THE INVESTIGATION OF AGE-RELATED CHANGES IN THREE-DIMENSIONAL KINEMATICS OF THE SPINE

ROONGTIWA VACHALATHITI

B.Sc., M.Sc. (Physiotherapy)

(Mahidol University, Thailand)

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Dr. Jack Crosbie

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TABLE OF CONTENTS

ABSTRACT

This study investigated the angular displacement and velocity characteristics of the overall thoracolumbar, lower thoracic and lumbar spine. The test group consisted of 100 healthy volunteer subjects (46 males and 54 females). Subjects were divided into three groups in each gender, a young group (20 to 35 years), a middle-aged group (36 to 59 years) and an elderly group (60 to 80^+ years). Kinematic data were acquired using a four camera Motion Analysis ExpertVision™ system, spherical reflective body markers being located over anatomical landmarks associated with the spine and pelvis. Subjects performed forward flexion, bilateral side flexion and bilateral rotation and a lifting simulation four times each in a sitting position. Movements were performed at both their preferred speed and at a self-determined faster speed.

The angular displacement and velocity characteristics were calculated and analysed. Multivariate Analysis of Variance (MANOVA) and regression analyses were used to elucidate age, gender and speed related effects during the various movements. Schéffé multiple comparison of pairs was used as a post-hoc procedure to test for the differences between age groups in the case of significant age effects as shown by MANOVA. An independent t-test was used to test for the differences between male and female subjects in the same age in the case of gender effects demonstrated by MANOVA. A paired t-test was used to test for the differences between the fast and the preferred speeds in each age group in the case of speed effects demonstrated by MANOVA.

The results revealed significant decreases in the ranges of forward flexion and lateral flexion in the lumbar spine with advancing age. The ranges of all three movements also significantly decreased with increasing age in the overall thoracolumbar and lower thoracic spine. Angular velocities decreased with advancing

age in all movements for all trunk segments. Male subjects showed a greater range of forward flexion and rotation compared to female subjects in the same age group in the overall thoracolumbar and the lumbar spine and female subjects demonstrated a greater range of lateral flexion in the lower thoracic spine. Male subjects generally demonstrated a higher value of angular velocity than female subjects in the same age group for all movements. The range of fast lateral flexion was generally reduced for all subjects compared to that demonstrated at the preferred speed, while fast rotation was associated with a greater range than the preferred speed.

The patterns of associated anatomical movements were consistent throughout for each condition. Forward flexion occurred with little or no accompanying spinal motion. Primary lateral flexion was accompanied by forward flexion and contralateral rotation in all the trunk segments. Primary rotation was generally accompanied by forward flexion and contralateral side flexion in the lumbar spine but was associated with lateral flexion towards the same side in the lower thoracic spine. No significant gender or speed effects were found in the amplitude or nature of the associated movements. Age-related decreases in the range of associated forward flexion and rotation with primary lateral flexion were found in the lower thoracic spine.

The results of this study indicate that range of motion and angular velocity are related to age, gender and speeds of motion. This study provides data not available in the literature regarding the velocity of movement and magnitudes of the accompanying movements. There are differences in patterns of the associated movements between the lower thoracic and the lumbar spine. Clinically, the physiotherapist should be aware of normal values for each motion based on the patient's age and gender as well as the normal pattern of movements during clinical assessment of patients with back pain.

The results of the lifting simulation indicated that the major movement components were forward flexion and lateral flexion when picking up an object at a direction of 45 degrees to the median plane of the subject in a seated position. Axial rotation was limited in the task. The findings of this study suggest that the attributes of the task which was simulated in the present study could be desirable in the work situation. No clear age or speed effects were detected in either ranges or patterns of the spinal motion although the results indicated significant decreases in angular velocities with advancing age.

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

INTRODUCTION

Ageing is an inevitable consequence of living. There is substantial evidence supporting the belief that a reduction in spinal range of motion is common in older people and may affect their activities of daily living. Since the range of spinal motion is decreased with age, problems such as back pain and dysfunction may become more prevalent (McKenzie, 1981), or functional impairment related to back movement e.g. getting up from a chair or lifting objects through range, may be more problematic (Bergstrom, et al., 1985a, 1985b). Moreover, increasing age is associated with a reduction of overall activity levels and physical capacity (Sidney and Shephard, 1977; Twomey and Taylor, 1984). As age increases, muscles and other soft tissues become less elastic and less flexible (Payton and Poland, 1983; Alnaqeeb, et al., 1984) and these reductions may result in decreasing ranges of motion, with a decrease in the speed of movement and consequent performance difficulties.

