (SEM) are presented in this table.

[a] Significant difference between groups 1 and 2 ($p<0.05$)

[b] Significant difference between groups 1 and 3 ($p<0.05$)

[c] Significant difference between groups 2 and 3 ($p<0.05$)

[d] For non-painful subjects in Group 1, movements of the two sides of the body were pooled together. The overall means of the movements were used for comparison with movements in the painful subjects in groups 2 and 3.

[e] No significant difference among the three groups ($p>0.05$)

from zero ($p>0.05$). This suggested that there was no phase difference between the movements of the lumbar spine and hip during forward and backward bending.

There were no significant differences in the correlation coefficients and time lag values among the three groups of subjects ($p>0.05$). The mean time required to complete one cycle of trunk forward and bending was found to be 4.4s for asymptomatic subjects. For subjects with back pain and limitation in SLR, the amount of time required was found to be more than doubled ranged from 8.35s to 9.33s ($p<0.05$).

4.3.2. *Lateral bending*

The mean peak cross-correlation coefficients for lateral bending were also high (0.76-0.84), indicating that the degree of association between the lumbar spine and hip movements was high. In regard to normal subjects, t-tests revealed that the mean time lags at peak correlation were not significantly different from zero ($p>0.05$). Thus the lumbar spine and hips moved simultaneously during lateral bending of the trunk. In group 2 subjects, there was a generally tendency that the movement of the hip on the painful side preceded that of the lumbar spine. This was reflected by the negative time lag values observed in these subjects. However, the mean time lag was generally positive for subjects in group 3, indicating that the lumbar spine moved earlier than the hip. Subjects in groups 2 and 3 exhibited large variations in how they modified the lumbar spine and hip movement coordination. The standard deviations of the mean time lags in these patients were large, and therefore statistically, the changes in the time lag values were found to be insignificant ($p>0.05$).

Subjects with back pain and limitation in SLR required significantly more time to complete one cycle of side bending when compared to asymptomatic subjects ($p<0.05$).

4.3.3. *Twisting*

The results of the cross-correlation analysis for twisting showed that there was a strong degree of association between the lumbar spine and hip movements. The mean peak correlation coefficients were ranged from 0.71 to 0.87. Subjects in group 2 had a significant decrease in the peak correlation coefficient ($p<0.05$), indicating that the lumbar spine and hips moved in a less cohesive manner. The mean time lags at peak correlation were not significantly different from zero for all groups ($p>0.05$). The time lag values were generally negative for subjects in group 2 and positive for subjects in group 3. However, due to the large standard deviations in the time lag values of these subjects, and statistical test did not show significant differences among these groups ($p>0.05$).

Subjects with back pain and limitation in SLR again required more time to complete one cycle of trunk twisting when compared with asymptomatic subjects ($p<0.05$).

4.4. Angle-angle diagram

The regression analysis of the angle-angle diagrams for sagittal, frontal and horizontal movements are summarised in Table 4.6, 4.7 and 4.8 respectively. In these tables, the numbers of subjects exhibiting each movement pattern (linear/exponential/neither) for different physiological movements are presented. The respective mean correlation coefficients (r) of the fitted curves, the slopes (m) and the y intercepts (c) of the linear polynomial function and the variables (a) & (b) of the exponential function (please see equation (3.14) and (3.14) of section 3.2.3.6.) are also presented.

4.4.1. *Forward bending and backward bending*

For forward bending of the trunk, the lumbar spine-hip coordination could be represented by a linear pattern in most subjects (see table 4.6). This implies that the lumbar spine and hip have similar contributions throughout the whole forward bending movement. The mean correlation coefficients for these fitted curves were high ranging from 0.94±0.05 to 0.96±0.20 (see table 4.7), suggesting that the appropriate function was employed. Figure 4.7 showed a typical example that the angle-angle curve was fitted by a linear polynomial function. The averaged slopes of groups 1, 2 and 3 were 1.12±0.33, 1.56±0.81 and 1.62±1.70 respectively, and they were gradually increased from group 1 to group 3.

In groups 1 and 2, there were 7 and 6 subjects where their lumbar spine-hip coordination was better fitted by an exponential function. This observation was not found in group 3. For subjects with exponential patterns, the lumbar spine had increasing contribution towards the end of range. A typical example that the angle-angle curve was best fitted by an exponential function is shown in Figure 4.8.

There were only 3 subjects exclusively in groups 2 and 3, where their lumbar spine- hip coordination could not be fitted either by a linear function or an exponential function. The main reason that these curves could not be fitted was due to the disorganised movement patterns throughout the range of movement.

For backward bending of the trunk, most of the angle-angle plots could not be fitted by neither a linear function nor an exponential function. There was, in general, less than 15% of plots that could be fitted with linear function in all the three groups.

Chi-square test showed that there was no significant difference among three groups in the frequency distribution of different patterns for forward and backward bending of the trunk ($p>0.05$).

4.4.2. *Lateral bending of the trunk towards painful side and non-painful side*

For the asymptomatic subjects in group 1, the curve fitting results of the angle-angle plot for side flexion of the lumbar spine towards the left side and left hip abduction were pooled together for comparison with symptomatic subjects. The same treatment was also applied to side flexion of the lumbar spine and hip adduction towards both sides.

4.4.2.1. Lumbar spine side flexion plots against hip abduction

For normal subjects, the majority of angle-angle curves were fitted either by linear (50%) or exponential (25%) functions (Table 4.8). The average correlation coefficients for the linear function and exponential function were 0.90±0.27 and 0.91±0.27 respectively (Table 4.9), thus the goodness of fit of these fitted curves were moderate to high.

Only 25% of all plots were classified as other patterns (Table 4.8). However, in groups 2 and 3, for lateral bending towards the painful side, more than half of the plots were classified as other patterns. For group 2, there were 9 plots out of 24 that could be fitted with a linear function and 2 out of 24 could be fitted with an exponential function. For lateral bending towards non-painful side, the number of plots that could be fitted by a linear function had were only 6 in group 2 and 5 in group 3; and only 2 could be plots fitted with the exponential

Table 4.6 Movement patterns of angle-angle diagrams for sagittal movements

Subject group	No. of subjects that were best fitted by linear polynomial function	No. of subjects that were best fitted by single exponential function	No. of subjects that were fitted by neither patterns
Forward bending			
Group 1	13	7	0
Group 2	17	6	1
Group 3	16	0	2
Backward bending			
Group 1	2	0	18
Group 2	6	0	18
Group 3	3	1	14

Table 4.7 Results of curve-fitting with linear and exponential functions for sagittal movements

Functions	*(h = ml+c)*[1]			[*h=a*exp(b*l)*] [2]		
	r	*m*	*c*	*r*	*a*	*b*
[3] Forward bending						
Group 1	**r=0.96(0.20)**	**m=1.1(0.3)**	**c=-0.8(3.4)**	**r =0.97(0.17)**	**a=5.0(1.3)**	**b=0.0(0.0)**
Group 2	**r=0.94(0.05)**	**m=1.6(0.8)**	**c=2.2(5.5)**	**r=0.97(0.22)**	**a=4.1(1.1)**	**b=0.1(0.0)**
Group 3	**r=0.95(0.28)**	**m=1.6(1.7)**	**c=2.5(4.1)**	**NA**	**NA**	**NA**
[4] Backward bending						
Group 1	**r=0.88(0.10)**	**m=1.6(0.4)**	**c=1.9(0.8)**	**NA**	**NA**	**NA**
Group 2	**r=0.91(0.24)**	**m=1.1(1.0)**	**c=2.1(3.3)**	**NA**	**NA**	**NA**
Group 3	**r=0.91(0.20)**	**m=1.9(1.8)**	**c=2.1(5.3)**	**r=0.94**	**a=0.63**	**b=0.3**

[1] The mean correlation coefficients (r) are shown in the table to indicate the goodness of fit. The constants of the linear polynomial equation (m) and (c) are also presented.
[2] The mean correlation coefficients (r) are shown in the table to indicate the goodness of fit. The constants of the exponential equation (a) and (b) are also presented.
[3] No significant difference among 3 groups, $\chi^2 = 9.08$ ($p>0.05$).
[4] No significant difference among 3 groups, $\chi^2 = 4.18$ ($p>0.05$).
[NA]Not applicable

Figure 4.7 **Angle-angle curve that was best fitted by a linear polynomial function for forward bending of the trunk**

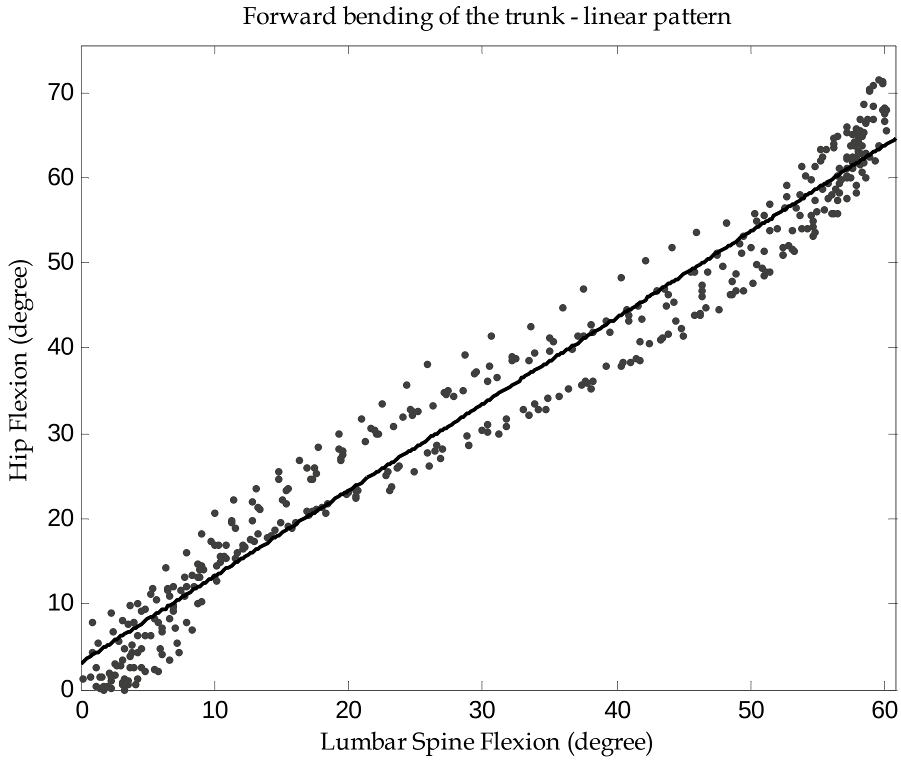
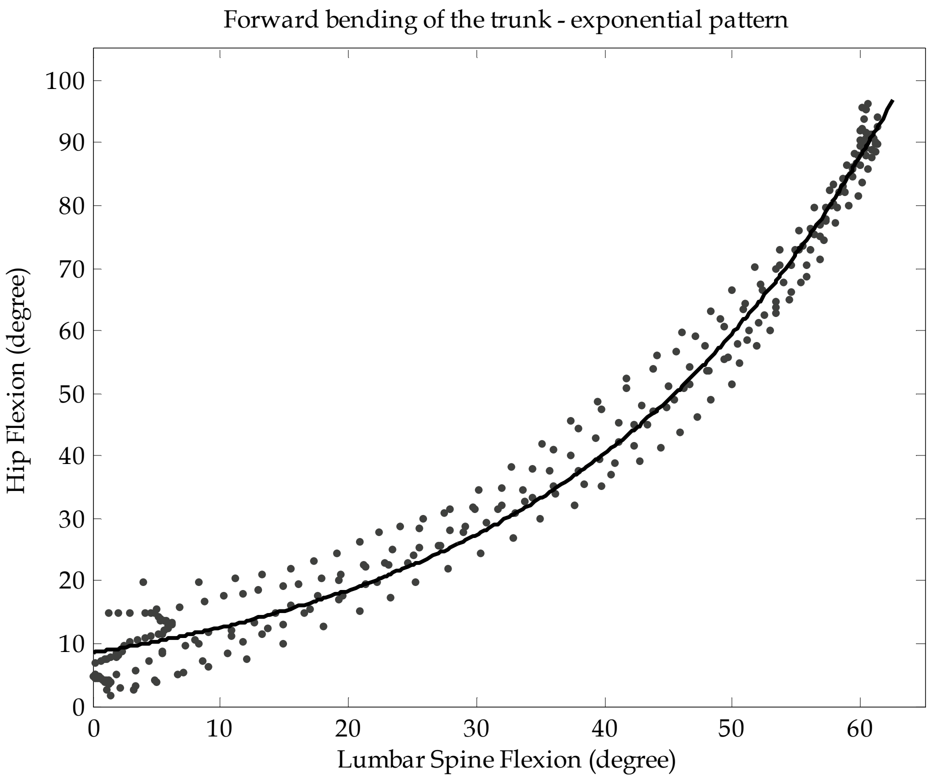


Figure 4.8 Angle-angle curve that was best fitted by an exponential function for forward bending of the trunk



function.

Chi-square test showed that the changes in the frequency distribution of different patterns among three groups were statistically significant ($p<0.05$).

4.4.2.2. Lumbar spine side flexion plots against hip adduction of hip

For normal subjects, the results were similar to the plots of lumbar spine side flexion-hip abduction that the majorities of angle-angle curves could be fitted by the linear function (~50%). There were less than 20% of plots, which could be fitted by an exponential function and around 35% of plots were classified as other patterns in group 1. However, for painful groups, there were less than half of the plots that could be fitted either by linear or exponential functions. Despite this, linear pattern seems to be a more preferable movement pattern in all the three groups as far as successful fittings are concerned. The average correlation coefficients for the plots of all the three groups were moderate to high ranging from 0.89 to 0.91.

Chi-square test showed that there was significant change in the distribution of patterns among three groups ($p<0.05$). The distribution showed that more curves were classified as linear pattern in group 1, but more curves were classified as other patterns in groups 2 and 3.

4.4.3. *Twisting towards painful and non-painful side*

For asymptomatic subjects in group 1, the curve fitting results for axial rotation of the lumbar spine towards the left side and left hip medial rotation were pooled together for comparison with symptomatic subjects in groups 2 and 3. The same treatment was also applied to axial rotation of the lumbar spine and hip lateral rotation.

Table 4.8 Movement patterns of angle-angle diagrams for frontal movements

Subject group	No. of subjects that were best fitted by linear polynomial function	No. of subjects that were best fitted by single exponential function	No. of subjects that were fitted by neither
Lateral bending towards painful side (Lx/PH Abduction)			
Group 1*	20	10	10
Group 2	9	2	12
Group 3	5	0	13
Lateral bending towards painful side (Lx/NPH Adduction)			
Group 1*	19	7	14
Group 2	8	2	13
Group 3	3	1	14
Lateral bending towards non-painful side (Lx/PH Adduction)			
Group 1*	19	7	14
Group 2	5	1	17
Group 3	2	2	14
Lateral bending towards non-painful side (Lx/NPH Abduction)			
Group 1*	20	10	10
Group 2	6	2	16
Group 3	5	2	11

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side

Table 4.9 Results of curve-fitting with linear and exponential functions for frontal movements

Functions	$(h = ml+c)^1$			$[h=a*exp(b*l)]^2$		
	r	*m*	*c*	*r*	*a*	*b*
[3] Lateral bending towards painful side (Lx/PH Abduction)						
Group 1*	**r=0.90(0.28)**	**m=0.5(0.3)**	**c= 0.4(1.8)**	**r=0.89(0.26)**	**a=1.2(0.8)**	**b= 0.1(0.1)**
Group 2	**r=0.91(0.3)**	**m=1.0(0.5)**	**c= 1.3(1.3)**	**r=0.92(0.28)**	**a=0.5(0.1)**	**b= 0.3(0.0)**
Group 3	**r=0.90(0.22)**	**m=0.8(0.2)**	**c= 0.9(0.9)**	**NA**	**NA**	**NA**
[4] Lateral bending towards painful side (Lx/NPH Adduction)						
Group 1*	**r=0.89(0.24)**	**m=0.4(0.2)**	**c= 0.5(1.5)**	**r=0.88(0.3)**	**a=0.9(0.3)**	**b= 0.1(0.1)**
Group 2	**r=0.91(0.3)**	**m=1.0(0.5)**	**c= 0.9(1.1)**	**r=0.94(0.26)**	**a=0.7(0.2)**	**b= 0.2(0.0)**
Group 3	**r=0.89(0.28)**	**m=0.8(0.1)**	**c= -0.1(0.5)**	**r=0.87**	**a=1.5**	**b= 0.2**
[5] Lateral bending towards non-painful side (Lx/PH Adduction)						
Group 1*	**r=0.89(0.24)**	**m=0.4(0.2)**	**c= 0.5(1.5)**	**r=0.88(0.3)**	**a=0.9(0.3)**	**b= 0.1(0.1)**
Group 2	**r=0.91(0.28)**	**m=0.9(0.2)**	**c= 0.5(1.5)**	**r=0.87**	**a=0.9**	**b= 0.3**
Group 3	**r=0.90(0.24)**	**m=1.3(0.4)**	**c= 1.2(0.3)**	**r=0.87(0.1)**	**a=0.6(0.2)**	**b= 0.2(0.1)**
[6] Lateral bending towards non-painful side (Lx/NPH Abduction)						
Group 1*	**r=0.90(0.28)**	**m=0.5(0.3)**	**c= 0.4(1.8)**	**r=0.89(0.26)**	**a=1.2(0.8)**	**b= 0.1(0.1)**
Group 2	**r=0.91(0.32)**	**m=1.1(0.3)**	**c= -0.2(1.5)**	**r=0.91(0.22)**	**a=1.5(0.5)**	**b= 0.2(0.1)**
Group 3	**r=0.90(0.26)**	**m=0.9(0.5)**	**c=0.8(0.7)**	**r=0.88(0.10)**	**a=1.0(0.2)**	**b= 0.2(0.2)**

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side
[1] The mean correlation coefficients (r) are shown in the table to indicate the goodness of fit. The constants of the linear polynomial equation (m) and (c) are also presented.
[2] The mean correlation coefficients (r) are shown in the table to indicate the goodness of fit. The constants of the exponential equation (a) and (b) are also presented.
[3] Significant difference among 3 groups, $\chi^2 = 14.95$ ($p<0.05$).
[4] Significant difference among 3 groups, $\chi^2 = 9.96$ ($p<0.05$).
[5] Significant difference among 3 groups, $\chi^2 = 14.87$ ($p<0.05$).
[6] Significant difference among 3 groups, $\chi^2 = 13.09$ ($p<0.05$).
* For non-painful subjects in Group 1, the results of curve fitting between side bending of the lumbar spine and left and right hip abduction were pooled together. The results of curve fitting between side bending of the lumbar spine and left and right hip adduction were also pooled together.
[NA]Not applicable

Table 4.10 Movement patterns of angle-angle diagrams for horizontal movements			
Subject group	**No. of subjects that were best fitted by linear polynomial function**	**No. of subjects that were best fitted by single exponential function**	**No. of subjects that were fitted by neither**
[3] Twisting towards painful side (Lx/PH Medial Rotation)			
Group 1*	**16**	**1**	**23**
Group 2	**7**	**0**	**16**
Group 3	**5**	**0**	**13**
[4] Twisting towards painful side (Lx/NPH Lateral Rotation)			
Group 1*	**16**	**0**	**24**
Group 2	**6**	**0**	**17**
Group 3	**2**	**0**	**16**
[5] Twisting towards non-painful side (Lx/PH Lateral Rotation)			
Group 1*	**16**	**0**	**24**
Group 2	**6**	**0**	**17**
Group 3	**4**	**0**	**14**
[6] Twisting towards non-painful side (Lx/NPH Medial Rotation)			
Group 1*	**16**	**1**	**23**
Group 2	**9**	**0**	**14**
Group 3	**2**	**0**	**16**

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side

Table 4.11 Results of curve-fitting with linear and exponential functions for horizontal movements

Functions	*(h = ml+c)*[1]			[*h=a*exp(b*l)*] [2]		
	r	*m*	*c*	*r*	*a*	*b*
[3] **Twisting towards painful side (Lx/PH Medial Rotation)**						
Group 1*	**r=0.90(0.24)**	**m=1.3(0.4)**	**c= 3.1(4.3)**	**r=0.96**	**a=3.6**	**b= 0.1(0.0)**
Group 2	**r=0.93(0.26)**	**m=2.3(0.7)**	**c= 0.2(2.7)**	**NA**	**NA**	**NA**
Group 3	**r=0.88(0.28)**	**m=1.8(0.8)**	**c= 4.8(5.5)**	**NA**	**NA**	**NA**
[4] **Twisting towards painful side (Lx/NPH Lateral Rotation)**						
Group 1*	**r=0.91(0.22)**	**m=1.3(0.6)**	**c= 1.9(2.9)**	**NA**	**NA**	**NA**
Group 2	**r=0.94(0.24)**	**m=2.5(0.9)**	**c= 0.7(2.9)**	**NA**	**NA**	**NA**
Group 3	**r=0.90(0.37)**	**m=1.7(0.7)**	**c= 0.4(1.2)**	**NA**	**NA**	**NA**
[5] **Twisting towards non-painful side (Lx/PH Lateral Rotation)**						
Group 1*	**r=0.91(0.22)**	**m=1.3(0.6)**	**c= 1.9(2.9)**	**NA**	**NA**	**NA**
Group 2	**r=0.83(0.03)**	**m=1.9(0.7)**	**c= 1.7(1.5)**	**NA**	**NA**	**NA**
Group 3	**r=0.88(0.24)**	**M2.6(1.5)**	**c= 0.9(2.5)**	**NA**	**NA**	**NA**
[6] **Twisting towards non-painful side (Lx/NPH Medial Rotation)**						
Group 1*	**r=0.90(0.24)**	**m=1.3(0.4)**	**c= 3.1(4.3)**	**r=0.96**	**a=3.6**	**b= 0.1(0.0)**
Group 2	**r=0.92(0.30)**	**m=2.1(0.7)**	**c= 0.9(3.5)**	**NA**	**NA**	**NA**
Group 3	**r=0.87(0.28)**	**m=1.3(0.5)**	**c=-1.6(1.8)**	**NA**	**NA**	**NA**

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side
[1] The mean correlation coefficients (r) are shown in the table to indicate the goodness of fit. The constants of the linear polynomial equation (m) and (c) are also presented.
[2] The mean correlation coefficients (r) are shown in the table to indicate the goodness of fit. The constants of the exponential equation (a) and (b) are also presented.
[3] No significant difference among 3 groups, $\chi^2 = 2.46$ ($p>0.05$).
[4] No significant difference among 3 groups, $\chi^2 = 5.30$ ($p>0.05$).
[5] No significant difference among 3 groups, $\chi^2 = 2.52$ ($p>0.05$).
[6] No significant difference among 3 groups, $\chi^2 = 6.33$ ($p>0.05$).
* For non-painful subjects in Group 1, the results of curve fitting between axial rotation of the lumbar spine and left and right hip lateral rotation were pooled together. The results of curve fitting between axial rotation of the lumbar spine and left and right hip medial rotation were also pooled together.
[NA]Not applicable

Less than half of the plots could be fitted by either the linear function or the exponential function in all the groups (Table 4.10). As pointed out in section 4.2.3., rotation was generally accompanied by movements of the hips with little contribution of the spine. Hence, there was no obvious pattern of coordination between spine and hip movements in most subjects.