Many everyday activities are performed in the sitting position and involve lifting and placing objects while seated. Lifting is a common activity involving movement of the spine and has been identified as one of the major causes of back pain and back injury. Currently, most kinematic information concerning lifting is restricted to spinal sagittally symmetric motion in a standing position. In order to understand the spinal kinematics and help prevent back injury during lifting, there is a need to examine the kinematic demands and identify the patterns of movement during the task in the sitting position.

Since spinal motion has long been considered an important component of the physical examination of patients with back pain, many researchers are interested in the movement characteristics of the spine (Mayer et al., 1984; Pearcy et al., 1985; Marras and Wongsam, 1986). Although kinematic data related to the lumbar spine have been obtained by a variety of methods, the data are generally reported in terms of maximum displacement without describing the characteristics of the movements, including their angular velocity values. Gomez et al. (1991) and McIntyre et al. (1993) reported that preferred movement characteristics of the lumbar spine were different from those in which a maximum effort was required when subjects moved their trunk against a resistance. Marras and Wongsam (1986) reported that significant decreases in range of motion and angular velocity of lumbar flexion were found in a group with back pain in both the preferred and fast speed movements compared to a pain-free group. Marras and Wongsam also suggested that the changes in trunk velocity associated with back problems are substantial and may be subject to less variability compared to changes in range of motion. The angular velocity of trunk motion should be introduced into the assessment of the spine. Normative data for angular velocity of the spine are therefore needed so that patient data may be compared against that data base. There does not appear to have been any study investigating speed effects on the kinematic characteristics of the spine nor any reports of the normal values of the angular velocity of spinal motion in a diverse age range. The collection of such data is, therefore, needed and long overdue.

There are known to be different contributions to anatomical movement from the different regions of the spine. However, there has been little research describing the kinematic characteristics of the lower thoracic, the lumbar or the overall thoracolumbar segment in normal subjects. The complexity of the structure of the spine is such that the movements too can be expected to be complex. Simple clinical measurement methods merely give confirmatory evidence about the restricted mobility and do not describe the characteristics of the movement. Individual patterns of spinal motion could be better quantified and identified by an analysis of the relevant displacements with respect to time. In the dynamic evaluation of spinal motion, the patterns of motion and angular velocity could provide a better indicator of movement performance than end point values of maximum displacement. A kinematic analysis of the spine, therefore, needs to take into account the patterns of displacement and velocity in three dimensions. Ideally, a three-dimensional (3D) measurement system should be employed to measure the kinematic features of the spine.

Advances in measurement technology have made the kinematic analysis of human motion more accessible to clinical and research applications. Numerous instruments such as radiographic measurements, optoelectronic devices, electromagnetic systems and videocamera systems have been used for this purpose (Hanley et al., 1976; Portek et al., 1983; Stokes et al., 1987; Pearcy and Hindle, 1989). Each instrument has its own advantages and disadvantages. Most techniques used in measuring the kinematics of the spine involve the attachment of equipment or straps to the subject's body. In some cases these may restrain or limit the subject's movement and interfere with the natural motion of the spine.

Radiographic techniques have been reported to be the most accurate measurements, but they are expensive and require exposure of subjects to harmful radiation. Analysis systems that require hand digitisation are subject to errors associated with the visual identification of joint or marker centres on the film, are restricted to lower playback frequencies and are also time consuming. In some video-based and optoelectronic systems, markers are digitised automatically, presumably reducing error of marker centroid identification. However, error associated with the calculation of joint centres or joint angles from the markers may be introduced. Electromagnetic systems (e.g. Isotrak, an electro-magnetic device locating the position and orientation of a sensor in three dimensional space) have been found to be accurate and reliable in measuring the kinematics of the spine. However, the system requires more careful attention during application than video-based systems in order to minimise interference with the movements from cables and the movement of the sensor itself. Although the video-based systems can measure the three dimensional movements without problems of the equipment attached to the subject, the movement of marker or skin may affect the kinematic characteristics of the underlying bone. It is clear that, whatever system is used, it is desirable to analyse non-invasively the motion of the spine as the subject moves freely in space. Such a system should be reasonably easy to use, accurate, reliable and easily interfaced with a computer for data reduction, storage and analysis.