Chi-square test showed that there were no significant differences in the distribution of different patterns in this movement ($p>0.05$) (Table 4.11).

Chapter 5 Discussion

5.1. Reliability of measurement

One of the aims of the present study was to establish the reliability of the Fastrak electromagnetic tracking device for measuring three dimensional movements of the lumbar spine and hip. In this study, the coefficient of multiple correlation (CMC) was employed to examine the repeatability of movement data. The advantage of CMC is that it can assess the similarity of waveform data rather than just non-continuous data. The CMC values observed in this study were very high. Thus, the measurement technique could provide highly repeatable data and the experimental observation was consistent. The technique developed in this study may be applied in routine clinical assessment to facilitate physical diagnosis and evaluate treatment effectiveness of low back pain patients. At present, Schober method is commonly used by clinicians to assess the range of movements of low back pain patients. However, this method is unreliable (Miller et al., 1992; Portek et al., 1983) and can be affected by physical size of the subject. It is also a linear representation of rotational movement. At present, evidence-based practices in physiotherapy and other medical practices are strongly advocated, and therefore a reliable assessment and evaluation method is extremely important. The measurement technique developed in this study can provide an alternative for clinical assessment of back pain patients. It is relatively easy and convenient, and able to provide highly repeatable results. However, in this study, only repeatability of repeated measurements was calculated. Inter-tester repeatability had not been determined as only one tester was used in this study. Furthermore, the test-retest repeatability was not required in this study as subjects were tested in only one session. Therefore, caution should be taken in interpreting the repeatability of this study and it was suggested inter-tester and test-retest repeatability should be determined if this information is required.

Another factor which may affect the reliability of the data is the accuracy of locating the correct spinous process. It was understood that incorrect location of spinous process would also contribute error in the measurement of lumbar spine movements. For instance, Simmonds and Kumar (1993) investigated the accuracy of locating the L4 spinous process by a group of physiotherapists. They found that the mean error level was 12 millimeters for within raters and 16 millimeters for between-raters. In order to minimise such error in our study, the palpation of L1 spinous process followed a strict guideline stated in the methodology section. The palpation of L1 spinous process was done by only one experienced physiotherapist to eliminate the possible error induced by different testers. However, concurrent radiographs need to be taken if the error due to palpation is to be determined precisely. This was not carried out in this study because of the risks of radiation.

5.2. Validity of measurement

The measurement error due to skin distraction is always a major problem for any surface measurement technique. To minimize the movement of the sensors on the overlying skin, the sensors were securely wrapped around the body by Velcro straps. The stability of the sensors was checked before the capturing of data. This attachment method was effective as there were no noticeable movements between the sensors and skin during the experiment. In our study, we found that the mean root-mean-square errors were 1.14±0.54°, 1.56±0.79° and 1.63±0.86° for the lumbar spine, left hip and right hip respectively. The small error size suggested that our attachment method can successfully reduce the errors associated with skin movements. Pearcy and Hindle (1989) suggested a similar attachment method in their experiment to minimize the movement of sensor on the overlying skin. Although every possible efforts had been put to avoid skin from sliding on the spinous processes, it was still possible that movement of skin did happen during the experiment. Radiographic measurements would be required to examine this source of error, and as explained earlier, this was not carried out due to the risks of radiation. However, it should be noted that the angle of tilt was relatively unaffected by the sliding movement, and this should be considered as a minor source of error. For instance, Van Herp et al (2000) and Mannion & Troke (1999) also employed electromagnetic device to measure spine movement. They found that the range of movements of the lumbar spine were in good level of agreement with X-ray measurements for flexion, extension, side bending towards the left and right side. However, there was large error in the range of movement of axial rotation. Van Herp et al (2000) observed 13.6° axial rotation in his study. He believes the finding was more reasonable than the X-ray measurement of 4.5° (Pearcy & Tibrewal, 1984) in his study when he compared the values of other studies (Dvorak et al., 1991; Panjabi et al., 1994). Our results were also compared with those results presented by Van Herp et al (2000) and Mannion & Troke (1999). The lumbar spine movements of the present study were generally in good agreement with their results. There were negligible discrepancies of less than 5° for flexion and extension. It is concluded, the concurrent validity of the measurements was established.

5.3. Magnitude of the lumbar spine and hip movements

5.3.1. *Effects of back pain on the movements of lumbar spine*

The three groups of subjects recruited in this study were similar in age, genders, height and weight. These variables do not present as confounding variables, allowing comparisons of dependent variables to be made among the three groups. This study demonstrated that back pain was associated with significant decreases in the ranges of movements of the lumbar spine in all directions. This was in general agreement with the findings of previous studies (Paquet et al., 1994; Pearcy et al., 1985; Porter & Wilkinson, 1997). It is not surprising that the ranges of movements of the lumbar spine were affected by back pain in all directions. The subjects recruited in this study were those with subacute back pain with mild degree of mild back pain (Numerical pain scale=6) during the time of experiment. Patients were asked to move as much as pain allowed. The limitations in the lumbar spine movements, in the patient groups could be due to the exacerbation of pain during movements as well as changes in the mechanical properties of tissues of the spine and hip.

To assess the symmetry of lateral flexion and axial rotation of the lumbar spine between the painful side and non-painful side, the ranges of movements towards the painful side were compared with the non-painful side. The results showed that the movements towards painful side were almost the same as the movements towards non-painful side. It suggested that, although back pain affected their lumbar movements in all directions, unilateral symptoms did not affect the movements towards their painful side only. Our finding was different from that of Gomez (1994). He found that both normal and low back pain subjects tended to have greater right rotation and left lateral flexion. However, there was no physiological reason that could explain his observation. Our finding are supported by the study of Hindle et al (1990). They found that there was a poor correlation between the location of pain and abnormalities in lateral bending and axial rotation to the symptomatic side. The differences between Gomez's study (1994) and ours in the findings of range of movements may be explained by the differences in methodology and the subjects recruited. Gomez (1994) used the B-200 Lumbar Dynamometer to measure the ranges of movements, but he did not report the placement of this dynamometer during the experiment and the accuracy of the equipment. The reliability of this equipment in measuring the movements of the lumbar spine was questionable. It was possible that the arrangement of the dynamometer might induce significant measurement error. Moreover, in Gomez's study, he recruited both male and female subjects with age ranging from 18 to 68 years old, whereas we only recruited middle-aged male subjects. This might be another possible explanation for the discrepancy.

5.3.2. *Effects of back pain on the movements of the hip*

Back pain was also found to be associated with decrease in the range of movement of hip flexion during forward bending of the trunk, but it did not appear to affect the hips in the other movement directions. The study of Esola et al (1996) had examined the association between back pain and hip flexion. They found that there were no significant differences for lumbar spine and hip flexion between control subjects and subjects with history of back pain. However, their results could not be compared with ours since the clinical characteristics of their subjects were different from ours. Esola et al recruited subjects with previous history of back pain but no current symptoms. However, our subjects experienced pain at the time this study was conducted. The study of Porter and Wilkinson (1997) examined subjects with chronic low back pain. They showed that painful subjects had less hip flexion when compared with control subjects, although the difference was not statistically significant. It is possible that the negative statistics results could be due to small sample size and limited power.

It was interesting to note that back pain was associated with changes in hip flexion movement only. This may suggest that during trunk bending, stretching of the posterior hip tissues may elicit pain. It had also been shown that back pain was associated with increase in stiffness of the hamstring muscles (Halbertsma et al., 2001; Li et al., 1996) or defensive hamstring muscle reaction (Goeken & Hof, 1991; Goeken & Hof, 1993). Goeken & Hof (1994) found that some back pain patients who actually had the same electromyographic activities in the hamstring muscles as those normal subjects. The decrease of hip flexion during forward bending in painful subjects may be due to poor extensibility of the hamstring muscle or protective hamstring reaction, but not pathological reason (Goeken & Hof, 1994). It should be pointed out that in this study, subjects with limitation in straight leg raising (SLR) were found to exhibited further reduction in hip flexion when compared with subjects with back pain only. This further suggests that the posterior hip tissues are involved for the reduction of hip flexion movement, although the mechanisms of actions remain unclear. Previous researchers (Fisk, 1975; Scham & Taylor, 1971; Takata & Takahashi, 1994) suggested that there could be increase in the tension of neural tissues (sciatic nerve) in the posterior area of the hip and it leads to compression of nerve root and induces pain during the movement. This may be another explanation why subjects with limitation in SLR have their hip flexion further affected when compared with subjects with back pain only. Future research should examine the precise mechanical mechanisms how back pain affects the posterior hip tissues, such as the stiffness of the hamstring muscle and the contribution of passive neural component e.g. sciatic nerve, to the limitation of SLR. Such knowledge is clinically important. For instance, the information could be used to help design exercise program for restoring the mechanical characteristics of the posterior hip tissues, or the extensibilities of the hamstring muscles, and subsequently the movements of the hips.

5.4. Correlation of lumbar spine and hip movements

In our study, we employed three different of methods analysis to study the correlation of lumbar spine and hip movements. These included the ratio of the hip movement to that of the lumbar spine, cross-correlation analysis and angle-angle diagram. Each method has its own advantages in describing correlation of movements. The ratio is relatively simple and easy to be calculated and it provides an overall idea of how the lumbar spine and hip move. However, this method does not describe the correlation of joint movements in different parts of the range and at different instants. Angle-angle diagram provides this missing information. It describes the correlation of joints movements graphically and can be quantified by fitting the movement-time curves with mathematical equations using the least squares method. In addition, the coefficient of cross-correlation would indicate the strength of the correlation between lumbar spine and hip movements. The time lags would indicate the time shift when the spine and hip movement patterns have strongest correlation. The advantage of cross correlation analysis is that it describes the cohesiveness of the lumbar spine and hip movements indicating the efficiency of motor control of the movements. Previous studies failed to provide this important information (Esola et al., 1996; Mayer et al., 1984; Paquet et al., 1994; Porter & Wilkinson, 1997). It is hoped that with the use of the above method of analysis, a more complete picture about the correlation of lumbar spine and hip movements could be made.

5.4.1. *Forward and backward bending*

This study showed that during forward and backward bending of the trunk, the relative contributions of the lumbar spine and hip were similar. The overall mean ratio of the hip to the lumbar spine was found to be close to one. This finding agrees with the ratios reported in other studies (Esola et al., 1996; Porter & Wilkinson, 1997). The results of curve-fitting for forward bending movement show that the coordination of the lumbar spine and hip follows linear pattern for the majority of normal and painful subjects. A linear pattern indicates that the contributions of the lumbar spine and hip are similar throughout the movement. The slope of the best straight-line was found to be steepest in subjects with limitation in SLR and least steep in normal subjects. Angle-angle plots provide more information than a simple ratio, which does not take into account of the patterns of movement coordination. A simple ratio assumes that the pattern is linear, but this study showed that there were 7 out of 20 normal subjects and 6 out of 23 back pain subjects demonstrating an exponential pattern. In these subjects, the usefulness of the movement ratio is limited. The present study thus provides more info than previous work which only employed movement ratios.

For forward and backward bending, very few subjects (n=3) did not show an obvious angle-angle plot patterns. This indicates that the lumbar spine and hip movement are well coordinated. The majority of subjects employed a linear coordination pattern. However, previous researches (Esola et al., 1996; Porter & Wilkinson, 1997) showed that subjects had more lumbar spine movement at the initial stage and more hip movement towards the final stage of movement. In our study, only about 30% of normal and back pain subjects adopted the movement strategies that followed exponential pattern. The difference in the finding might be due to the variations in lumbar spine-hip rhythm. The lumbar spine/hip ratios in different phases as reported in previous work might not be sensitive enough to demonstrate these variations. Nelson et al (1995) observed that there was considerable inter-subject variation in lumbar-pelvis rhythm among individuals during loaded spinal flexion and extension. The coefficients of variation among different subjects during the down lift phase ranged from 13.66% to 16.55% for the lumbar and pelvis movements respectively, whereas the coefficient ranged 10.98% to 17.86% for the two movements during the up lift phase. Another interesting finding was that subjects with limitation in SLR did not adopt a positive exponential movement pattern during forward bending of the trunk. Such angle-angle plot pattern would imply increased hip contribution towards the end of range of forward bending. However, as shown in this study, subjects with limited SLR had significantly less hip flexion movements when compared with normal subjects and subjects with back pain only. Therefore, it might be physiologically difficult for them to have increased hip flexion, particularly at the later stage of movement. Hence a linear pattern might be more preferable for this group of subjects.

The results of curve fitting of the angle-angle plot for backward bending were not as good as forward bending. Most of the curves could not be fitted by neither pattern. For backward bending of the trunk, the mean lumbar spine extension were ranged from 12.7° to 15.5° and the mean hip extension were ranged from 11.1° to 16.0°. Data was thus fitted over a very small movement and the numbers of points available for curve fitting were limited. This could increase the residuals of curve fitting and the pattern could be difficult to be identified.

Previous study of lumbar spine/hip interaction during trunk extension was limited. Oddsson (1988) studied the interaction between primary movements and associated postural adjustments during trunk extension movements in standing. His results showed that trunk extension was achieved by lumbar spine extension and hip extension which were accompanied by ankle and knee flexion. The author explained that the movements at the ankle probably were to counteract the backward shift of the centre of gravity caused by the extension of the lumbar spine and hip. We made the same observation during the experiment, although we had instructed our subjects to keep their knee straight during the movement prior to the experiment. Small movements at ankle and knee were still unavoidable as subjects had to keep their balance during backward bending of the trunk. As a result, subjects had to control, not only the lumbar spine and hips movements, but also the knee and ankle movements as well. The degrees of freedom of movements that the subjects had to control were large. This might explain why there were large inter-subject variations in coordinating the hip and lumbar spine movements during trunk extension.

The cross-correlation coefficients were found to range 0.89 to 0.96. for forward and backward bending. The high coefficient suggests that the movements of the lumbar spine and hip are highly cohesive. However, the cohesiveness of movements was affected by the presence of back pain and limitation in SLR, as shown by the decreases in the cross-coefficient coefficient, although the decreases were not statistically significant ($p<0.05$). Despite the presence of back pain and limitation in SLR, the lumbar spine and hips were still able to move simultaneously, as the time lags for this movement were very small and it was closed to zero in all groups. However, back pain and limitation in SLR did significantly increase the duration of movement time for forward and backing bending. It is possible that the efficiency of coordination was affected by back pain, and movement coordination could be made easier by reducing the trunk velocity. The study of Paquet et al (1994) confirm our finding. They reported that patients with low back pain moved about 40% slower than normal subjects when they were asked to move at their comfortable speed during forward bending. It had been shown that the decreases in velocities could seriously affect the functional activities and the quality of life of patients (Marras et al., 2000).

5.4.2. *Lateral bending*

The ratio of hip to lumbar spine movement was found to be smaller than one (mean=0.51±0.29). This implied that side bending of the trunk movement was primarily accomplished by lateral bending of the spine with some contributions from the hips. These findings are related to the fact that the lumbar spine is relatively compliant in the coronal plane (Markolf, 1972; McGill et al., 1994). The study of Markolf (1972) showed that the lateral bending stiffness of the cadaveric lumbar segments were much less when compared with the lower thoracic and the upper thoracic spine. McGill et al (1994) had similar finding in their in-vivo study.

Back pain and limitation in SLR were found to affect the relative contributions of the lumbar spine and hips in accomplishing lateral bending of the trunk. The hip to lumbar spine ratios for lateral bending were increased, indicating that the contributions of the lumbar spine to these two movements were less but the contributions of the hip to these movements remained relatively unchanged. This finding was also reflected by the increase in the slope of the best straight line of the angle-angle plot of lumbar spine and hip movements of subjects with back pain and limitation in SLR.

The cross-correlation analysis for lateral bending showed that the lumbar spine and hips were less cohesive as indicated by the decreases in the peak correlation coefficients in all the three groups when compared with forward and backward bending. The strength of correlation for lateral bending was affected by the presence of back pain as there were further reductions in the coefficients in groups 2 and 3. This finding indicated that the correlation of the lumbar spine and hips movements were affected to certain extent, although the reductions in the correlation coefficient were not statistically significant. The lack of significant could be due to relatively small sample size and large inter-subject variance, leading to limited power. Back pain and limitation in SLR appeared to affect the time lag during lateral bending. The mean time lag for back pain subjects was negative whereas the other two groups were positive. It is possible that the lumbar spine delays its movement when there is pain induced during the movement. But the time lags for this movement did not show significant differences among groups, due to large standard deviations. Power analysis showed that if effect size is equal 0.8*standard deviation and number of subjects are 25, the power is 70% for one-way ANOVA and it could be considered as a satisfactory power. In any case, it should be pointed out that the mean time lag in back pain subjects was less than half second and it might not be clinically insignificant.

In contrast to forward bending of trunk, which predominately followed a linear movement coordination pattern, there were larger numbers of angle-angle patterns of lateral bending which could be fitted by exponential pattern or other patterns in all the three groups. There are thus large inter-subject variations in the way lumbar spine and hip movements are coordinated during lateral bending. In back pain subjects, there are only 27% to 45% of subjects whose movement patterns could be classified into either linear or exponential. Most subjects moved in a rather irregular movement pattern. This might suggest a loss of coordination pattern in back pain subjects. The results of the angle-angle plot analysis showed that the distribution of patterns for lumbar spine side flexion and hip abduction did not greatly differ from that for lumbar spine side flexion and hip adduction. The changes in hip and lumbar spine correlation were thus found to both hips. It was shown that the correlation coefficient of goodness of curve fit was decreased in back pain patients. This agrees with the results of cross-correlation which also showed decreased correlation coefficient.

The present study was the first which examined the coordination of hip and lumbar spine movements during lateral bending. Lariviere et al (2000) had studied the effect of load on the coordination of the trunk during lateral bending tasks. However, the authors omitted the contribution of pelvis and the hip during these tasks. They only studied the thoracic and lumbar contributions. In their study, the placement of markers in their experiment failed to reveal hip abduction and adduction. Comparison could be made between their results and ours.

5.4.3. *Twisting*

In contrast to lateral bending of the trunk, the hips were the predominate sources of movement for trunk twisting. This was reflected by the ratio of hip to lumbar spine movement which was more than one. The mean slopes of the linear fit of angle-angle plot in all groups were also greater than 1, which confirms the observation that the magnitude of rotation of hip is larger than that of axial rotation of the lumbar spine. The lumbar spine has little contribution to the movement because the facets of the lumbar spine effectively resist any axial rotation of the vertebrae (Adams & Hutton, 1983). Adams & Hutton (1983) showed that the flat, medially facing facet of each superior articular process apposed the laterally facing facet of the inferior articular process when a torsional stress was applied to the lumbar spine. This mechanism is important to protect the intervertebral discs from excessive torsional stress and prevents disc rupture. The ratios of hip to lumbar spine were greater in the painful subjects than in the normal subjects. This was because there was a reduction in the range of movement of the lumbar spine in painful subjects (please see table 4.4).

In regard to the angle-angle plot, majorities of the curves could be fitted by neither linear nor exponential patterns. Most subjects followed an irregular pattern, largely because the amount of axial rotation of the lumbar spine was generally small (mean=8.6°±0.8) and an obvious pattern could not be revealed. The coefficient of cross-correlation for movements in horizontal plane was not as high as the movements in other two planes. The above findings suggest that the lumbar spine and hip movements are less cohesive in horizontal plane movements. The strength of correlation was most markedly affected by back pain in the twisting movement. The finding indicated the correlation of the lumbar spine and hip movements in the horizontal plane was altered in back pain subjects. The decrease in cross-correlation coefficient in group 2 was the most and the decrease was found to be statistically significant. However it is interesting that the strength of correlation in group 3 was comparable to that of normal subjects.

The time lag between the lumbar spine and hip movements also appeared to be altered by pain and limitation in SLR for twisting. The time lag was negative for normal subjects and subjects with back pain, but the time lag was positive for subjects with limitation in SLR. The time lag for back pain subjects was more negative than normal subjects. This could be because the lumbar spine might move later than the hips, perhaps due to the reluctance to move the painful back. On the other hand, in patients with limitation in straight leg raise, when movements of the hip elicited discomfort, the lumbar spine appeared to move earlier than the hip. However, it should be pointed out that the changes in time lag were found to be statistically insignificant in this study due to large standard deviations. It is suggested that further research would be required to clarify this particular finding.

5.5. Scientific and clinical significance

The present study has attempted to address several issues of scientific and clinical significance. Firstly, the Fastrak™ electromagnetic tracking device was found to be the highly reliable for studying the kinematics of the lumbar spine and hip in various anatomical planes. It is easy to use and could be employed for routine clinical assessment. Secondly, the normal ranges of movements of the lumbar spine and hips were established during different trunk movements, allowing the effects of back pain on kinematics to be examined. Moreover, we were the first researchers to employ techniques, such as cross correlation and angle-angle diagrams to show the coordination of the lumbar spine and hips movements. These techniques provided a thorough analysis of the correlation of lumbar spine and hip movements, which could not be simply addressed by range of movement, movement ratio as reported in previous studies.

Our study clearly revealed an association between back pain and altered kinematic characteristics of the lumbar spine and hips. But it is yet unclear whether back pain alters the kinematic pattern or whether the altered kinematic characteristics are the causes of low back pain. For instance, Dolan & Adams (1993) showed that changes in lumbar spine and hip mobility would alter the bending stresses of the spinal motion segment. Such changes may also alter the loads in the facets and posterior spinal ligaments (Adams & Hutton, 1983) and subsequently, leads to injuries of these spinal tissues. It is possible that altered kinematics of the lumbar spine and hips is one of the many causative factors of low back pain. On the other hand, it is also possible that the altered kinematic characteristics of the lumbar spine and hip are a consequence of low back pain. It may be a compensatory response to reduce pain or to protect injured tissues. In any case, the aim of rehabilitation is to restore the normal kinematic characteristics of the lumbar spine and hip in order to prevent back injury or to restore the kinematic pattern as a result of back pain. Clinically, it is important to evaluate the kinematic characteristics of both the lumbar spine and hip for back pain patients as they have a very close relationship. Assessment of lumbar spine motions alone will not be able to reveal how joints coordination is affected by low back pain and the potential effects on functional performances. Assessment of hip motions will allow the clinicians to decide whether there are changes in the mechanical properties of posterior hip tissues and whether an exercise programme is required to modify these properties. At present, visual observation or simple tape measurement of back movements is still the most commonly used method to assess and monitor patients' progress. The accuracy of these techniques is questionable. Moreover, these methods cannot provide the time history of movements. In this study, we have demonstrated the complex relationship between the movements of the lumbar spine and hips throughout the range. It is almost impossible to assess these relationships by tape measure or visual observation. Therefore, an alternative method has to be employed to provide the missing information. Electromagnetic tracking device is one of the equipment that can fulfill the above requirements. Another issue is that, the correlation of the lumbar spine and hips movements was found to be altered in back pain patients as demonstrated in this study. Thus, restoring the normal movement pattern should be another important goal of rehabilitation of low back pain. The Electromagnetic tracking device may be used to evaluate the efficiency of an exercise program in restoring the coordination pattern.

In this study, we have successfully applied angle-angle diagram to show the complex relationship of two adjacent joints graphically. We have also successfully applied curve fitting method to quantify the angle-angle diagrams. Indeed, the application of angle-angle diagram to assess correlation of joints movements can be extended to other body parts, such as the movements of the scapular and glenohumeral joint during shoulder elevation. It is particularly useful in providing a visual illustration of joints coordination and some other important information, such as the relative contributions from joints in different phases of movement. Such information would help clinicians to precisely define the kinematic problem of a pattern.

5.6. Future research

This study provided strong evidence that back pain and limitation in SLR altered the kinematics and coordination of the lumbar spine and hip. However, the role of posterior hip tissues and neural structure (see section 5.3.2.) need to be examined in future research. From the evidence from our study, it is very likely that both of them might lead to limited hip flexion in trunk. Lee & Munn (2000) have derived an elegant method to test the passive moment of the hip during straight leg raising. Such method could be employed to further investigate the mechanical properties of posterior hip tissues and neural structures. Normal and back pain subjects could be compared regarding such properties. The resulting effect on spinal kinematics will that be determined.

In our study, we did not investigate the kinetics of the lumbar spine and hip. This study provides information on the kinematics of back pain and limited straight leg raising subjects had changed, but we did not know the forces and moments acting on the hip and the lumbar spine. Such information could be obtained by inverse dynamic method. Kinetic information will help explain the kinematic changes observed in this study. Electromyographic technique (EMG) may provide us the activations of the spine and hips muscles during trunk movements. This will help identify if such activations could have altered the kinematic pattern of the spine. Back pain and limited straight leg raising subjects may have changes in the muscle coordination patterns in different activities. The re-education or restoration of normal movement patterns may also require muscle re-education. EMG may give us the insight about the activities of muscles that control the movements and should be the subject of future research.

Finally, our study recruited subjects with sub-acute back problems and with pain at the time the experiment was conducted. The findings might not be inferred to acute or chronic back pain subjects. It would be useful to repeat the present experiment in other back pain populations.

Chapter 6 Conclusion

The aim of the present study was to examine the effects of back pain on the correlations of the lumbar spine and hips movements. Previous research provided limited information in regard to the coordination of the lumbar spine and hips and the effect of back pain and limited straight leg raising on such coordination in different anatomical movements. The present study attempted to fill this knowledge gap.

The electromagnetic tracking device was found to be highly repeatable for measurements of lumbar spine and hip movements. The normative data was used completed with the data collected from subjects with sub-acute low back pain and limitation in straight leg raise. The results showed that low back pain was found to be associated with significant decreases in the ranges of movements of the lumbar spine in all directions. Subjects with limited SLR exhibited greater decreases in lumbar spine movements when compared with subjects with back pain only. Back pain was also found to be associated with decreases in the range of hip flexion during forward bending of the trunk, but it did not appear to affect the movements of hips in other directions. Cross-correlation analysis showed that back pain patients modified their joint coordination strategies in accomplishing trunk movements. These patients were also found to take a longer time to complete the movements. These may seriously affect the functional activities and the quality of life of the patients. Angle-angle diagram provided valuable information about the coordination pattern both visually and mathematically. This suggests that back pain subjects had an increased tendency to adopt an irregular hip-spine angle plot, suggesting that they had poor motor control leading to in-coordination of movements.

Future studies should look into the mechanisms of how back pain affects lumbar spine and hip movements. These may involve inverse dynamic analysis of the loads acting at the spine and hips. The mechanisms of how posterior hip tissues affect the kinematics of lumbar spine and hip should be examined. Another important area for future research is to examine the movement patterns of the lumbar spine and hip in subjects with acute or chronic low back pain.

The present research has provided fundamental information on the effects of back pain and limitation in SLR on the kinematics of lumbar spine and hip. Such information would be extremely valuable to therapists in clinical assessment and treatment planning. It is hoped that this study will help stimulate further research, leading to the advancement of science and promotion of evidence-based practice.

References:

1. Adams, M. A., Dolan, P., & Hutton, W. C. (1988). The lumbar spine in backward bending. *Spine, 13*(9), 1019-1026.
2. Adams, M. A., & Hutton, W. C. (1983). The mechanical function of the lumbar apophyseal joints. *Spine, 8*(3), 327-330.
3. Adams, M. A., Hutton, W. C., & Stott, J. R. (1980). The resistance to flexion of the lumbar intervertebral joint. *Spine, 5*(3), 245-253.
4. Agur, A. M. R., Lee, M. J., & Grant, J. C. B. (1999). *Grant's atlas of anatomy* (10th ed.). Philadelphia, PA: Lippincott Williams & Wilkins.
5. Allbrook, D. (1957). Movements of the lumbar spinal column. *J Bone Joint Surg Br, 39-B*(2), 339-345.
6. An, K. N., Jacobsen, M. C., Berglund, L. J., & Chao, E. Y. (1988). Application of a magnetic tracking device to kinesiologic studies. *J Biomech, 21*(7), 613-620.
7. Atalay, A., Akbay, A., Atalay, B., & Akalan, N. (2003). Lumbar disc herniation and tight hamstrings syndrome in adolescence. *Childs Nerv Syst, 19*(2), 82-85.
8. Barker, T. M., Nicol, A. C., Kelly, I. G., & Paul, J. P. (1996). Three-dimensional joint co-ordination strategies of the upper limb during functional activities. *Proc Inst Mech Eng [H], 210*(1), 17-26.
9. Beattie, P. F., Meyers, S. P., Stratford, P., Millard, R. W., & Hollenberg, G. M. (2000). Associations between patient report of symptoms and anatomic impairment visible on lumbar magnetic resonance imaging. *Spine, 25*(7), 819-828.
10. Biryukova, E. V., Roby-Brami, A., Frolov, A. A., & Mokhtari, M. (2000). Kinematics of human arm reconstructed from spatial tracking system recordings. *J Biomech, 33*(8), 985-995.
11. Blackburn, J. T., Riemann, B. L., Myers, J. B., & Lephart, S. M. (2003). Kinematic analysis of the hip and trunk during bilateral stance on firm, foam, and multiaxial support surfaces. *Clin Biomech (Bristol, Avon), 18*(7), 655-661.

12. Bogduk, N. (1997). *Clinical anatomy of the lumbar spine and sacrum* (3rd ed.). New York: Churchill Livingstone.

13. Bohannon, R. W. (1984). Effect of repeated eight-minute muscle loading on the angle of straight-leg raising. *Phys Ther, 64*(4), 491-497.

14. Borenstein, D. G. (2001). Epidemiology, etiology, diagnostic evaluation, and treatment of low back pain. *Curr Opin Rheumatol, 13*(2), 128-134.

15. Breen, A., Allen, R., & Morris, A. (1989a). A digital videofluoroscopic technique for spine kinematics. *J Med Eng Technol, 13*(1-2), 109-113.

16. Breen, A. C., Allen, R., & Morris, A. (1989b). Spine kinematics: a digital videofluoroscopic technique. *J Biomed Eng, 11*(3), 224-228.

17. Brown, R. H., Burstein, A. H., Nash, C. L., & Schock, C. C. (1976). Spinal analysis using a three-dimensional radiographic technique. *J Biomech, 9*(6), 355-365.

18. Bull, A. M., & Amis, A. A. (1997). Accuracy of an electromagnetic tracking device. *J Biomech, 30*(8), 857-859.

19. Bull, A. M., Berkshire, F. H., & Amis, A. A. (1998). Accuracy of an electromagnetic measurement device and application to the measurement and description of knee joint motion. *Proc Inst Mech Eng [H], 212*(5), 347-355.

20. Burdett, R. G., Brown, K. E., & Fall, M. P. (1986). Reliability and validity of four instruments for measuring lumbar spine and pelvic positions. *Phys Ther, 66*(5), 677-684.

21. Burnett, A. F., Barrett, C. J., Marshall, R. N., Elliott, B. C., & Day, R. E. (1998). Three-dimensional measurement of lumbar spine kinematics for fast bowlers in cricket. *Clin Biomech (Bristol, Avon), 13*(8), 574-583.

22. Burton, A. K., Tillotson, K. M., & Troup, J. D. (1989). Variation in lumbar sagittal mobility with low-back trouble. *Spine, 14*(6), 584-590.

23. Chatfield, C. (2004). *The analysis of time series : an introduction* (6th ed.). Boca Raton, FL: Chapman & Hall/CRC.

24. Cheng, P. L. (2000). A spherical rotation coordinate system for the description of three-dimensional joint rotations. *Ann Biomed Eng, 28*(11), 1381-1392.

25. Cheng, P. L., Nicol, A. C., & Paul, J. P. (2000). Determination of axial rotation angles of limb segments - a new method. *J Biomech, 33*(7), 837-843.

26. Cole, G. K., Nigg, B. M., Ronsky, J. L., & Yeadon, M. R. (1993). Application of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. *J Biomech Eng, 115*(4A), 344-349.

27. Crawford, N. R., Yamaguchi, G. T., & Dickman, C. A. (1996). Methods for determining spinal flexion/extension, lateral bending, and axial rotation from marker coordinate data: Analysis and refinement. *Human Movement Science, 15*(1), 55-78.

28. Crosbie, J., Vachalathiti, R., & Smith, R. (1997). Patterns of spinal motion during walking. *Gait & Posture, 5*(1), 6-12.

29. Cunningham, D. J., & Romanes, G. J. (1972). *Cunningham's textbook of anatomy* (11th / ed.). London: Oxford U.P.

30. Dillard, J., Trafimow, J., Andersson, G. B., & Cronin, K. (1991). Motion of the lumbar spine. Reliability of two measurement techniques. *Spine, 16*(3), 321-324.

31. Dimnet, J., Fischer, L. P., Gonon, G., & Carret, J. P. (1978). Radiographic studies of lateral flexion in the lumbar spine. *J Biomech, 11*(3), 143-150.

32. Dolan, P., & Adams, M. D. (1993). Influence of lumbar and hip mobility on the bending stresses acting on the lumbar spine. *Clin Biomech (Bristol, Avon), 8*, 185-192.

33. Dopf, C. A., Mandel, S. S., Geiger, D. F., & Mayer, P. J. (1994). Analysis of spine motion variability using a computerized goniometer compared to physical examination. A prospective clinical study. *Spine, 19*(5), 586-595.

34. Drerup, B. (1985). Improvements in measuring vertebral rotation from the projections of the pedicles. *J Biomech, 18*(5), 369-378.

35. Dvorak, J., Panjabi, M. M., Chang, D. G., Theiler, R., & Grob, D. (1991). Functional radiographic diagnosis of the lumbar spine. Flexion-extension and lateral bending. *Spine, 16*(5), 562-571.

36. Ellison, J. B., Rose, S. J., & Sahrmann, S. A. (1990). Patterns of hip rotation range of motion: a comparison between healthy subjects and patients with low back pain. *Phys Ther, 70*(9), 537-541.

37. Esola, M. A., McClure, P. W., Fitzgerald, G. K., & Siegler, S. (1996). Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. *Spine, 21*(1), 71-78.

38. Evans, J. H., & Nachemson, A. L. (1969). Biomechanical study of human lumbar ligamentum flavum. *J Anat, 105*(1), 188-189.

39. Fagerson, T. L. (1998). *The hip handbook*. Boston, Mass.: Butterworth-Heinemann.

40. Fairbank, J. C., Pynsent, P. B., Van Poortvliet, J. A., & Phillips, H. (1984). Influence of anthropometric factors and joint laxity in the incidence of adolescent back pain. *Spine, 9*(5), 461-464.

41. Ferrigno, G., & Pedotti, A. (1985). ELITE: a digital dedicated hardware system for movement analysis via real-time TV signal processing. *IEEE Trans Biomed Eng, 32*(11), 943-950.

42. Fisk, J. W. (1975). The straight leg raising test: its relevance to possible disc pathology. *N Z Med J, 81*(542), 557-560.

43. Frymoyer, J. W., Frymoyer, W. W., Wilder, D. G., & Pope, M. H. (1979). The mechanical and kinematic analysis of the lumbar spine in normal living human subjects in vivo. *J Biomech, 12*(2), 165-172.

44. Goeken, L. N., & Hof, A. L. (1991). Instrumental straight-leg raising: a new approach to Lasegue's test. *Arch Phys Med Rehabil, 72*(12), 959-966.

45. Goeken, L. N., & Hof, A. L. (1993). Instrumental straight-leg raising: results in healthy subjects. *Arch Phys Med Rehabil, 74*(2), 194-203.

46. Goeken, L. N., & Hof, A. L. (1994). Instrumental straight-leg raising: results in patients. *Arch Phys Med Rehabil, 75*(4), 470-477.

47. Gomez, T. T. (1994). Symmetry of lumbar rotation and lateral flexion range of motion and isometric strength in subjects with and without low back pain. *J Orthop Sports Phys Ther, 19*(1), 42-48.

48. Gracovetsky, S., Newman, N., Pawlowsky, M., Lanzo, V., Davey, B., & Robinson, L. (1995). A database for estimating normal spinal motion derived from noninvasive measurements. *Spine, 20*(9), 1036-1046.

49. Gray, H., Williams, P. L., & Bannister, L. H. (1995). *Gray's anatomy : the anatomical basis of medicine and surgery* (38th / ed.). Edinburgh ; New York: Churchill Livingstone.

50. Grenier, S. G., Russell, C., & McGill, S. M. (2003). Relationships between lumbar flexibility, sit-and-reach test, and a previous history of low back discomfort in industrial workers. *Can J Appl Physiol, 28*(2), 165-177.

51. Grood, E. S., & Suntay, W. J. (1983). A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng, 105*(2), 136-144.

52. Gunzburg, R., Hutton, W., & Fraser, R. (1991). Axial rotation of the lumbar spine and the effect of flexion. An in vitro and in vivo biomechanical study. *Spine, 16*(1), 22-28.

53. Guo, H. R., Tanaka, S., Halperin, W. E., & Cameron, L. L. (1999). Back pain prevalence in US industry and estimates of lost workdays. *Am J Public Health, 89*(7), 1029-1035.

54. Halbertsma, J. P., Goeken, L. N., Hof, A. L., Groothoff, J. W., & Eisma, W. H. (2001). Extensibility and stiffness of the hamstrings in patients with nonspecific low back pain. *Arch Phys Med Rehabil, 82*(2), 232-238.

55. Hanley, E. N., Matteri, R. E., & Frymoyer, J. W. (1976). Accurate roentgenographic determination of lumbar flexion-extension. *Clin Orthop*(115), UNKNOWN.