Scope and Rationale of Study

The purpose of this study was to investigate the age-related changes in the three-dimensional kinematics of the lower thoracic and the lumbar spine during three anatomical movements and a lifting simulation by using the automated video system (Motion Analysis ExpertVision™ system). The study was also concerned with the differences in the kinematics of the spine during preferred and fast speed motion in normal subjects. The investigation was separated into 2 parts; the spinal kinematics of anatomical movements (forward flexion, lateral flexion and axial rotation in chapters 3 to 5) and spinal kinematics in the seated lift (chapter 6).

This study has three principal hypotheses:-

(1). Spinal range of motion and angular velocity are inversely related to age.

(2). Spinal range of motion and angular velocity are gender-specific.

(3). The lower thoracic and the lumbar spine demonstrate significant differences with respect to their patterns of movement.

Null Hypotheses of Study

- There are no differences in range of motion among the young, middle-aged and the elderly groups.
- There are no differences in peak or average angular velocity among the young, middle-aged and the elderly groups.
- There are no differences in range of motion between male and female subjects in the same age group.

- There are no differences in peak or average angular velocity between male and female subjects in the same age group.
- There are no differences between range of motion derived from the preferred and the fast speeds of movement.
- There are no differences between peak angular velocity derived from the preferred and the fast speeds of movement.
- There are no differences between average angular velocity derived from the preferred and the fast speeds of movement.
- There are no differences between the patterns of movement derived from the lower thoracic and the lumbar spine.
- There are no correlations between age and range of motion in male or female subjects.
- There are no correlations between age and peak and average angular velocity in male or female subjects.

The data presented in this study will demonstrate the three dimensional movement characteristics of the lower thoracic and lumbar spine. They will also help in understanding the anatomical characteristics of the different spinal motion segments. It is believed that three dimensional data will clearly demonstrate age-related changes in the kinematic characteristics of the spine. Information related to the kinematics of the spine will help in understanding normal dynamic functions of the back in different age groups and may assist in understanding the demands placed upon the spine during everyday activities.

CHAPTER 2

LITERATURE REVIEW

CONTENTS

LITERATURE REVIEW

2.1 Applied Anatomy and Kinematics of the Spine

The spine is the most complex and functionally significant segment of the human body (Hall, 1991; White and Panjabi, 1990). Providing the linkage between the upper and lower extremities, the spine enables motion in all three planes of movements, and also functions as a bony protector of the delicate spinal cord.

From the cervical through the lumbar regions, there is a progressive increase in vertebral size and a change in the orientation of the articular facets [Figure 2.1]. The bodies of the lumbar vertebrae are larger and thicker than those located in the more superior regions of the spine. Because each vertebra supports the weight of the portion of the body above it, the increased surface area of the lumbar vertebrae reduces the amount of stress to which these vertebrae would otherwise be subjected (Hall, 1991; Grieve, 1988; White and Panjabi, 1990).

The size and orientation of the spinous and transverse processes and the articular facets also vary with vertebral location. The shape of the articulating surfaces of the facet joints physically limits the ranges of movement at different levels of the spine. In this review the anatomical and kinematic features of the thoracic and lumbar spine are presented.

2.1.1 The Thoracic Spine

The thoracic spine is a transitional region between the relatively more mobile cervical and lumbar regions. While the upper thoracic and lower thoracic spines have similarities to the cervical and lumbar regions respectively, the thoracic spine itself is a distinct section.