56. Harryman, D. T., 2nd, Sidles, J. A., Clark, J. M., McQuade, K. J., Gibb, T. D., & Matsen, F. A., 3rd. (1990). Translation of the humeral head on the glenoid with passive glenohumeral motion. *J Bone Joint Surg Am, 72*(9), 1334-1343.

57. Harvey, S. B., Smith, F. W., & Hukins, D. W. (1998). Measurement of lumbar spine flexion-extension using a low-field open-magnet magnetic resonance scanner. *Invest Radiol, 33*(8), 439-443.

58. Hayes, M. A., Howard, T. C., Gruel, C. R., & Kopta, J. A. (1989). Roentgenographic evaluation of lumbar spine flexion-extension in asymptomatic individuals. *Spine, 14*(3), 327-331.

59. Hewitt, J., Guilak, F., Glisson, R., & Vail, T. P. (2001). Regional material properties of the human hip joint capsule ligaments. *J Orthop Res, 19*(3), 359-364.

60. Hindle, R. J., Pearcy, M. J., Cross, A. T., & Miller, D. H. T. (1990). Three-dimensional kinematics of the human back. *Clinical Biomechanics, 5*, 218-228.

61. Johns, R. E., Jr., Bloswick, D. S., Elegante, J. M., & Colledge, A. L. (1994). Chronic, recurrent low back pain. A methodology for analyzing fitness for duty and managing risk under the Americans with Disabilities Act. *J Occup Med, 36*(5), 537-547.

62. Jonsson, B., & Stromqvist, B. (1993). Symptoms and signs in degeneration of the lumbar spine. A prospective, consecutive study of 300 operated patients. *J Bone Joint Surg Br, 75*(3), 381-385.

63. Kadaba, M. P., Ramakrishnan, H. K., Wootten, M. E., Gainey, J., Gorton, G., & Cochran, G. V. (1989). Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *J Orthop Res, 7*(6), 849-860.

64. Khalil, T. M., Asfour, S. S., Martinez, L. M., Waly, S. M., Rosomoff, R. S., & Rosomoff, H. L. (1992). Stretching in the rehabilitation of low-back pain patients. *Spine, 17*(3), 311-317.

65. Kinzel, G. L., Hall, A. S., Jr., & Hillberry, B. M. (1972). Measurement of the total motion between two body segments. I. Analytical development. *J Biomech, 5*(1), 93-105.

66. Kortelainen, P., Puranen, J., Koivisto, E., & Lahde, S. (1985). Symptoms and signs of sciatica and their relation to the localization of the lumbar disc herniation. *Spine, 10*(1), 88-92.

67. Lariviere, C., Gagnon, D., & Loisel, P. (2000). The effect of load on the coordination of the trunk for subjects with and without chronic low back pain during flexion-extension and lateral bending tasks. *Clin Biomech (Bristol, Avon), 15*(6), 407-416.

68. Lau, E. M., Egger, P., Coggon, D., Cooper, C., Valenti, L., & O'Connell, D. (1995). Low back pain in Hong Kong: prevalence and characteristics compared with Britain. *J Epidemiol Community Health, 49*(5), 492-494.
69. Lee, R. (2002). Measurement of movements of the lumbar spine . *Physiotherapy Theory & Practice* (Vol. 18, pp. 159): Taylor & Francis Ltd.
70. Lee, R. Y. (2001). Kinematics of rotational mobilisation of the lumbar spine. *Clin Biomech (Bristol, Avon), 16*(6), 481-488.
71. Lee, R. Y., Laprade, J., & Fung, E. H. (2003). A real-time gyroscopic system for three-dimensional measurement of lumbar spine motion. *Med Eng Phys, 25*(10), 817-824.
72. Lee, R. Y., & Munn, J. (2000). Passive moment about the hip in straight leg raising. *Clin Biomech (Bristol, Avon), 15*(5), 330-334.
73. Lee, R. Y., & Wong, T. K. (2002). Relationship between the movements of the lumbar spine and hip. *Hum Mov Sci, 21*(4), 481-494.
74. Leung, A. S., Lam, T. H., Hedley, A. J., & Twomey, L. T. (2003). Psychometric properties of a generic health measure in Chinese patients with low back pain in Hong Kong. *Man Ther, 8*(3), 151-160.
75. Li, L., & Caldwell, G. E. (1999). Coefficient of cross correlation and the time domain correspondence. *J Electromyogr Kinesiol, 9*(6), 385-389.
76. Li, Y., McClure, P. W., & Pratt, N. (1996). The effect of hamstring muscle stretching on standing posture and on lumbar and hip motions during forward bending. *Phys Ther, 76*(8), 836-845; discussion 845-839.
77. Loebl, W. Y. (1967). Measurement of spinal posture and range of spinal movement. *Ann Phys Med, 9*(3), 103-110.
78. Macrae, I. F., & Wright, V. (1969). Measurement of back movement. *Ann Rheum Dis, 28*(6), 584-589.
79. Magee, D. J. (2002). *Orthopedic physical assessment* (4th ed.). Philadelphia, PA: Saunders.
80. Maniadakis, N., & Gray, A. (2000). The economic burden of back pain in the UK. *Pain, 84*(1), 95-103.

81. Mannion, A., & Troke, M. (1999). A comparison of two motion analysis devices used in the measurement of lumbar spinal mobility. *Clin Biomech (Bristol, Avon), 14*(9), 612-619.

82. Markolf, K. L. (1972). Deformation of the thoracolumbar intervertebral joints in response to external loads: a biomechanical study using autopsy material. *J Bone Joint Surg Am, 54*(3), 511-533.

83. Marras, W. S., Lewis, K. E., Ferguson, S. A., & Parnianpour, M. (2000). Impairment magnification during dynamic trunk motions. *Spine, 25*(5), 587-595.

84. Mayagoitia, R. E., Nene, A. V., & Veltink, P. H. (2002). Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems. *J Biomech, 35*(4), 537-542.

85. Mayer, T. G., Tencer, A. F., Kristoferson, S., & Mooney, V. (1984). Use of noninvasive techniques for quantification of spinal range-of-motion in normal subjects and chronic low-back dysfunction patients. *Spine, 9*(6), 588-595.

86. McClure, P. W., Esola, M., Schreier, R., & Siegler, S. (1997). Kinematic analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain. *Spine, 22*(5), 552-558.

87. McGill, S., Seguin, J., & Bennett, G. (1994). Passive stiffness of the lumbar torso in flexion, extension, lateral bending, and axial rotation. Effect of belt wearing and breath holding. *Spine, 19*(6), 696-704.

88. McGill, S. M., Cholewicki, J., & Peach, J. P. (1997). Methodological considerations for using inductive sensors (3SPACE ISOTRAK) to monitor 3-D orthopaedic joint motion. *Clin Biomech (Bristol, Avon), 12*(3), 190-194.

89. McGregor, A. H., Anderton, L., Gedroyc, W. M., Johnson, J., & Hughes, S. P. (2001). Assessment of spinal kinematics using open interventional magnetic resonance imaging. *Clin Orthop*(392), 341-348.

90. McGregor, A. H., Anderton, L., Gedroyc, W. M., Johnson, J., & Hughes, S. P. (2002). The use of interventional open MRI to assess the kinematics of the lumbar spine in patients with spondylolisthesis. *Spine, 27*(14), 1582-1586.

91. McGregor, A. H., McCarthy, I. D., Dore, C. J., & Hughes, S. P. (1997). Quantitative assessment of the motion of the lumbar spine in the low back pain population and the effect of different spinal pathologies of this motion. *Eur Spine J, 6*(5), 308-315.

92. McGregor, A. H., McCarthy, I. D., & Hughes, S. P. (1995). Motion characteristics of the lumbar spine in the normal population. *Spine, 20*(22), 2421-2428.

93. Mellin, G. (1986). Measurement of thoracolumbar posture and mobility with a Myrin inclinometer. *Spine, 11*(7), 759-762.

94. Mellin, G. (1990). Decreased joint and spinal mobility associated with low back pain in young adults. *J Spinal Disord, 3*(3), 238-243.

95. Miller, S. A., Mayer, T., Cox, R., & Gatchel, R. J. (1992). Reliability problems associated with the modified Schober technique for true lumbar flexion measurement. *Spine, 17*(3), 345-348.

96. Milne, A. D., Chess, D. G., Johnson, J. A., & King, G. J. (1996). Accuracy of an electromagnetic tracking device: a study of the optimal range and metal interference. *J Biomech, 29*(6), 791-793.

97. Miyazaki, S. (1997). Long-term unrestrained measurement of stride length and walking velocity utilizing a piezoelectric gyroscope. *IEEE Trans Biomed Eng, 44*(8), 753-759.

98. Moller, H., Sundin, A., & Hedlund, R. (2000). Symptoms, signs, and functional disability in adult spondylolisthesis. *Spine, 25*(6), 683-689; discussion 690.

99. Muggleton, J. M., & Allen, R. (1997). Automatic location of vertebrae in digitized videofluoroscopic images of the lumbar spine. *Med Eng Phys, 19*(1), 77-89.

100. Murphy, P. L., & Volinn, E. (1999). Is occupational low back pain on the rise? *Spine, 24*(7), 691-697.

101. Nash, C. L., Jr., & Moe, J. H. (1969). A study of vertebral rotation. *J Bone Joint Surg Am, 51*(2), 223-229.

102. Nelson, J. M., Walmsley, R. P., & Stevenson, J. M. (1995). Relative lumbar and pelvic motion during loaded spinal flexion/extension. *Spine, 20*(2), 199-204.

103. Ng, J. K., Kippers, V., Richardson, C. A., & Parnianpour, M. (2001). Range of motion and lordosis of the lumbar spine: reliability of measurement and normative values. *Spine, 26*(1), 53-60.

104. Nigg, B. M., & Herzog, W. (1999). *Biomechanics of the musculo-skeletal system* (2nd ed.). Chichester ; New York: Wiley.

105. Nitschke, J. E., Nattrass, C. L., Disler, P. B., Chou, M. J., & Ooi, K. T. (1999). Reliability of the American Medical Association guides' model for measuring spinal range of motion. Its implication for whole-person impairment rating. *Spine, 24*(3), 262-268.

106. Novacheck, T. F. (1998). The biomechanics of running. *Gait Posture, 7*(1), 77-95.

107. Oddsson, L. (1988). Co-ordination of a simple voluntary multi-joint movement with postural demands: trunk extension in standing man. *Acta Physiol Scand, 134*(1), 109-118.

108. Panjabi, M., Chang, D., & Dvorak, J. (1992). An analysis of errors in kinematic parameters associated with in vivo functional radiographs. *Spine, 17*(2), 200-205.

109. Panjabi, M. M., Oxland, T. R., Yamamoto, I., & Crisco, J. J. (1994). Mechanical behavior of the human lumbar and lumbosacral spine as shown by three-dimensional load-displacement curves. *J Bone Joint Surg Am, 76*(3), 413-424.

110. Paquet, N., Malouin, F., & Richards, C. L. (1994). Hip-spine movement interaction and muscle activation patterns during sagittal trunk movements in low back pain patients. *Spine, 19*(5), 596-603.

111. Paquet, N., Malouin, F., Richards, C. L., Dionne, J. P., & Comeau, F. (1991). Validity and reliability of a new electrogoniometer for the measurement of sagittal dorsolumbar movements. *Spine, 16*(5), 516-519.

112. Peach, J. P., Sutarno, C. G., & McGill, S. M. (1998). Three-dimensional kinematics and trunk muscle myoelectric activity in the young lumbar spine: a database. *Arch Phys Med Rehabil, 79*(6), 663-669.

113. Pearcy, M., Portek, I., & Shepherd, J. (1984). Three-dimensional x-ray analysis of normal movement in the lumbar spine. *Spine, 9*(3), 294-297.

114. Pearcy, M., Portek, I., & Shepherd, J. (1985). The effect of low-back pain on lumbar spinal movements measured by three-dimensional X-ray analysis. *Spine, 10*(2), 150-153.

115. Pearcy, M. J. (1985). Stereo radiography of lumbar spine motion. *Acta Orthop Scand Suppl, 212*, 1-45.

116. Pearcy, M. J. (1986). Measurement of back and spinal mobility. *Clinical Biomechanics, 1*, 44-51.

117. Pearcy, M. J., Gill, J. M., Hindle, R. J., & Johnson, G. R. (1987a). Measurement of human back movements in three dimensions by opto-electronic devices. *Clinical Biomechanics, 2*, 199-204.

118. Pearcy, M. J., Gill, J. M., Whittle, M. W., & Johnson, G. R. (1987b). Dynamic back movement measured using a three-dimensional television system. *J Biomech, 20*(10), 943-949.

119. Pearcy, M. J., & Hindle, R. J. (1989). New method for the non-invasive three-dimesional measurement of human back movement. *Clinical Biomechanics, 4*, 73-79.

120. Pearcy, M. J., & Tibrewal, S. B. (1984). Axial rotation and lateral bending in the normal lumbar spine measured by three-dimensional radiography. *Spine, 9*(6), 582-587.

121. Pearcy, M. J., & Whittle, M. W. (1982). Movements of the lumbar spine measured by three-dimensional X-ray analysis. *J Biomed Eng, 4*(2), 107-112.

122. Pennal, G. F., Conn, G. S., McDonald, G., Dale, G., & Garside, H. (1972). Motion studies of the lumbar spine: a preliminary report. *J Bone Joint Surg Br, 54*(3), 442-452.

123. Portek, I., Pearcy, M. J., Reader, G. P., & Mowat, A. G. (1983). Correlation between radiographic and clinical measurement of lumbar spine movement. *Br J Rheumatol, 22*(4), 197-205.

124. Porter, J. L., & Wilkinson, A. (1997). Lumbar-hip flexion motion. A comparative study between asymptomatic and chronic low back pain in 18- to 36-year-old men. *Spine, 22*(13), 1508-1513; discussion 1513-1504.

125. Portney, L. G., & Watkins, M. P. (2000). *Foundations of clinical research : applications to practice* (2nd ed.). Upper Saddle River, N.J.: Prentice Hall Health.

126. Poulin, F., & Amiot, L. P. (2002). Interference during the use of an electromagnetic tracking system under OR conditions. *J Biomech, 35*(6), 733-737.

127. Putto, E., & Tallroth, K. (1990). Extension-flexion radiographs for motion studies of the lumbar spine. A comparison of two methods. *Spine, 15*(2), 107-110.

128. Quanbury, A. O., Cooper, J. E., & Grahame, R. E. (1986). An electrogoniometer for the measurement of thoracolumbar rotation. *J Biomech, 19*(10), 791-797.

129. Ramakrishnan, H. K., & Kadaba, M. P. (1991). On the estimation of joint kinematics during gait. *J Biomech, 24*(10), 969-977.

130. Rebain, R., Baxter, G. D., & McDonough, S. (2002). A systematic review of the passive straight leg raising test as a diagnostic aid for low back pain (1989 to 2000). *Spine, 27*(17), E388-395.

131. Rebain, R., Baxter, G. D., & McDonough, S. (2003). The passive straight leg raising test in the diagnosis and treatment of lumbar disc herniation: a survey of United kingdom osteopathic opinion and clinical practice. *Spine, 28*(15), 1717-1724.

132. Reynolds, P. M. (1975). Measurement of spinal mobility: a comparison of three methods. *Rheumatol Rehabil, 14*(3), 180-185.

133. Rizzo, J. A., Abbott, T. A., 3rd, & Berger, M. L. (1998). The labor productivity effects of chronic backache in the United States. *Med Care, 36*(10), 1471-1488.

134. Rowe, P. J., & White, M. (1996). Three dimensional, lumbar spinal kinematics during gait, following mild musculo-skeletal low back pain in nurses. *Gait & Posture, 4*(3), 242-251.

135. Russell, P., Pearcy, M. J., & Unsworth, A. (1993). Measurement of the range and coupled movements observed in the lumbar spine. *Br J Rheumatol, 32*(6), 490-497.

136. Saur, P. M., Ensink, F. B., Frese, K., Seeger, D., & Hildebrandt, J. (1996). Lumbar range of motion: reliability and validity of the inclinometer technique in the clinical measurement of trunk flexibility. *Spine, 21*(11), 1332-1338.

137. Schache, A. G., Bennell, K. L., Blanch, P. D., & Wrigley, T. V. (1999). The coordinated movement of the lumbo-pelvic-hip complex during running: a literature review. *Gait Posture, 10*(1), 30-47.

138. Schache, A. G., Blanch, P., Rath, D., Wrigley, T., & Bennell, K. (2002). Three-dimensional angular kinematics of the lumbar spine and pelvis during running. *Hum Mov Sci, 21*(2), 273-293.

139. Schache, A. G., Blanch, P. D., Rath, D. A., Wrigley, T. V., Starr, R., & Bennell, K. L. (2001a). A comparison of overground and treadmill running for measuring the three-dimensional kinematics of the lumbo-pelvic-hip complex. *Clin Biomech (Bristol, Avon), 16*(8), 667-680.

140. Schache, A. G., Wrigley, T. V., Blanch, P. D., Starr, R., Rath, D. A., & Bennell, K. L. (2001b). The effect of differing Cardan angle sequences on three dimensional lumbo-pelvic angular kinematics during running. *Med Eng Phys, 23*(7), 493-501.

141. Scham, S. M., & Taylor, T. K. (1971). Tension signs in lumbar disc prolapse. *Clin Orthop, 75*, 195-204.

142. Simmonds, M. J., & Kumar, S. (1993). Health care ergonomics Part II: Location of body structures by palpation - A reliability study. *International Journal of Industrial Ergonomics, 11*(2), 145-151.

143. Snell, R. S. (2000). *Clinical anatomy for medical students* (6th ed.). Baltimore, Md.: Lippincott Williams & Wilkins.

144. Steffen, T., Rubin, R. K., Baramki, H. G., Antoniou, J., Marchesi, D., & Aebi, M. (1997). A new technique for measuring lumbar segmental motion in vivo. Method, accuracy, and preliminary results. *Spine, 22*(2), 156-166.

145. Stergiou, N. (2004). *Innovative analyses of human movement*. Champaign, Ill.: Human Kinetics.

146. Stokes, I. A., Wilder, D. G., Frymoyer, J. W., & Pope, M. H. (1981). 1980 Volvo award in clinical sciences. Assessment of patients with low-back pain by biplanar radiographic measurement of intervertebral motion. *Spine, 6*(3), 233-240.

147. Suh, C. H. (1974). The fundamentals of computer aided X-ray analysis of the spine. *J Biomech, 7*(2), 161-169.

148. Svensson, H. O., & Andersson, G. B. (1982). Low back pain in forty to forty-seven year old men. I. Frequency of occurrence and impact on medical services. *Scand J Rehabil Med, 14*(2), 47-53.

149. Swezey, R. L. (2003). Overdiagnosed sciatica and stenosis, underdiagnosed hip arthritis. *Orthopedics, 26*(2), 173-174; discussion 174.

150. Takata, K., & Takahashi, K. (1994). Hamstring tightness and sciatica in young patients with disc herniation. *J Bone Joint Surg Br, 76*(2), 220-224.

151. Tanz, S. S. (1953). Motion of the lumbar spine; a roentgenologic study. *Am J Roentgenol Radium Ther Nucl Med, 69*(3), 399-412.

152. Taylor, J. R., & Twomey, L. T. (1986). Age changes in lumbar zygapophyseal joints. Observations on structure and function. *Spine, 11*(7), 739-745.

153. Tong, K., & Granat, M. H. (1999). A practical gait analysis system using gyroscopes. *Med Eng Phys, 21*(2), 87-94.

154. Troup, J. D., Hood, C. A., & Chapman, A. E. (1968). Measurements of the sagittal mobility of the lumbar spine and hips. *Ann Phys Med, 9*(8), 308-321.

155. Van Herp, G., Rowe, P., Salter, P., & Paul, J. P. (2000). Three-dimensional lumbar spinal kinematics: a study of range of movement in 100 healthy subjects aged 20 to 60+ years. *Rheumatology (Oxford), 39*(12), 1337-1340.

156. Vanneuville, G., Kyndt, T., Massaux, M., Harmand, Y., Garcier, J. M., Monnet, J. P., et al. (1994). Preliminary opto-electronic study on vertebral movement. *Surg Radiol Anat, 16*(4), 385-391.

157. Vogt, L., Pfeifer, K., Portscher, & Banzer, W. (2001). Influences of nonspecific low back pain on three-dimensional lumbar spine kinematics in locomotion. *Spine, 26*(17), 1910-1919.