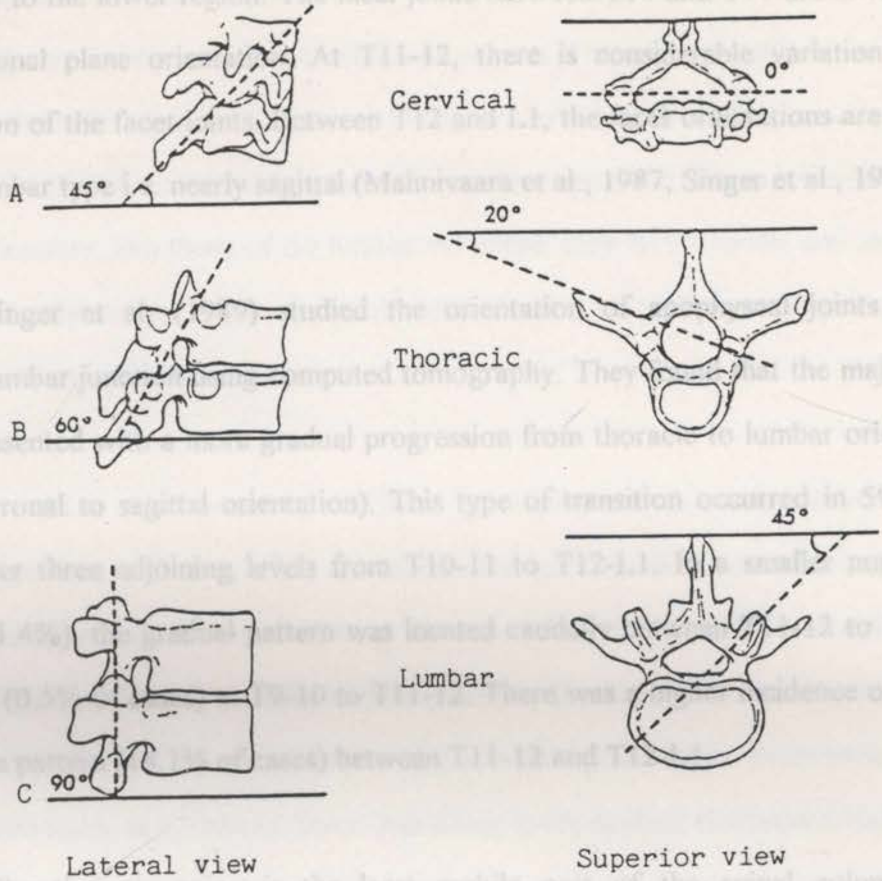


Figure 2.1 Approximate orientation of the facet joints to the transverse and frontal planes. (A) Cervical spine, with facets oriented 45 degrees to the transverse plane and parallel to the frontal plane (0 degree). (B) Thoracic spine, with facets oriented 60 degrees to the transverse plane and 20 degrees to the frontal plane. (C) Lumbar spine, with facets oriented 90 degrees to the transverse plane and 45 degrees to the frontal plane (Hall, 1991).

The upper thoracic vertebrae are relatively small, similar to those in the cervical region. The spatial orientation of the facet joints is somewhat similar to that in the cervical spine, but the angulation of the articular facets in the sagittal plane is more than that of the cervical region. The approximate orientation of the facet joints in most of the thoracic spine is 60 degrees to the transverse plane and 20 degrees to the frontal plane. The plane of the facet is almost flat, directed slightly anteriorly and laterally. The spatial orientation of the facet joints in the thoracic spine changes from the upper to the lower region. The facet joints between T10 and T11 are always in a near coronal plane orientation. At T11-12, there is considerable variation in the orientation of the facet joints. Between T12 and L1, the facet orientations are usually of the lumbar type i.e. nearly sagittal (Malmivaara et al., 1987; Singer et al., 1989).

Singer et al. (1989) studied the orientation of apophyseal joints at the thoracolumbar junction using computed tomography. They found that the majority of cases presented with a more gradual progression from thoracic to lumbar orientation (from coronal to sagittal orientation). This type of transition occurred in 59.6% of cases over three adjoining levels from T10-11 to T12-L1. In a smaller number of cases (11.4%), the gradual pattern was located caudally between T11-12 to L1-2 or cranially (0.5% of cases) at T9-10 to T11-12. There was a higher incidence of abrupt transition pattern (18.1% of cases) between T11-12 and T12-L1.

The thoracic spine is the least mobile part of the spinal column. The attachment of the rib cage, together with the thin intervertebral discs comprising only one-seventh to one-fifth of the height of the vertebral body (compared with one-third in lumbar region and two-fifths in cervical region), combine to reduce its movement considerably (White and Panjabi. 1990).

The vertebral bodies, in effect short, waisted tubes, diminish in size from T1 to T3 and then progressively increase to T12, the body of which shares the kidney-shape characteristic of the lumbar vertebrae. The bodies are slightly anterior to the two demifacets for articulation with the heads of the ribs which are situated at the posterior aspects of the bodies in the upper region. In the lower half of the thorax these articular facets have migrated backwards to be located beside the bases of the pedicles.

The last thoracic vertebra (T12) acting as a bridge between the thoracic and lumbar regions, has certain characteristics of its own. The superior articular processes resemble the other thoracic vertebrae, facing posteriorly and slightly superiorly and laterally, but the inferior articular processes must correspond to the superior processes of L1. Therefore, like those of the lumbar vertebrae, they face laterally and anteriorly and are slightly convex transversely with their centres of curvature lying roughly at the origin of the spinous process.

In neutral erect postures, the facet joints play only a small part in weight-bearing, gravity exerting its effect almost entirely upon the discs and vertebral bodies in the thoracic region. However, during vigorous lifting and handling where the trunk is in a flexed and often somewhat rotated position, the facet joints are inevitably and considerably stressed by compression forces. Strong muscular contractile forces stabilise the trunk as a dynamic lever, sustaining loads applied at almost a right angle to the longitudinal body axis. The orientation and the plane of the facets also contribute to the marked limitation of movement in the sagittal plane (Grieve, 1988).