158. Watson, P. J., Main, C. J., Waddell, G., Gales, T. F., & Purcell-Jones, G. (1998). Medically certified work loss, recurrence and costs of wage compensation for back pain: a follow-up study of the working population of Jersey. *Br J Rheumatol, 37*(1), 82-86.

159. Weitz, E. M. (1981). The lateral bending sign. *Spine, 6*(4), 388-397.

160. White, A. A., & Panjabi, M. M. (1990). *Clinical biomechanics of the spine* (2nd ed.). Philadelphia: Lippincott.

161. Whittle, M. W., & Levine, D. (1999). Three-dimensional relationships between the movements of the pelvis and lumbar spine during normal gait. *Human Movement Science, 18*(5), 681-692.

162. Williams, D. A., Feuerstein, M., Durbin, D., & Pezzullo, J. (1998). Health care and indemnity costs across the natural history of disability in occupational low back pain. *Spine, 23*(21), 2329-2336.

163. Woltring, H. J. (1991). Representation and calculation of 3-D joint movement*1. *Human Movement Science, 10*(5), 603-616.

164. Woltring, H. J. (1994). 3-D attitude representation of human joints: a standardization proposal. *J Biomech, 27*(12), 1399-1414.

165. Xin, S. Q., Zhang, Q. Z., & Fan, D. H. (1987). Significance of the straight-leg-raising test in the diagnosis and clinical evaluation of lower lumbar intervertebral-disc protrusion. *J Bone Joint Surg Am, 69*(4), 517-522.

166. Yamamoto, I., Panjabi, M. M., Crisco, T., & Oxland, T. (1989). Three-dimensional movements of the whole lumbar spine and lumbosacral joint. *Spine, 14*(11), 1256-1260.

167. Yu, B., Kienbacher, T., Growney, E. S., Johnson, M. E., & An, K. N. (1997). Reproducibility of the kinematics and kinetics of the lower extremity during normal stair-climbing. *J Orthop Res, 15*(3), 348-352.

168. Zatsiorsky, V. M. (1998). *Kinematics of human motion*. Champaign, Ill.: Human Kinetics.

169. Zheng, Y., Nixon, M. S., & Allen, R. (2003). Lumbar spine visualisation based on kinematic analysis from videofluoroscopic imaging. *Med Eng Phys, 25*(3), 171-179.

Appendix I

Effects of back pain on the correlation between hip and lumbar spine movements

Subject Information Sheet

You are invited to take part in a research project that examines the effects of back pain on the correlation between hip and lumbar spine movements. There is some preliminary evidence that back pain may affect the correlation between hip and lumbar spine during forward bending. However, the precise effects of back pain on the interaction of hip and lumbar spine in other planes of movements are not fully understood. The purposes of this research are to find out the fundamental information on the kinematics of hip-lumbar spine in all the anatomical planes movements, and the effects of back pain on these movements. With such information, strategies may be developed to regain or restore the normal kinematics of hip-lumbar spine complex. And thus enhance recovery and reduce the chance of recurrence of back problems. This research is conducted by Dr Raymond Lee, Associate Professor, and Thomas Wong of the Department of Rehabilitation Sciences.

Twenty healthy subjects and forty male subjects with central low back pain or low back pain with refer pain down to the leg, 18-36 years of age, will be recruited for this study. If you agree to participate in this study, you will be requested to answer a few questions. This is to acertain that you are suitable for participating this study.

You will be requested to expose your back, to which four electromagnetic sensors will be attached. These sensors allow movements of the back to be determined. You will then be asked to perform forward bending, side bending and twisting of the trunk in a random order. There will be a demonstration of how these movements should be performed. You will be requested to repeat the movements three times. Data collection will be completed in about 45 minutes.

You should experience no pain or discomfort during the test. There is no known risk associated with electromagnetic tracking of spinal movements. Participation in this study is entirely voluntary. You are not obliged to participate, and if you do participate, you can withdraw at any time without penalty or prejudice.

All aspects of the study including the results will be strictly confidential and only the researchers named above will have access to information on participants in this study may be submitted for publication in international journals, but individual participants will not be identified in such a report. The procedure will be explained clearly to you. If you have any questions or concerns at any stage in the study, please feel free to contact Dr Raymond Lee at 27664889. This information sheet is for you to keep. Thank you for your participation.

Effects of back pain on the correlation between hip and lumbar spine movements

Consent Form

I, _______________________________, voluntarily consent to participate in the above- mentioned research conducted by Dr Raymond Lee and Thomas Wong.

I understand that the information and results obtained from this research study are strictly confidential, and that if they are submitted for publication, my right to privacy will be retained, that is, my personal details will not be revealed.

The procedure as set out in the attached information sheet has been fully explained to me and I understand what is expected of me as well as any benefits and risks involved. My participation in the project is entirely voluntary.

I acknowledge I have the right to question or query any part of the procedure and can withdraw at any time without penalty or prejudice.

I have been familiarised with the procedure.

Name of
Participant:____

of
(Address)____

Signature of
Participant:____

Signed
(Researcher)____

Name of
Witness:____

Signature of
Witness:____

Appendix II

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Relationship between the movements of the lumbar spine and hip

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Abstract

Movements of the lumbar spine and hips were measured in 20 healthy subjects using an electromagnetic tracking device. Movement sensors were attached to the L1 spinous process, the sacrum and the thighs. Each subject was requested to perform the following movements of the trunk: forward and backward bending, lateral bending and twisting. The ratio of the maximum magnitude of spine movement to that of the hip was determined. Angle–angle plot and cross-correlation were used to examine the relationship between the movements of the spine and hip. It was shown that during forward and backward bending of the trunk, the overall contributions of the lumbar spine and hip were similar, but the spine had a greater contribution to the early stage of the movement. Lateral bending of the trunk was found to be primarily accomplished by movement of the spine, whereas the hips were the predominate sources of movement for twisting. Moreover, it was shown that in the sagittal and horizontal planes, the movement patterns of the spine and hip were in phase, whereas in the coronal plane, the spine generally moved earlier than the hips. It is concluded that clinical examination of the back should include kinematic measures of both the lumbar spine and hips.

PsycINFO classification: 2330; 3380
Keywords: Kinematics; Spine motion; Hip motion; Biomechanics

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1. Introduction

Low back pain is a serious health problem (Chase, 1992; Frymoyer, 1988; Indahl, Velund, & Reikeraas, 1995; Pope, Andersson, Fromoyer, & Chaffin, 1991; Stubbs, 1983), and is frequently associated with a change in the mobility of the lumbar spine and hip (Dolan & Adams, 1993; Ellison, Rose, & Sahrmann, 1990; Fairbank, Pynsent, Poortvliet, & Phillips, 1984; Mellin, 1990). Impairment of spinal mobility has been shown to result in various forms of functional disabilities (Cox et al., 2000; Mayer, Tencer, Kristoferson, & Mooney, 1984), which have profound effects on the quality of life. An understanding of the kinematics of the lumbar spine and hip is clinically important, as this would facilitate the development of effective clinical examination techniques and rehabilitation programmes.

Previous research had examined the relationship between lumbar spine and hip movements during forward and backward bending of the trunk (Esola, McClure, Fitzgerald, & Siegler, 1996; Mayer et al., 1984; McClure, Esola, Schreier, & Siegler, 1997; Paquet, Malouin, & Richards, 1994; Porter & Wilkinson, 1997). It was found that during the early stage of forward bending, the magnitude of movement of the spine was greater than that of the hip, but the relative contribution of the spine was reduced in the final stage of forward bending (Esola et al., 1996; Mayer et al., 1984; Paquet et al., 1994; Rose, Sahrmann, & Norton, 1988). The movement pattern of the spine and hip during backward bending of the trunk was generally a reversal of the forward bending pattern (Esola et al., 1996; McClure et al., 1997).

Gracovetsky et al. (1990) suggested that the kinematics of lumbar spine and hip could be affected by injury and therapeutic interventions. Some research studies (Mayer et al., 1984; Paquet et al., 1994) showed that the contribution of the lumbar spine to forward bending was reduced in subjects with low back pain. However, the studies of Porter and Wilkinson (1997) and Esola et al. (1996) found that the contribution of the lumbar spine was increased in back patients and in asymptomatic subjects with a past history of back pain. The differences in the results of previous investigations could be due to differences in the clinical history and characteristics of the subjects recruited.

A limitation of previous research (Esola et al., 1996; Mayer et al., 1984; McClure et al., 1997; Nelson, Walmsley, & Stevenson, 1995; Paquet et al., 1994; Porter & Wilkinson, 1997) was that they examined only the relative magnitude of the movements of the spine and hip in different stages of the movement. The similarity or dissimilarity of the time history patterns of the movements of the spine and hip had not been studied. There was no information on the phase relationship between the movement–time curves of the two joints. Such information should be sought, as it would provide further insights into coordination strategies of our body. The present study attempted to use the mathematical technique of cross-correlation to study the above kinematic information (Kendall, 1976; Li & Caldwell, 1999).

Previous kinematic studies of the relationship between the lumbar spine and hip were limited to movements in the sagittal plane (Esola et al., 1996; Mayer et al., 1984; McClure et al., 1997; Nelson et al., 1995; Paquet et al., 1994; Porter & Wilkinson, 1997). This was largely because forward bending was recognised as a major risk factor for low back pain (Bergquist-Ullman, 1977; Magora, 1973; Mellin, 1986). However, back pain has also been associated with lateral bending, twisting and various asymmetrical movements of the trunk (Andersson, 1981; Jin et al., 2000; Marras et al., 1993). There is currently no information on the relationship between spine and hip movements in the coronal and horizontal planes.

Previous research generally employed video techniques to study the correlation between spine and hip movements (Esola et al., 1996; Mayer et al., 1984; McClure et al., 1997; Paquet et al., 1994; Porter & Wilkinson, 1997). Technical difficulties in three-dimensional analysis might also explain why previous studies were limited to sagittal movements of the trunk. Three-dimensional video analysis was time-consuming, expensive and inaccurate due to closely positioned markers and changing inter-marker distances (Pearcy, Gill, Hindle, & Johnson, 1987).

Recently, electromagnetic tracking devices have been developed and successfully used for three-dimensional kinematic analysis of spinal movements (An, Jacobsen, Berglund, & Chao, 1988; Burnett, Barrett, Marshall, Elliott, & Day, 1998; Lee, 2001; Mannion & Troke, 1999; Pearcy & Hindle, 1989). These devices were easy to use, highly accurate and reliable (Burnett et al., 1998; Lee, 2001; Pearcy & Hindle, 1989). A major attraction was that they were able to provide real-time kinematic data (Lee, 2001).

The purpose of the present study was to examine the relationship between the movements of the lumbar spine and hips in the three anatomical planes. The benefits of electromagnetic tracking devices made them most suitable for measuring spine and hip movements in this study.

2. Methods

2.1. Subjects

Twenty male healthy subjects (mean age $= 20 \pm 1$ years, mean weight $= 62.4 \pm 5.0$ kg, mean height $= 1.71 \pm 0.04$) were recruited for this study. They were in good health with no history of back pain or leg pain that may be attributed to the back within the last 12 months. They were excluded if they had undergone previous back surgery, had a fracture, dislocation or any structural defects of the spine.

Ethics approval for this study was obtained from the Departmental Research Committee of the Hong Kong Polytechnic University. Subjects were informed about the experimental procedure and any potential risks prior to the attainment of a written consent form.

2.2. Instrumentation

The 3SPACE Fastrak (Polhemus Inc., Colchester, VT 05446, USA) was used to measure movements of the lumbar spine and hips. The system had a source that generated a low-frequency magnetic field which was detected by the sensors. The source was placed in a fixed position close to the subject (within 0.7 m). Two sensors of the system were employed to measure the movements of the lumbar spine – one sensor was placed over the L1 spinous process and the second sensor over the sacrum. Two other sensors were used to measure the movements of the hips by placing them over the lateral aspect of the left and right thighs. Each sensor was attached to a small, mouldable plastic plate with plastic screws. A Velcro band was threaded through the plate and tightly wrapped around the subject's trunk or leg so as to minimise the movement between the sensor and the underlying skin. The cables of the sensors were attached to the skin on the side of the trunk so that they did not move the sensor erroneously during the movement. Initial testing showed that the above arrangement provided the most secure sensor attachments.

The Fastrak had an electronic unit that calculated the three-dimensional positions and orientations of the sensors relative to the source. The unit was linked to a personal computer via an RS232C serial interface. Specifically developed custom software was used to control the Fastrak operation, data acquisition and display in real time. The software developed in this study was able to perform fast serial communication at 115.2 kBaud allowing a data update rate of 120 Hz. As four sensors were used in this experiment, the sampling rate was 30 Hz per sensor. The experimental set-up of the Fastrak system has been described in a previous study (Lee, 2001).

The Fastrak output comprised the 3×3 matrices of direction cosines that described the orientations of the sensors relative to the source. Lumbar spine movements were derived from the relative orientation between the L1 and sacral sensors, and hip movements from that between the thigh and sacral sensors. The method of computation was based on the mathematical techniques described by earlier authors (Cole, Nigg, Ronsky, & Yeadon, 1993; Grood & Suntay, 1983; Lee, 2001; Pearcy et al., 1987). The Joint Coordinate System angles proposed by Grood and Suntay (1983) were derived from the direction cosine matrices. The flexion/extension axis of the spine and hip was fixed to the pelvis and defined by a line joining the two anterior superior iliac spines. Axial rotation of the spine was defined as rotation about the longitudinal axis of the thorax, and that of the hip as rotation about the longitudinal axis of the femur. The third axis of the spine and hip was obtained by the cross-product of the two segment-fixed axes of the respective joint. This defined lateral bending of the spine and abduction/adduction of the hip. The following sign convention was adopted: (a) the lumbar spine: flexion, left lateral flexion and left axial rotation (i.e. leftward turn of the thorax relative to the pelvis) were considered to be positive, and (b) the hip: flexion, abduction and lateral rotation were positive. Movements in the opposite directions were represented by negative values.

2.3. Procedure

After the sensors were attached to the subjects, they were requested to stand upright in their most comfortable posture with feet shoulder-width apart and palms facing inwards. The positions of the lumbar spine and hips in this posture were recorded by the Fastrak, and taken as the zero reference positions. The movements of the spine and hips were calculated with respect to these reference positions.

Each subject then performed three continuous cycles of each of the anatomical movements of the trunk: maximal forward then backward bending, lateral bending to left and right, and axial rotation to left and right. The three anatomical movements were tested in a random order. Each movement trial was performed over a 12 s period at a speed that was most comfortable for the subject. There was a rest period of 5 min after each movement trial. In order to examine the repeatability of the movement data, the above experimental procedure was repeated three times. The sensors were not detached and remained securely attached to the body when the experiment was repeated. This eliminated any error due to removal and reattachment of the sensors.

2.4. Data analysis

The movements of each body joint were plotted against time. In order to examine the repeatability of measurements of each joint movement, the angle–time curves obtained in the three measurement trials were first normalised with respect to time to a uniform length. The coefficient of multiple determination (Kadaba et al., 1989; Yu, Kienbacher, Growney, Johnson, & An, 1997) was then calculated to determine the degree of similarity of the three sets of angle–time curves. The means and standard deviations of the maximum range in each direction of movements were determined for each subject. The standard deviations would indicate the variability of the movement data in a given subject.

The ratios of the absolute values of the maximum movements of the lumbar spine to those of the left and right hips (the S/LH and S/RH ratios) were determined for each trunk movement. This describes the relative contribution of the two joints at the end position of the movement. However, the ratio does not show how the joints arrived at the end position. Angle–angle plots (Barker, Kelly, & Paul, 1996; Grieve, 1968; Hershler & Milner, 1980; Miller, 1983) were thus used to reveal the trajectory of the movement pattern. The movement of the hips was plotted against that of the lumbar spine for each movement of the trunk. The general shape of the curve describes the trajectory of the movement. A straight line in the angle–angle plot indicates "exact" coordination of the lumbar spine and hips, and deviation from a straight line indicates the relative magnitude of movements of the lumbar spine and hip varies at different stages of the trunk movement.

Cross-correlation (Kendall, 1976; Li & Caldwell, 1999) between the movements of the lumbar spine and hips was calculated over the three consecutive movement cycles of the trunk. The movement of the lumbar spine was used as a reference for establishing the correlation. Cross-correlation was calculated for each trial of forward/backward bending, lateral bending and axial rotation of the trunk. The analysis compared the time histories of the kinematics of the lumbar spine and hip. The phase relationship between the spine and hip movements was examined by determining the time lag at which the absolute value of the correlation coefficient was maximal. *t*-tests were employed to determine if the mean time lags were significantly different from zero. The signs of the lumbar spine movement and the accompanying hip movement were made the same in the cross-correlation analysis so that the phase difference could be properly detected. For instance, in analysing the cross-correlation between left lateral flexion of the spine and the accompanying right hip adduction, the right hip adduction would have to be made positive so that it would not appear to be half cycle out of phase. Similarly, the left hip medial rotation that accompanied left axial rotation was made positive in the cross-correlation analysis of these two movements.

3. Results

3.1. Repeatability of data

The mean coefficient of multiple determination for measuring the various anatomical movements was 0.98 ± 0.01, suggesting that the movement–time curves were highly similar in repeated measurements. The mean standard deviation of the maximum movements was found to be $2.1 \pm 1.0°$. The measurement system was thus considered to be sufficiently reliable for the purpose of this study.

3.2. Forward and backward bending

The mean S/LH and S/RH ratios for forward and backward bending were close to 1 (Table 1). This suggests that the maximum magnitude of flexion and extension of lumbar spine and hips were approximately equal (Fig. 1). All subjects showed similar movement trajectories. The typical pattern is illustrated by Fig. 2, which shows the angle–angle plot of movements of the lumbar spine and the left hip for one of the subjects. The plot was similar in the case of the right hip. In regard to forward bending, the curves are concave to the left, indicating that the lumbar spine contributed greater to the early stage of the movement and movement occurred predominantly at the hips in the final stage. The shape of the curves is generally reversed for backward bending.

The mean peak cross-correlation coefficients for forward and backward bending were high (0.89 and 0.87 for the cross-correlation between the lumbar spine and the

Table 1
The mean (SD) ratios of the absolute values of the maximum movements of the lumbar spine to those of the left and right hips (the S/LH and S/RH ratios)

	Lumbar spine and left hip S/LH ratio		Lumbar spine and right hip S/RH ratio	
	Mean	SD	Mean	SD
Forward bending	1.2	0.2	1.1	0.2
Backward bending	1.3	0.4	1.2	0.5
Left side bending	9.2	0.3	4.3	0.3
Right side bending	3.6	0.3	9.3	0.4
Left twisting	0.2	0.5	0.5	0.5
Right twisting	0.7	0.4	0.2	0.4

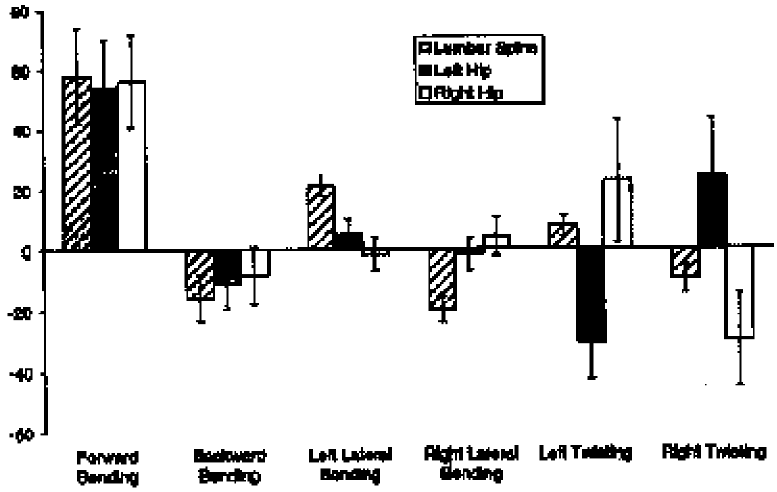

Fig. 1. Means and standard deviations for the maximum movements of the lumbar spine and hips in the three anatomical planes. For sign convention, see text. The following movements are shown in the graph: (a) forward and backward bending: flexion and extension of the spine and hips, (b) lateral bending: lateral flexion of the spine, and abduction and adduction of the hips, and (c) twisting: axial rotation of the spine, and medial and lateral rotation of the hips.

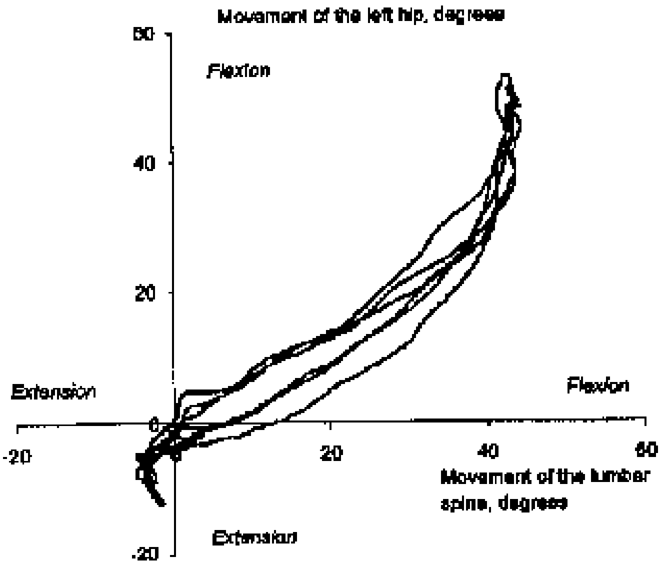

Fig. 2. Angle–angle plot of the movements of the lumbar spine and the left hip in the sagittal plane during forward and backward bending of the trunk (subject 05).

Table 2
Results of cross-correlation analysis of the movements of the lumbar spine and hips

		Forward and backward bending	Left and right lateral bending	Left and right twisting
Lumbar spine and left hip	Mean (SD) peak correlation coefficient	0.89 (0.06)	0.54 (0.25)	0.71 (0.16)
	Mean (SD) time lag at peak correlation (s)	−0.01 (0.04)	1.21 (2.30)	0.59 (1.93)
Lumbar spine and right hip	Mean (SD) peak correlation coefficient	0.87 (0.07)	0.53 (0.23)	0.80 (0.22)
	Mean (SD) time lag at peak correlation (s)	0.02 (0.06)	1.28 (3.29)	0.48 (1.37)

left and right hips respectively, Table 2). The shapes of the movement–time curves of the lumbar spine and hips were thus very similar. The time lags at peak correlation were negligible (Table 2), and found to be not significantly different from zero ($p > 0.05$). This suggested that there was no phase difference between the movements of the spine and hips during forward and backward bending.

3.3. Lateral bending

Left lateral flexion of the lumbar spine was found to be accompanied by abduction of the left hip and adduction of the right hip (Fig. 1). The pattern was reversed in right lateral bending. Fig. 1 shows that lateral bending of the trunk was mainly achieved by lateral flexion of the lumbar spine and the contributions of both hips were small. Hence, the S/LH and S/RH ratios were found to be large (Table 1). The movements of the two hips were asymmetrical. In regard to left side bending, the magnitude of abduction of the left hip was smaller than the adduction of the right hip (Fig. 1). The S/LH ratio was thus higher than the S/RH ratio (Table 1). The asymmetry was reversed for right side bending of the trunk.

Fig. 3 shows the angle–angle plot of the movements of the spine and the left hip for one of the subjects. The pattern for the right hip was a mirror image of Fig. 3. There were large variations in the shapes of the angle–angle plots among the subjects. However, in all cases, as shown in Fig. 3, the curves were close to the horizontal axis, indicating that the contribution of the hips was small.

The mean peak cross-correlation coefficient was small (Table 2). The degree of association between the spine and hip movements was weak. The mean time lags at peak correlation were 1.21 and 1.28 s for the left and right hips respectively. t-tests showed that these mean values were significantly different from zero ($p < 0.05$). Thus the lumbar spine generally moved earlier than the hips during lateral bending of the trunk. But it should be pointed out that there were large variations in the time lag values among the subjects studied, as shown by the large standard deviations in Table 2.

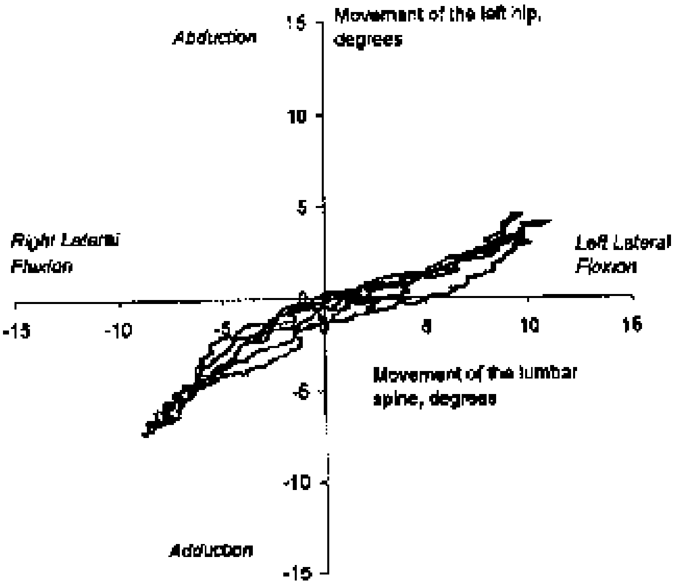

Fig. 3. Angle–angle plot of the movements of the lumbar spine and the left hip in the coronal plane during lateral bending of the trunk (subject 06).

3.4. Twisting

During twisting of the trunk to the left, the lumbar spine rotated to the left, the left hip rotated medially and the right hip rotated laterally (Fig. 1). The pattern was reversed for right twisting. The S/LH and S/RH ratios were less than 1 (Table 1). Unlike lateral bending, trunk twisting was mainly achieved by movements of the hips with small amount of movement of the lumbar spine (Fig. 1). In regard to left twisting, the S/LH ratio was smaller than the S/RH ratio (Fig. 1), indicating that the magnitude of medial rotation of the left hip was larger than that of the lateral rotation of the right hip. This asymmetric movement pattern was reversed for right twisting of the trunk.

Fig. 4 shows the angle–angle plot of the movements of the spine and the left hip for trunk twisting in one of the subjects. The case of the right hip was a mirror image of Fig. 4. About 70% of subjects showed this pattern, and the remaining subjects showed plots with various shapes. In subjects where the plots were almost straight lines as shown in Fig. 4, the relative contribution of the spine and the hips was similar throughout the movements. In all subjects, since the contribution of the lumbar spine was small, the lines were close to the vertical axis.

The results of the cross-correlation analysis show there was a strong degree of association between the spine and hip movements (Table 2). The mean time lags at peak correlation were 0.59 and 0.48 s for left and right twisting respectively (Table 2), and the standard deviations of the time lags were found to be large (Table 2). t-tests showed that the mean time lags were not significantly different from zero

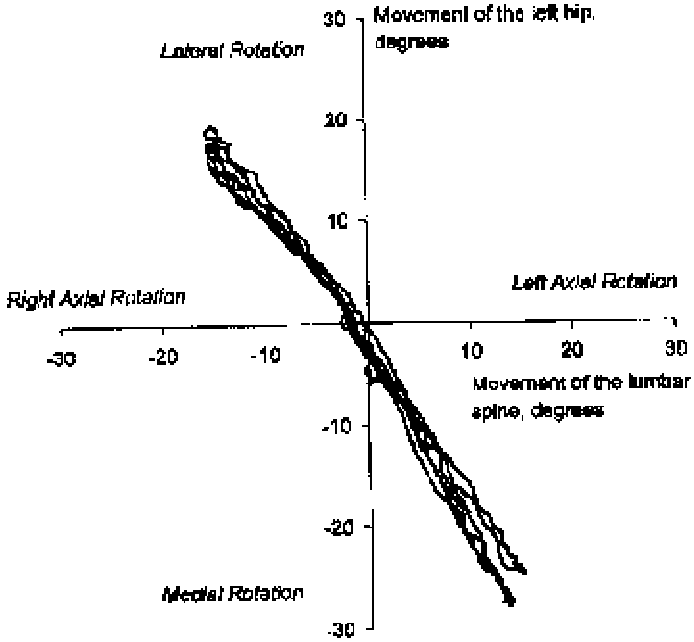

Fig. 4. Angle–angle plot of the movements of the lumbar spine and the left hip in the horizontal plane during twisting of the trunk (subject 05).

($p > 0.05$). It was concluded that the timing of the spine and hip movements was not different for the twisting movement.

4. Discussion

The present study provides useful information on the normal kinematic patterns of the spine and hips. The measurement technique was found to provide repeatable data. The experimental observations of the study were consistent, enabling conclusions to be drawn on the relationship between the movements of the lumbar spine and hips. However, the study was performed in a small group of young healthy subjects, and precautions should be exercised if the results were to be generalised to other populations.

The range of movements of the lumbar spine and hip observed in this study were similar to those reported elsewhere (Dolan & Adams, 1993; Ellison et al., 1990; Esola et al., 1996; Mayer et al., 1984; McClure et al., 1997; Nelson et al., 1995; Paquet et al., 1994; Pearcy & Hindle, 1989; Porter & Wilkinson, 1997). However, it should be noted that hip movements were not measured in some previous studies (Dolan & Adams, 1993; Mayer et al., 1984; Nelson et al., 1995). They measured the absolute movement of the pelvis or femur in space rather than the relative motion between the pelvis and the femur. In these cases, direct comparison of the experimental data is not possible.

This study showed that during forward and backward bending of the trunk, the overall contributions of the lumbar spine and hip were similar, but the spine had a greater contribution to the early stage of the movement. Similar observations were also made in previous research (Esola et al., 1996; McClure et al., 1997; Paquet et al., 1994; Porter & Wilkinson, 1997). However, no previous research had performed cross-correlation analysis of the movement data. In this study, such analysis showed that the lumbar spine and hip had very similar movement patterns and there was no time lag between them.

This study also provided information on the relationship between movements of the spine and hip in the coronal and horizontal planes. This had never been reported in previous studies. In the coronal plane, trunk movement was primarily accomplished by lateral bending of the spine, whereas in the horizontal plane, the hips were the predominate sources of movement. This observation could be due to the fact that the spine is relatively compliant in the coronal plane when compared to the horizontal plane (Markolf, 1972; McGill, Seguin, & Bennett, 1994). In the horizontal plane, the facets of the lumbar spine effectively resist any axial rotation of the vertebrae (Adams & Hutton, 1983). In addition, as shown by the cross-correlation analysis, there was no phase difference in the spine and hip movements in the horizontal plane, but the lumbar spine appears to move earlier than the hip during lateral bending. It should be pointed out the standard deviations of the time lag values were large, suggesting that there were large variations in the timing of the lumbar spine and hip among normal individuals. Therefore, clinically, a small change in the timing of the spine and hip would unlikely indicate a dysfunction of these joints.

The angle–angle plots reveal interesting relationship between the spine and hip in different stages of the movement. Regarding forward and bending of the trunk, the shape of the plot was the same for all the subjects. This indicates that all subjects used the same coordination strategy in completing the movement. The lumbar spine had a great contribution to the movement in the early stage than in the final stage. In regard to lateral bending, the shape of the plot was less consistent, but in most subjects, the relative contributions of the spine and hip did not appear to change throughout the movement. In the coronal plane, there were large variations in the shape of the plots. Different subjects appear to adopt different strategies in accomplishing the movement. However, it should be pointed out that the plot is highly consistent among the various movement cycles for a given subject. Thus each individual uses a specific coordination strategy which does not appear to change in repeated movements.

There is evidence to suggest that back pain could alter the relationship between the movements of the lumbar spine and hip (Esola et al., 1996; Mayer et al., 1984; Paquet et al., 1994; Porter & Wilkinson, 1997), although this had only been studied in the sagittal plane. It is therefore important that clinical examination of back patients should include measurement of the movements of both the spine and hips. Such examination should not only include measurement of the magnitude of the movements but also their timing and temporal relationship. It should be noted that some clinical measurement methods, such as finger-tip-to-floor distance and single inclinometry (Merritt, McLean, Erickson, & Offord, 1986; Rondinelli, Murphy, Esler, Marciano, & Cholmakjian, 1992; Stude, Goertz, & Gallinger, 1994), are rather misleading. These techniques are thought to provide information on the movements of the lumbar spine, but actually measure the total movements of both the spine and the hips. The contribution of the hip to the measurements could not be ignored since this would be very significant as suggested by the results of this study, especially in the sagittal and coronal planes.

Altered movement patterns of the spine and hip may be a potential factor that contributes to the development of low back pain. For instance, Dolan and Adams (1993) showed that changes in spine and hip mobility would alter the bending stresses of the spinal motion segment. Such changes may also alter the loads in the facets and posterior spinal ligaments (Adams & Hutton, 1983). On the other hand, it may also be argued that altered movement patterns of the spine and hip may be the consequence of low back pain. It may be a compensatory response to reduce pain or to protect injured tissues.

Future research should examine the effects of back pain and various spinal disorders on the three-dimensional kinematics of these joints. It should also be directed at the characterisation of the movement strategies in various functional activities, such as walking, running, and climbing stairs. The present study demonstrated that various techniques, such as angle–angle plot and cross-correlation, could be used to provide a thorough analysis of the movement patterns of the spine and hips. These techniques provide further insights into the coordination strategies of our body, and should be utilised in future studies.

5. Conclusion

The present study showed that the lumbar spine and hip had similar contribution to forward and backward bending of the trunk, but the spine had a greater contribution to the early stage of the movement. Lateral bending of the trunk was primarily accomplished by movement of the spine, whereas the hips were the predominate sources of movement for twisting. Regarding the timing of movements in the sagittal and horizontal planes, the movement patterns of the spine and hip were in phase, whereas in the coronal plane, the spine moved earlier than the hips. It is recommended that clinical examination of the back should include kinematic measures of both the lumbar spine and hips. Measurement methods that do not discriminate the movements of the two joints, such as the finger-to-tip method and single inclinometry, could provide misleading information. Further research should be carried out to examine the effects of back pain and various spinal disorders on the movement coordination of the spine and hip during functional activities.

References

Adams, M. A., & Hutton, W. C. (1983). The mechanical function of the lumbar apophyseal joints. *Spine, 8*, 327–330.

An, K. N., Jacobsen, M. C., Berglund, L. J., & Chao, E. Y. (1988). Application of a magnetic tracking device to kinesiologic studies. *Journal of Biomechanics, 21*(7), 613–620

Andersson, G. B. (1981). Epidemiologic aspects on low-back pain in industry. *Spine, 6*(1), 53–60.

Barker, T. M., Kelly, I. G., & Paul, J. P. (1996). Three-dimensional joint co-ordination strategies of the upper limb during functional activities. *Proceedings of the Institution of Mechanical Engineers, 210*, 17–26.

Bergquist-Ullman, M. (1977). Acute low back pain in industry: a controlled prospective study with special reference to therapy and vocational factors. *Acta Orthopaedica Scandinavica Supplement, 170*, 1–117.

Burnett, A. F., Barrett, C. J., Marshall, R. N., Elliott, B. C., & Day, R. E. (1998). Three-dimensional measurement of lumbar spine kinematics for fast bowlers in cricket. *Clinical Biomechanics, 13*, 574–583.

Chase, J. A. (1992). Outpatient management of low back pain. *Orthopaedic Nursing, 11*(1), 11–21.

Cole, G. K., Nigg, B. M., Ronsky, J. L., & Yeadon, M. R. (1993). Applications of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. *Journal of Biomechanical Engineering, 115*(11A), 344–349.

Cox, M. E., Asselin, S., Gracovetsky, S. A., Richards, M. P., Newman, N. M., Karakusevic, V., Zhong, L., & Fogel, J. N. (2000). Relationship between functional evaluation measures and self-assessment in nonacute low back pain. *Spine, 25*(14), 1817–1826.

Dolan, P., & Adams, M. D. (1993). Influence of lumbar and hip mobility on the bending stresses acting on the lumbar spine. *Clinical Biomechanics, 8*, 185–192.

Ellison, J. B., Rose, S. J., & Sahrmann, S. A. (1990). Patterns of hip rotation range of motion: a comparison between healthy subjects and patients with low back pain. *Physical Therapy, 70*, 537–541.

Esola, M. A., McClure, P. W., Fitzgerald, G. K., & Siegler, S. (1996). Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. *Spine, 21*(1), 71–78.

Fairbank, J. C. T., Pynsent, P. B., Poortvliet, J. A. V., & Phillips, H. (1984). Influence of anthropometric factors and joint laxity in the incidence of adolescent back pain. *Spine, 9*, 461–464.

Frymoyer, J. W. (1988). Back pain and sciatica. *New England Journal of Medicine, 318*, 291–300.

Gracovetsky, S., Kary, M., Levy, S., Ben Said, R., Pitchen, I., & Helie, J. (1990). Analysis of spinal and muscular activity during flexion/extension and free lifts. *Spine, 15*, 1333–1339.

Grieve, D. W. (1968). Gait patterns and speed of walking. *Journal of Biomechanical Engineering, 3*, 119–122.

Grood, E. S., & Suntay, W. J. (1983). A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *Journal of Biomechanical Engineering, 105*, 136–144.

Hershler, C., & Milner, M. (1980). Angle–angle diagrams in the assessment of locomotion. *American Journal of Physical Medicine, 59*(3), 109–125.

Indahl, A., Velund, L., & Reikeraas, O. (1995). Good prognosis for low back pain when left untampered. *Spine, 20*(4), 473–477.

Jin, K., Sorock, G. S., Courtney, T., Liang, Y., Yao, Z., Matz, S., & Ge, L. (2000). Risk factors for work-related low back pain in People's Republic of China. *International Journal of Occupational Medicine and Enviornmental Health, 6*(1), 26–33.

Kadaba, M. P., Ramakrishnan, H. K., Wootten, M. E., Gainey, J., Gorton, G., & Cochran, G. V. B. (1989). Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research, 7*, 849–860.

Kendall, M. G. (1976). *Time-series* (2nd ed.). London: Griffin.

Lee, R. Y. W. (2001). Kinematics of rotational mobilization of the lumbar spine. *Clinical Biomechanics, 16*, 481–488.

Li, L., & Caldwell, C. E. (1999). Coefficient of cross-correlation and the time domain correspondence. *Journal of Electromyography and Kinesiology, 9*, 385–389.

Magora, A. (1973). Investigation of the relation between low back pain and occupation. IV. Physical requirements: bending, rotation, reaching and sudden maximal effort. *Scandinavian Journal of Rehabilitation Medicine, 5*(4), 186–190.

Mannion, A., & Troke, M. (1999). A comparison of two motion analysis devices used in the measurement of lumbar spinal mobility. *Clinical Biomechanics, 14*, 612–619.

Markolf, K. L. (1972). Deformation of the thoracolumbar intervertebral joints in response to external loads. *Journal of Bone and Joint Surgery, 54A*, 511–533.

Marras, W. S., Lavender, S. A., Leurgans, S. E., Rajulu, S. L., Allread, W. G., Fathallah, F. A., & Ferguson, S. A. (1993). The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. *Spine, 18*(5), 617–628.

Mayer, T. G., Tencer, A. F., Kristoferson, S., & Mooney, V. (1984). Use of noninvasive techniques for quantification of spinal range of motion in normal subjects and chronic low back dysfunction patients. *Spine, 9*(6), 588–595.

McClure, P. W., Esola, M., Schreier, R., & Siegler, S. (1997). Kinematics analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain. *Spine, 22*(5), 552–558.

McGill, S., Seguin, J., & Bennett, G. (1994). Passive stiffness of the lumbar torso in flexion, extension, lateral bending, and axial rotation. Effect of belt wearing and breath holding. *Spine, 19*(6), 696–704.

Mellin, G. (1986). Chronic low back pain in men 54–63 years of age correlation of physical measurements with the degree of trouble and progress after treatment. *Spine, 11*(5), 421–426.

Mellin, G. (1990). Decreased joint and spinal mobility associated with low back pain in young adults. *Journal of Spinal Disorders, 3*, 238–243.

Merritt, J. L., McLean, T. J., Erickson, R. P., & Offord, K. P. (1986). Measurement of trunk flexibility in normal subjects: reproducibility of three clinical methods. *Mayo Clinic Proceedings, 61*(3), 192–197.

Miller, D. I. (1983). Biomechanical considerations in lower extremity amputee running and sports performance. In *Collected papers on sports biomechanics*. University of Western Australia.

Nelson, J. M., Walmsley, R. P., & Stevenson, J. M. (1995). Relative lumbar and pelvic motion during loaded spinal flexion/extension. *Spine, 20*, 199–204.

Paquet, N., Malouin, F., & Richards, C. L. (1994). Hip-spine movement interaction and muscle activation patterns during sagittal trunk movements in low back pain patients. *Spine, 19*(5), 596–603.

Pearcy, M. J., Gill, J. M., Hindle, R. J., & Johnson, G. R. (1987). Measurement of human back movement in three dimensions by opto-electronic devices. *Clinical Biomechanics, 2*, 199–204.

Pearcy, M. J., & Hindle, R. J. (1989). New method for the non-invasive three-dimensional measurement of human back movement. *Clinical Biomechanics, 4*, 73–79.

Pope, M. H., Andersson, G. B. J., Frymoyer, J. W., & Chaffin, D. B. (1991). *Occupational Low back pain: Assessment, Treatment and Prevention*. St. Louis: Mosby Yearbook.

Porter, J. L., & Wilkinson, A. (1997). Lumbar-hip flexion motion – a comparative study between asymptomic and chronic low back pain in 18 to 36 year-old men. *Spine, 22*(13), 1508–1514.

Rondinelli, R., Murphy, J., Esler, A., Marciano, T., & Cholmakjian, C. (1992). Estimation of normal lumbar flexion with surface inclinometry. A comparison of three methods. *American Journal of Physical Medicine and Rehabilitation, 71*(4), 219–224.

Rose, S. J., Sahrmann, S. A., & Norton, B. T. (1988). Quantitative assessment of lumbar-pelvic rhythm. *Physical Therapy, 68*, 824.

Stubbs, B. A. (1983). Back problems in work and leisure. *Physiotherapy, 68*, 174–176.

Stude, D. E., Goertz, C., & Gallinger, M. (1994). Inter- and intraexaminer reliability of a single, digital inclinometric range of motion measurement technique in the assessment of lumbar range of motion. *Journal of Manipulative and Physiological Therapeutics, 17*(2), 83–87.

Yu, B., Kienbacher, T., Growney, E. S., Johnson, M. E., & An, K. N. (1997). Reproducibility of the kinematics and kinetics of the lower extremity during normal stair-climbing. *Journal of Orthopaedic Research, 15*(3), 348–352.

Appendix III

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Effects of low back pain on the relationship between the movements of the lumbar spine and hip

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Abstract

Previous research had examined the effects of back pain on spinal movements, but information concerning movement coordination between the lumbar spine and hips was limited. The purpose of this study was to examine the effects of back pain and limitation in straight leg raise on the relationship between the movements of the lumbar spine and hip. An electromagnetic tracking system was employed to measure the movements of these joints in asymptomatic subjects ($n = 20$), and back pain subjects with ($n = 24$) and without ($n = 17$) limitation in straight leg raise. Subjects were requested to perform forward, backward and side bending, and twisting of the trunk. Back pain subjects were found to exhibit significant reductions in the magnitude of spine movements in all directions. Back pain was also associated with decrease in the magnitude of hip flexion but not hip movements in other directions. Cross-correlation analysis showed that there were changes in the strength of correlation and the time lag between lumbar spine and hip motions in normal and back pain subjects. In addition, back pain and limitation in straight leg raise were found to cause significant increases in the time required to complete the trunk movements. It was concluded that clinical assessment and treatment planning should take into account of the effects of back pain on the relationship between spine and hip movements.

PsycINFO classification: 2330; 3380
Keywords: Kinematics; Lumbar spine; Hip; Back pain

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1. Introduction

Low back pain is a serious health problem affecting eighty percent of people at some time in their life (Andersson, Svensson, & Oden, 1983; Chase, 1992; Frymoyer, 1988; Indahl, Velund, & Reikeraas, 1995; Pope, 1991; Stubbs, 1982). It affects the mobility of the lumbar spine and adjacent joints (Dolan & Adams, 1993; Ellison, Rose, & Sahrmann, 1990; Fairbank, Pynsent, Van Poortvliet, & Phillips, 1984; Mellin, 1990) leading to functional disabilities (Cox et al., 2000; Mayer, Tencer, Kristoferson, & Mooney, 1984). It is clinically important to increase our understanding of the effects of back pain on the relationship between the movements of the lumbar spine and hip in the three anatomical planes. This would provide insight into the motor functions of back patients, in particular, their lumbar spine–hip coordination strategies, and would help develop rehabilitation programmes for restoring their motor functions.

Previous kinematic studies of the relationship between the lumbar spine and hip movements were mostly limited to sagittal plane (Adams & Hutton, 1983). It was shown that during the early stage of forward bending, the magnitude of movement of the spine was greater than that of the hip, but the relative contribution of the spine was reduced in the final stage of forward bending (Esola, McClure, Fitzgerald, & Siegler, 1996; Mayer et al., 1984; Paquet, Malouin, & Richards, 1994; Rose, Sahrmann, & Norton, 1988). Lee and Wong (2002) examined the correlation between the lumbar spine and hip movements in the other anatomical planes. They found that side bending of the trunk was mainly achieved by lateral flexion of the lumbar spine with adduction of the ipsilateral hip and abduction of the contralateral hip. Twisting of the trunk was found to be mainly achieved by hip rotations with small amount of contribution from the spine.

The effects of back pain on the relationship between the movements of the lumbar spine and hip were inconclusive. Some research studies (Mayer et al., 1984; Paquet et al., 1994) showed that the contribution of the lumbar spine to forward bending was reduced in subjects with low back pain. However, the studies of Porter and Wilkinson (1997) and Esola et al. (1996) found that the contribution of the lumbar spine was increased in back pain patients and in asymptomatic subjects with a past history of back pain. The differences in the results of previous investigations could be due to the differences in the clinical history and characteristics of the subjects being studied. One limitation of these previous studies was that they only examined movements in the sagittal plane. Numerous studies (Andersson, 1981; Jin et al., 2000; Marras et al., 1993) suggested that back pain is associated with side bending, twisting and various asymmetrical movements of the trunk. There is currently no information about the effects of back pain on the correlation between the movements of the lumbar spine and hips in frontal and horizontal planes.

The radiographic study of Pearcy, Portek, and Shepherd (1985) showed that patients with limited straight leg raise (SLR) exhibited restricted lumbar spine movements. Gajdosik, Albert, and Mitman (1994) also demonstrated that hamstring tightness was associated with decrease in lumbar spine flexion, although they did not examine the movements in the other anatomical planes. Gocken and

Hof (1994) observed that patients with limitation in SLR showed earlier onset of electromyographic activity of the hamstring muscles during the SLR procedure. Hall, Zusman, and Elvey (1998) made similar observation and suggested that the change in muscular response was a defense reaction to protect the inflamed nerve roots. The above research work clearly shows that limitation in SLR is associated with changes in the motor functions of the lumbar spine and hip. It would be clinically useful to further explore these changes, and examine how limitation in SLR affects the coordination between the movements of the lumbar spine and hip.

The purpose of the present study was to examine the effects of back pain and limitation in SLR on the relationship between the movements of the lumbar spine and hips in the three anatomical planes.

2. Materials and methods

2.1. Subjects

Sixty-one subjects were recruited from local university and outpatient physiotherapy clinic of local hospital. They were divided into three groups: Group 1 – twenty normal subjects who were in good health with no history of back pain or leg pain that might be attributed to the back within the last 12 months. Group 2 – twenty-four subjects with current low back pain (i.e. pain over the L1-sacrum region without any radiation to areas distal to the gluteal crease) but no SLR limitation. Twelve of these subjects had pain over the left side of the back and the remaining subjects over the right side. Group 3 – seventeen subjects with back pain and restricted SLR (i.e. SLR with a pain free range of less than 55°). Ten of group 3 subjects had pain over the left side of the back accompanied by limited SLR of the left leg, and the remaining subjects had pain and limited SLR on the right side. There were no significant differences among the three groups of subjects regarding age, weight and height ($p > 0.05$) (Table 1).

Subjects were excluded if they had inflammatory joint disease, fracture/dislocation of the vertebral column, history of spinal surgery, neurological signs or unable to perform trunk movements due to unbearable pain.

Ethics approval for this study was obtained from the Departmental Research Committee of the Hong Kong Polytechnic University. Subjects were informed about

Table 1
Personal and clinical characteristics of the study subjects

Group	Number of subjects	Age	Height (cm)	Weight (kg)	PAS	RMQ
1	20	42 (8)	170 (6)	71.4 (10.5)	0	0
2	24	41 (11)	172 (4)	68.6 (5.5)	6 (2)	10 (4)
3	17	34 (10)	174 (4)	71.4 (4.5)	6 (2)	12 (4)

Group mean values (SD) are presented in this table.
PAS = pain analog scale, RMQ = Roland–Morris questionnaire score.

the experimental procedure and any potential risks prior to the attainment of written consent.

2.2. Instrumentation

The 3SPACE Fastrak (Polhemus Inc., Colchester, VT 05446, USA) was used to measure movements of the lumbar spine and hips. The experimental set-up of the system have been described in a previous study (Lee, 2001; Lee & Wong, 2002). It had a source that generated a low-frequency magnetic field which was detected by the sensors. The source was placed in a fixed position close to the subject (within 0.7 m). Two sensors of the system were employed to measure the movements of the lumbar spine – one sensor was placed over the L1 spinous process and the second sensor over the sacrum. Two other sensors were used to measure the movements of the hips by placing them over the posterior aspect of the left and right thighs. Each sensor was attached to a small, mouldable plastic plate with plastic screws. A Velcro band was threaded through the plate and tightly wrapped around the subject's trunk or leg so as to minimise the movement between the sensor and the underlying skin. The cables of the sensors were attached to the skin on the side of the trunk so that they did not move the sensor erroneously during the movement. Initial testing showed that the above arrangement provided the most secure sensor attachments.

The Fastrak had an electronic unit that calculated the three-dimensional positions and orientations of the sensors relative to the source. The unit was linked to a personal computer via an RS232C serial interface. Specifically developed custom software was used to control the Fastrak operation, data acquisition and display the results in real time. The software developed in this study was able to perform fast serial communication at 115.2 kB and allowing a data update rate of 120 Hz. As four sensors were used in this experiment, the sampling rate was 30 Hz per sensor.

The Fastrak output comprised the 3×3 matrices of direction cosines that described the orientations of the sensors relative to the source. Lumbar spine movements were derived from the relative orientation between the L1 and sacral sensors, and hip movements from that between the thigh and sacral sensors. The method of computation was based on the mathematical techniques proposed by earlier authors (Cole, Nigg, Ronsky, & Yeadon, 1993; Grood & Suntay, 1983; Lee, 2001; Lee & Wong, 2002; Pearcy, Gill, Whittle, & Johnson, 1987). Movements in the coronal and horizontal planes were classified according to the side where pain was felt. This was not applicable, however, for asymptomatic subjects in Group 1, and in this case, movements of the two sides of the body were pooled together. This was acceptable because t-tests revealed that there were no significant differences in the magnitude between the two sides ($p > 0.05$). The overall means of the movements were used for comparison with the magnitude of movements of the painful subjects.

2.3. Procedure

Routine clinical examination of the subjects was conducted by a qualified physiotherapist prior to data collection. This included history taking, clinical examination, palpation, passive SLR test, radiographic examination and screening tests to exclude subjects with pathologies that would prevent them from participating in this study. Subjects were asked to perform warm up exercise which included forward, backward and side bending, and twisting of the trunk. Sensors were then attached to the subjects. They were requested to stand upright in their most comfortable posture with feet shoulder-width apart and palms facing inwards. The positions of the lumbar spine and hips in this posture were recorded by the Fastrak and taken as the zero reference positions. The movements of the lumbar spine and hips were calculated with respect to these reference positions.

Subjects were requested to perform three continuous cycles of each of the following movements of the trunk: (1) forward and then backward bending, (2) side bending towards the left and right, and (3) twisting towards the left and right. The three movement trials were tested in a random order. Each trial was performed over a 30 s period at a speed that was most comfortable for the subjects. They were instructed to move to the limit of the available range, or to the point where the pain or symptoms (if any) became intolerable. There was a rest period of 5 min after each movement trial. In order to examine the repeatability of the movement data, the above experimental procedure was repeated three times.

2.4. Data analysis

The movements of the lumbar spine and hips were plotted again time. The duration of the three cycles of trunk movement was averaged to determine the mean duration of one complete movement cycle. This allowed the velocity of the trunk to be evaluated. The angle-time curves obtained in the various movement cycles were then normalised with respect to time so that each movement cycle corresponded to a uniform length of 50 sample points (representing 100% of the movement cycle), each interval represent 2% of the cycle. The coefficient of multiple determination (Kadaba et al., 1989; Yu, Kienbacher, Growney, Johnson, & An, 1997) was calculated to determine the degree of similarity of the movement-time curves obtained in the three trials. The maximum magnitudes of the movements of the lumbar spine and hips movements were determined. The ratios of the magnitude of the movement of the lumbar spine to those of the hips were computed for each movement trial.

Cross-correlation (Kendall, 1993; Li & Caldwell, 1999) between the movements of the lumbar spine and hips was calculated over the three consecutive movement cycles of the trunk. The movement of the lumbar spine was used as a reference for establishing the correlation. The analysis compared the time histories of the kinematics of the lumbar spine and hip. The peak correlation coefficient would show the strength of correlation of the movements of the spine and hip. The phase relationship between the spine and hip movements was examined by determining the time lag at which the absolute value of the correlation coefficient was maximal. A positive time lag implied that the lumbar spine moved earlier than the hip in the movement cycle.

One-way analysis of variance (ANOVA) was performed using the software SPSS Version 10.0.0 (SPSS Inc., Illinois 60606) to compare the mean magnitude of the movements of the spine and hip, the mean peak correlation coefficients and the mean time lags among the three groups of subjects. Post-hoc analysis was carried out using the Tukey procedure if any significant difference was revealed. For each group of subjects, t-tests were also carried out to determine if the mean time lags were significantly different from zero. Statistical significance was accepted at the 5% level for all tests.

3. Results

3.1. Repeatability of data

The mean coefficient of multiple determination for measuring the various anatomical movements was 0.98 ± 0.01, suggesting that the movement-time curves were highly similar in repeated measurements. The mean standard deviation of the maximum movements among the three movement trials was found to be $2.1 \pm 1.0°$. The measurement system was considered to be able provide sufficiently repeatable data for the purpose of this study.

3.2. Forward and backward bending

During forward bending of the trunk, the mean lumbar spine flexion to hip flexion ratios were close to 1 (Table 2). This suggests that the contributions of the lumbar spine and hips were approximately equal. It was shown that back pain and limitation in SLR were associated with significant decreases in the ranges of spine and hip flexion ($p < 0.05$). The decrease in hip flexion was significantly larger in subjects with limited SLR than in subjects with back pain only. The ratio of lumbar spine to hip flexion was not significantly affected in subjects of groups 2 and 3 ($p > 0.05$) as back pain and limitation in SLR produced decreases in the ranges of movement in both the lumbar spine and hips.

During backward bending of the trunk, the ratio of lumbar spine to hip extension was about 1.4. Back pain and limitation in SLR were associated with decreases in the ranges of lumbar spine and hip extension, but such decrease was found to be statistically significant only in subjects with limitation in SLR ($p < 0.05$).

The mean peak cross-correlation coefficients for forward and backward bending were high (0.89–0.96). The shapes of the movement-time curves of the lumbar spine and hips were thus very similar. The time lags at peak correlation were negligible, and t-tests showed that the values were not significantly different from zero ($p > 0.05$). This suggests that there was no phase difference between the movements of the lumbar spine and hips during forward and backward bending. There were no significant differences in the correlation coefficient and time lag values among the three groups of subjects ($p > 0.05$).

In asymptomatic subjects, the mean time required to complete one cycle of trunk forward and backward bending was found to be 4.4 s. For subjects with back pain and limitation in SLR, the amount of time required was found to be more than doubled ($p < 0.05$).

Table 2
Movements of the lumbar spine and hips during forward and backward bending of the trunk

Group	1	2	3
Forward bending			
Mean Lx flexion ROM (°)[a,b]	61.9 (5.9)	33.2 (8.7)	29.8 (11.9)
Mean PH flexion ROM (°)[a,b,c]	72.1 (15.9)[d]	52.4 (19.2)	39.5 (13.5)
Mean NPH flexion ROM (°)[a,b,c]		51.9 (18.9)	40.4 (13.9)
Ratio of Lx/PH movements[e]	0.91 (0.24)	0.70 (0.31)	0.85 (0.52)
Ratio of Lx/NPH movements[e]		0.70 (0.30)	0.84 (0.53)
Backward bending			
Mean Lx extension ROM (°)[e]	15.5 (7.4)	14.9 (7.7)	12.7 (5.9)
Mean PH extension ROM (°)[b]	15.7 (6.3)[d]	13.5 (4.8)	11.1 (5.7)
Mean NPH extension ROM (°)[b]		13.7 (5.7)	11.1 (6.4)
Ratio of Lx/PH movements[e]	1.36 (1.45)	1.43 (1.52)	1.12 (0.96)
Ratio of Lx/NPH movements[e]		1.37 (1.10)	1.66 (1.43)
Cross-correlation analysis			
Mean peak correlation coefficient – Lx and PH[e]	0.96 (0.05)	0.93 (0.1)	0.89 (0.13)
Mean peak correlation coefficient – Lx and NPH[e]	0.96 (0.05)	0.93 (0.09)	0.89 (0.13)
Mean time lag between Lx and PH (s)[e]	−0.02 (0.07)	−0.05 (0.08)	−0.03 (0.1)
Mean time lag between Lx and NPH (s)[e]	−0.05 (0.08)	−0.04 (0.08)	0.03 (0.1)
Mean duration of one cycle of forward and backward bending (s)[a,b]	4.44 (0.9)	8.30 (2.39)	9.33 (2.53)

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side; ROM = range of movement.
Group mean values (SEM) are presented in this table.
[a] Significant difference between groups 1 and 2 ($p < 0.05$).
[b] Significant difference between groups 1 and 3 ($p < 0.05$).
[c] Significant difference between groups 2 and 3 ($p < 0.05$).
[d] For non-painful subjects in Group 1, movements of the two sides of the body were pooled together. The overall means of the movements were used for comparison with movements in the painful subjects in groups 2 and 3.
[e] No significant difference among the three groups ($p > 0.05$).

3.3. Side bending

During side-bending of the trunk, lateral flexion of the lumbar spine was found to be accompanied by abduction of the ipsilateral hip and adduction of the contralateral hip (Table 3). The magnitude of the lumbar spine movement was more than twice of those of the hips, as shown by the spine to hip movement ratios. Subjects with back pain and limitation in SLR showed significant reduction in the range of lateral flexion of the lumbar spine ($p < 0.05$). But there were no significant differences in the ranges of hip abduction and adduction among the three groups of subjects ($p > 0.05$). Since back pain affected the movements of the lumbar spine only but not those of the hips, the ratios of spine to hip movements were significantly reduced in subjects of groups 2 and 3.

Table 3
Movements of the lumbar spine and hips during side bending of the trunk

Group	1	2	3
Lateral bending towards painful side			
Mean Lx side flexion ROM (°)[a,b]	23.7 (5.4)[d]	11.8 (4.3)	12.8 (4.7)
Mean PH abduction ROM (°)[e]	11.9 (6.2)[d]	11.6 (5.4)	10.1 (5.0)
Mean NPH adduction ROM (°)[e]	11.5 (7.2)[d]	9.3 (5.1)	8.4 (5.2)
Ratio of Lx/PH movements[a,b]	2.36 (0.78)[d]	1.39 (1.23)	1.52 (0.84)
Ratio of Lx/NPH movements[a,b]	2.67 (1.40)[d]	1.97 (1.82)	2.28 (1.82)
Lateral bending towards non-painful side			
Mean Lx side flexion ROM (°)[a,b]	23.7 (5.4)[d]	11.2 (3.7)	12.5 (4.6)
Mean PH adduction ROM (°)[e]	11.5 (7.2)[d]	9.0 (6.2)	6.8 (5.8)
Mean NPH abduction ROM (°)[e]	11.9 (6.2)[d]	11.3 (6.7)	8.4 (5.9)
Ratio of Lx/PH movements[a,b]	2.67 (1.40)[d]	1.86 (1.36)	2.58 (1.71)
Ratio of Lx/NPH movements[a,b]	2.36 (0.78)[d]	1.58 (1.41)	1.68 (0.94)
Cross-correlation analysis			
Mean peak correlation coefficient – Lx and PH[e]	0.84 (0.18)	0.76 (0.19)	0.77 (0.21)
Mean peak correlation coefficient – Lx and NPH[e]	0.84 (0.18)	0.78 (0.18)	0.80 (0.21)
Mean time lag between Lx and PH (s)[e]	0.07 (0.26)	−0.56 (2.54)	0.28 (2.40)
Mean time lag between Lx and NPH (s)[e]	0.07 (0.26)	−0.06 (2.23)	0.30 (0.75)
Mean duration of one cycle of side bending towards the left and right sides (s)[a,b,c]	3.66 (0.71)	6.36 (1.53)	7.29 (1.51)

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side; ROM = range of movement.
Group mean values (SEM) are presented in this table.
[a]Significant difference between groups 1 and 2 ($p < 0.05$).
[b]Significant difference between groups 1 and 3 ($p < 0.05$).
[c]Significant difference between groups 2 and 3 ($p < 0.05$).
[d]For non-painful subjects in Group 1, movements of the two sides of the body were pooled together. The overall means of the movements were used for comparison with movements in the painful subjects in groups 2 and 3.
[e]No significant difference among the three groups ($p > 0.05$).

The mean peak cross-correlation coefficient ranged from 0.76 to 0.84, indicating that the degree of association between the lumbar spine and hip movements was high. In regard to normal subjects, *t*-tests revealed that the mean time lags at peak correlation were not significantly different from zero ($p > 0.05$). Thus the lumbar spine and hips moved simultaneously during lateral bending of the trunk. In group 2 subjects, there was a generally tendency that the movement of the hip on the painful side preceded that of the lumbar spine. This was reflected by the negative time lag values observed in these subjects. However, the mean time lag was generally positive for subjects in group 3, indicating that the lumbar spine moved earlier than the hip. Subjects in groups 2 and 3 exhibited large variations in how they modified the spine and hip movement coordination. The standard deviations of the mean time lag in these patients were large, and statistically, the changes in the time lag values were found to be insignificant ($p > 0.05$).

Subjects with back pain and limitation in SLR required significantly more time to complete one cycle of side bending when compared to asymptomatic subjects ($p < 0.05$).

3.4. Twisting

During twisting of the trunk, the lumbar spine rotated to the same side, the ipsilateral hip rotated medially and the contralateral hip rotated laterally (Table 4). The ratios of lumbar spine to hip movements were less than 1, indicating that the contribution of the spine was smaller than that of the hips in accomplishing the movement. Subjects with back pain and limitation in SLR exhibited significant decreases in the range of lumbar rotation ($p < 0.05$). This led to significant decreases in the ratios of lumbar spine to hip movements ($p < 0.05$).

Table 4
Movements of the lumbar spine and hips during twisting of the trunk

Group	1	2	3
Twisting towards painful side			
Mean Lx axial rotation ROM (°)[a,b]	12.2 (4.6)[d]	7.3 (3.7)	9.0 (3.4)
Mean PH medial rotation ROM (°)[e]	20.5 (4.4)[d]	22.3 (5.9)	18.4 (6.5)
Mean NPH lateral rotation ROM (°)[e]	17.5 (4.9)[d]	20.8 (5.3)	18.9 (6.6)
Ratio of Lx/PH movements[a,b]	0.64 (0.29)[d]	0.36 (0.17)	0.58 (0.39)
Ratio of Lx/NPH movements[a,b]	0.85 (0.40)[d]	0.38 (0.19)	0.56 (0.29)
Twisting towards non-painful side			
Mean Lx axial rotation ROM (°)[a,b]	12.2 (4.6)[d]	6.7 (2.9)	8.0 (3.1)
Mean PH medial rotation ROM (°)[e]	17.5 (4.9)[d]	17.3 (3.1)	20.8 (4.8)
Mean NPH lateral rotation ROM (°)[e]	20.5 (4.4)[d]	19.7 (4.9)	19.2 (5.7)
Ratio of Lx/PH movements[a,b]	0.85 (0.40)[d]	0.41 (0.21)	0.38 (0.16)
Ratio of Lx/NPH movements[a,b]	0.64 (0.29)[d]	0.37 (0.21)	0.48 (0.23)
Cross-correlation analysis			
Mean peak correlation coefficient – Lx and PH[e]	0.87 (0.08)	0.71 (0.27)	0.85 (0.12)
Mean peak correlation coefficient – Lx and NPH[e]	0.87 (0.06)	0.73 (0.19)	0.83 (0.14)
Mean time lag between Lx and PH (s)[e]	−0.06 (0.11)	−0.55 (1.52)	0.15 (0.80)
Mean time lag between Lx and NPH (s)[e]	−0.06 (0.11)	−0.60 (0.18)	0.15 (0.81)
Mean duration of one cycle of twisting towards the left and right sides (s)[a,b]	3.51 (0.63)	5.92 (1.65)	6.23 (1.53)

Lx = lumbar spine; PH = hip on the painful side; NPH = hip on the non-painful side; ROM = range of movement.
Group mean values (SEM) are presented in this table.
[a]Significant difference between groups 1 and 2 ($p < 0.05$).
[b]Significant difference between groups 1 and 3 ($p < 0.05$).
[c]Significant difference between groups 2 and 3 ($p < 0.05$).
[d]For non-painful subjects in Group 1, movements of the two sides of the body were pooled together. The overall means of the movements were used for comparison with movements in the painful subjects in groups 2 and 3.
[e]No significant difference among the three groups ($p > 0.05$).

The results of the cross-correlation analysis show there was a strong degree of association between the lumbar spine and hip movements. Subjects in group 2 exhibited significant decrease in the peak correlation coefficient ($p < 0.03$), indicating that the spine and hips of these subjects moved in a less cohesive manner. The mean time lags at peak correlation were not significantly different from zero for subjects in group 1 ($p > 0.05$). The time lag values were generally negative for subjects in group 2 and positive for subjects in group 3. However, due to the large standard deviations, ANOVA did not show that the differences in the mean time lag values among the three groups of subjects were statistically significant ($p > 0.05$).

Significant increases in the time required to complete one cycle of trunk twisting were observed in subjects of groups 2 and 3 ($p < 0.05$).

4. Discussion

This study provides valuable information on the movement characteristics of the lumbar spine and hips in subjects with back pain and limited SLR. The measurement technique was found to provide highly repeatable data and the experimental observations were consistent. The technique developed in this study may be used in routine clinical assessment to help establish physical diagnosis and evaluate treatment effectiveness of low back pain patients.

Our patient samples comprised two groups of male subjects with subacute back pain (subjects with current symptoms with more than 2 weeks and less than 3 months). There were no significant differences between the two samples regarding their severity of pain and level of disability as measured by the Roland–Morris questionnaire. Their age was also not significantly different from that of the asymptomatic subjects. The control of the above potential confounding variables enables conclusions to be drawn from the findings of this study.

This study demonstrated that back pain was associated with significant decreases in the ranges of movements of the lumbar spine in all directions. This was in general agreement with the findings of previous studies (Paquet et al., 1994; Pearcy et al., 1985; Porter & Wilkinson, 1997). Back pain was also found to be associated with decrease in the range of movement of hip flexion during forward bending of the trunk, but it did not appear to affect the hips in the other movement directions. Only the study of Esola et al. (1996) had examined the association between back pain and hip flexion. Their results could not be compared with ours since the clinical characteristics of their subjects were different from ours. Esola et al. recruited subjects with previous history of back pain but no current symptoms. However, our subjects were experiencing pain at the time this study was conducted.

It was interesting to note that back pain was associated with changes in hip flexion movement only. This may suggest that stretching the posterior hip tissues may elicit pain but not tissues in the other areas of the hips. Another suggestion of this finding is that back pain is associated with changes in the mechanical characteristics of the posterior hip tissues or changes in the level of activity of the posterior hip muscles such as the hamstrings. It should be pointed out that subjects with limited SLR exhibited further reduction in hip flexion when compared with subjects with back pain only. This further suggests that the posterior hip tissues were involved, although the mechanisms of actions remain unclear. Previous researchers (Fisk, 1975; Scham & Taylor, 1971; Takata & Takahashi, 1994) suggested that there could be increase in the tension of neural tissues (sciatic nerve) in the posterior area of the hip. It had also been shown that back pain was associated with increase in stiffness of the hamstring muscles (Halbertsma, Goeken, Hof, Groothoff, & Eisma, 2001; Li, McClure, & Pratt, 1996). Future research should examine how back pain affects the posterior hip tissues. Such knowledge is clinically important as it could be used to design exercise program for restoring the mechanical characteristics of the posterior hip tissues and subsequently the movements of the hips.

This study showed that during forward and backward bending of the trunk, the relative contributions of the lumbar spine and hip were similar. Side bending of the trunk movement was primarily accomplished by lateral bending of the spine with some contributions from the hips. Regarding trunk twisting, the hips were the predominate sources of movement. These findings are related to the fact that the lumbar spine is relatively compliant in the coronal plane when compared to the horizontal plane (Markolf, 1972; McGill, Seguin, & Bennett, 1994). In the horizontal plane, the facets of the lumbar spine effectively resist any axial rotation of the vertebrae (Adams & Hutton, 1983).

Back pain and limitation in SLR were found to affect the relative contributions of the lumbar spine and hips in accomplishing side bending and twisting of the trunk. The lumbar spine and hips were also found to be less cohesive in performing these trunk movements as indicated by the decreases in the peak correlation coefficients. The strength of correlation was most markedly affected in the twisting movement. The above findings clearly indicated the motor coordination of the lumbar spine and hip was affected in back pain subjects, especially in the horizontal plane.

Regarding forward and backward bending of the trunk, the lumbar spine and hips were still able to move simultaneously despite the presence of back pain and limitation in SLR. However, the time lag between the lumbar spine and hip movements appeared to be altered by pain and limited SLR for lateral bending and twisting. The time lag was generally negative for subjects with back pain only. In these patients, the lumbar spine moved later than the hips, probably because of the reluctance to move the painful back. On the other hand, in patients with limitation in straight leg raise, when movements of the hip elicited pain, the lumbar spine appeared to move earlier than the hip. However, it should be pointed out that the changes in time lag were found to be statistically insignificant in this study due to the large standard deviations. Further research would be required to clarify the effects of back pain and limitation in SLR on the timing of the movements of the lumbar spine and hips.

In this study, it was also shown that back pain subjects required significantly more time to perform the trunk movements. This observation was in agreement with those of previous work (Malchaire & Masset, 1995; Marras & Wongsam, 1986) which also reported significant decreases in trunk velocities in back pain patients. It had been shown that the decreases in velocities could seriously affect the functional activities and the quality of life of patients (Marras, Lewis, Ferguson, & Parnianpour, 2000). The present study did not examine the effects of trunk velocity on the movement patterns of the lumbar spine and hip and their coordination strategies, and this is an important area for future research.

The present study clearly revealed an association between back pain and altered kinematic characteristics of the lumbar spine and hips. But it is as yet unclear whether the altered kinematic characteristics are the causes of low back pain. For instance, Dolan and Adams (1993) showed that changes in lumbar spine and hip mobility would alter the bending stresses of the spinal motion segment. Such changes may also alter the loads in the facets and posterior spinal ligaments (Adams & Hutton, 1983). On the other hand, it is also possible that the altered kinematic characteristics of the lumbar spine and hip are a consequence of low back pain. It may be a compensatory response to reduce pain or to protect injured tissues.

Clinically, it is important to evaluate the kinematic characteristics of both the lumbar spine and hip for back pain patients. Assessment of lumbar spine motions alone will not be able to reveal how joint coordination is affected by back pain and the potential implications on functional performance. Assessment of hip motions will allow the clinicians to decide whether there are changes in the mechanical properties of posterior hip tissues and whether an exercise programme may be required to modify these properties.

5. Conclusion

Low back pain was found to be associated with significant decreases in the ranges of movements of the lumbar spine in all directions. Subjects with limited SLR exhibited greater decreases in lumbar spine movements when compared with subjects with back pain only. Back pain was also found to be associated with decreases in the range of hip flexion during forward bending of the trunk, but it did not appear to affect the movements of hips in other directions. The results of this study suggest that back pain patients modify their joint coordination strategies in accomplishing trunk movements and take a longer time to complete the movements. These may seriously affect the functional activities and the quality of life of the patients. Future studies should look into the mechanisms of how back pain affects lumbar spine and hip movements. This may involve inverse dynamic analysis of the loads acting at the spine and hips. Another important area for future research is to examine the effects of trunk velocity on the movement patterns of the lumbar spine and hip and their coordination strategies.

References

Adams, M. A., & Hutton, W. C. (1983). The mechanical function of the lumbar apophyseal joints. *Spine, 8*, 327–330.

Andersson, G. B. (1981). Epidemiologic aspects on low-back pain in industry. *Spine, 6*, 53–60.

Andersson, G. B., Svensson, H. O., & Oden, A. (1983). The intensity of work recovery in low back pain. *Spine, 8*, 880–884.

Chase, J. A. (1992). Outpatient management of low back pain. *Orthopaedic Nursing, 11*, 11–21.

Cole, G. K., Nigg, B. M., Ronsky, J. L., & Yeadon, M. R. (1993). Application of the joint coordinate system to three-dimensional joint attitude and movement representation: A standardization proposal. *Journal of Biomechanical Engineering, 115*, 344–349.

Cox, M. E., Asselin, S., Gracovetsky, S. A., Richards, M. P., Newman, N. M., Karakusevic, V., et al (2000). Relationship between functional evaluation measures and self-assessment in nonacute low back pain. *Spine, 25*, 1817–1826.

Dolan, P., & Adams, M. D. (1993). Influence of lumbar and hip mobility on the bending stresses acting on the lumbar spine. *Clinical Biomechanics, 8*, 185–192.

Ellison, J. B., Rose, S. J., & Sahrmann, S. A. (1990). Patterns of hip rotation range of motion: A comparison between healthy subjects and patients with low back pain. *Physical Therapy, 70*, 537–541.

Esola, M. A., McClure, P. W., Fitzgerald, G. K., & Siegler, S. (1996). Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. *Spine, 21*, 71–78.

Fairbank, J. C., Pynsent, P. B., Van Poortvliet, J. A., & Phillips, H. (1984). Influence of anthropometric factors and joint laxity in the incidence of adolescent back pain. *Spine, 9*, 461–464.

Fisk, J. W. (1975). The straight leg raising test: Its relevance to possible disc pathology. *The New Zealand Medical Journal, 81*, 557–560.

Frymoyer, J. W. (1988). Back pain and sciatica. *The New England Journal of Medicine, 318*, 291–300.

Gajdosik, R. L., Albert, C. R., & Mitman, J. J. (1994). Influence of hamstring length on the standing position and flexion range of motion of the pelvic angle, lumbar angle, and thoracic angle. *Journal of Orthopaedic and Sports Physical Therapy, 20*, 213–219.

Goeken, L. N., & Hof, A. L. (1994). Instrumental straight-leg raising: Results in patients. *Archives of Physical Medicine and Rehabilitation, 75*, 470–477.

Grood, E. S., & Suntay, W. J. (1983). A joint coordinate system for the clinical description of three-dimensional motions: Application to the knee. *Journal Biomechanical Engineering, 105*, 136–144.

Halbertsma, J. P., Goeken, L. N., Hof, A. L., Groothoff, J. W., & Eisma, W. H. (2001). Extensibility and stiffness of the hamstrings in patients with nonspecific low back pain. *Archives of Physical Medicine and Rehabilitation, 82*, 232–238.

Hall, T., Zusman, M., & Elvey, R. (1998). Adverse mechanical tension in the nervous system. Analysis of straight leg raise. *Manual Therapy, 3*, 140–146.

Indahl, A., Velund, L., & Reikeraas, O. (1995). Good prognosis for low back pain when left untampered. A randomized clinical trial. *Spine, 20*, 473–477.

Jin, K., Sorock, G. S., Courtney, T., Liang, Y., Yao, Z., Matz, S., et al. (2000). Risk factors for work-related low back pain in the People's Republic of China. *International Journal of Occupational and Environmental Health, 6*, 26–33.

Kadaba, M. P., Ramakrishnan, H. K., Wootten, M. E., Gainey, J., Gorton, G., & Cochran, G. V. (1989). Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research, 7*, 849–860.

Kendall, M. G. (1993). *Time-series* (3rd ed.). Kent: E. Arnold.

Lee, R. Y. (2001). Kinematics of rotational mobilisation of the lumbar spine. *Clinical Biomechanics, 16*, 481–488.

Lee, R. Y., & Wong, T. K. (2002). Relationship between the movements of the lumbar spine and hip. *Human Movement Science, 21*, 481–494.

Li, L., & Caldwell, G. E. (1999). Coefficient of cross correlation and the time domain correspondence. *Journal of Electromyography and Kinesiology, 9*, 385–389.

Li, Y., McClure, P. W., & Pratt, N. (1996). The effect of hamstring muscle stretching on standing posture and on lumbar and hip motions during forward bending. *Physical Therapy, 76*, 836–845, discussion 845–839.

Malchaire, J. B., & Masset, D. F. (1995). Isometric and dynamic performances of the trunk and associated factors. *Spine, 20*, 1649–1656.

Markolf, K. L. (1972). Deformation of the thoracolumbar intervertebral joints in response to external loads: A biomechanical study using autopsy material. *Journal of Bone and Joint Surgery: American volume, 54*, 511–533.

Marras, W. S., Lavender, S. A., Leurgans, S. E., Rajulu, S. L., Allread, W. G., Fathallah, F. A., et al. (1993). The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury. *Spine, 18*, 617–628.

Marras, W. S., Lewis, K. E., Ferguson, S. A., & Parnianpour, M. (2000). Impairment magnification during dynamic trunk motions. *Spine, 25*, 587–595.

Marras, W. S., & Wongsam, P. E. (1986). Flexibility and velocity of the normal and impaired lumbar spine. *Archives of Physical Medicine Rehabilitation, 67*, 213–217.

Mayer, T. G., Tencer, A. F., Kristoferson, S., & Mooney, V. (1984). Use of noninvasive techniques for quantification of spinal range-of-motion in normal subjects and chronic low-back dysfunction patients. *Spine, 9*, 588–595.

McGill, S., Seguin, J., & Bennett, G. (1994). Passive stiffness of the lumbar torso in flexion, extension, lateral bending, and axial rotation. Effect of belt wearing and breath holding. *Spine, 19*, 696–704.

Mellin, G. (1990). Decreased joint and spinal mobility associated with low back pain in young adults. *Journal of Spinal Disorders, 3*, 238–243.

Paquet, N., Malouin, F., & Richards, C. L. (1994). Hip-spine movement interaction and muscle activation patterns during sagittal trunk movements in low back pain patients. *Spine, 19*, 596–603.

Pearcy, M., Portek, I., & Shepherd, J. (1985). The effect of low-back pain on lumbar spinal movements measured by three-dimensional X-ray analysis. *Spine, 10*, 150–153.

Pearcy, M. J., Gill, J. M., Whittle, M. W., & Johnson, G. R. (1987). Dynamic back movement measured using a three-dimensional television system. *Journal of Biomechanics, 20*, 943–949.

Pope, M. H. (1991). *Occupational low back pain: Assessment, treatment, and prevention*. St. Louis: Mosby Year Book.

Porter, J. L., & Wilkinson, A. (1997). Lumbar-hip flexion motion. A comparative study between asymptomatic and chronic low back pain in 18- to 36-year-old men. *Spine, 22*, 1508–1513.

Rose, S. J., Sahrmann, S. A., & Norton, B. T. (1988). Quantitative assessment of lumbar-pelvic rhythm. *Physical Therapy, 68*, 824.

Scham, S. M., & Taylor, T. K. (1971). Tension signs in lumbar disc prolapse. *Clinical Orthopaedics and Related Research, 75*, 195–204.

Stubbs, D. A. (1982). Back problems in work and leisure. *Physiotherapy, 68*, 174–176.

Takata, K., & Takahashi, K. (1994). Hamstring tightness and sciatica in young patients with disc herniation. *Journal of Bone and Joint Surgery. British volume, 76*, 220–224.

Yu, B., Kienbacher, T., Growney, E. S., Johnson, M. E., & An, K. N. (1997). Reproducibility of the kinematics and kinetics of the lower extremity during normal stair-climbing. *Journal of Orthopaedic Research, 15*, 348–352.