At each level of the thoracic vertebral column a pair of ribs is connected to a vertebra by means of two synovial joints:-

- the costovertebral joint between the head of the rib, the intervertebral disc and the vertebral bodies, and,
- the costotransverse joint between the rib tubercle and the transverse process of the underlying vertebra.

The ribs are curved bones of elliptical cross section joining the vertebral column to the sternum and thus forming a closed cylindrical cavity, the thorax. The first seven ribs join the sternum by means of individual costal cartilages, the next three by means of a fused costal cartilage. The last two ribs are free floating and the ends of these ribs lie in the muscles of the abdominal wall.

The rib cage, consisting of the sternum, costal cartilages and the 12 pairs of ribs has several important biomechanical functions related to the spine. It has the mechanical role of protecting and supporting internal organs (heart, lungs, etc) and allowing motion of the trunk in respiration as well as in spinal flexion. It is a protective barrier against any traumatic impact directed from the front or the sides. It stiffens and strengthens the spine, thus providing greater resistance to displacement. Roaf (1972) has elucidated the biomechanical importance of the ribs in maintaining spinal stability. Andriacchi et al. (1974) have also confirmed the role that the ribs play in lateral stability of the spine. However, the mechanical interaction between the complex rib cage structure and the spinal structure is poorly described (Dansereau and Stokes, 1988).

Schultz et al. (1974) studied the physical properties of the ribs by fixing the ribs at their heads, and applying loads to the free ends of the costal cartilage in six different directions: anterior, posterior, lateral, medial, superior and inferior. They found that the highest stiffness value was exhibited by the shortest "true" rib (rib 2) when pulled in the anterior direction, while the lowest stiffness (greatest compliance) was shown by the longest rib (rib 10) when loaded in the superior and inferior directions. All ribs demonstrated greater stiffness in the anterior direction compared to the posterior direction. The ribs also exhibited coupling effects. For example, superior loading also produced posterior and medial displacements. This was probably due to the curved geometry of the ribs and may be related to the patterns of coupled movements in the thoracic spine.

Although the individual components of the rib cage (the ribs and their joints) are quite flexible, the rib cage as a whole greatly enhances the stiffness of the spine (White and Panjabi, 1990). Andriacchi et al. (1974) utilized a mathematical model performing computer simulations to determine the effects of the rib cage on the stiffness properties of the normal spine during forward flexion, extension, lateral flexion and rotation. They reported that the stiffness properties of the spine were greatly enhanced by the presence of the rib cage for all the four movements, particularly into extension. Removal of the sternum from the rib cage had a profound effect, almost completely destroying the stiffening effect of the thorax. This suggested that sternum significantly increased stiffness of the thoracic spine. They also reported that removal of one or two ribs, as is sometimes carried out in the surgical correction of scoliosis did not significantly affect thoracic stiffness.

Panjabi et al. (1976a, 1976b) studied three-dimensional flexibility and stiffness of the thoracic spine in cadavers. The results revealed a higher relative stiffness in the axial direction compared with other directions. More motion occurred in the direction of loading than in other directions, except when the loading was axially directed. Axial loads resulted in significant horizontal displacements. Panjabi and colleagues also reported that although motion is generally greatest in the direction of loading and less for the direction of coupled motions, coupled motion is always present.

In the thoracic spine the body architecture, facet positions and close proximity of spinous processess allow a little forward flexion and a slight lateral flexion but limit hyperextension (Markolf, 1972). The lower portion of the thoracic spine is capable of ample flexion/extension, a motion that gradually increases into the lumbar spine (White and Panjabi, 1990). For axial rotation, the upper thoracic spine exhibits more motion than the lower thoracic spine. Table 2.1 demonstrates ranges of motion at the various levels of the thoracic spine (White and Panjabi, 1990).

Table 2.1 Representative values (limits of range) in degrees of range of motion in the thoracic spine.

Interspace	Flexion/Extension	One side lateral flexion	One side axial rotation
T1-T2	4 (3-5)	5 (5)	9 (14)
T2-T3	4 (3-5)	6 (5-7)	8 (4-12)
T3-T4	4 (2-5)	5 (3-7)	8 (5-11)
T4-T5	4 (2-5)	6 (5-6)	8 (5-11)
T5-T6	4 (3-5)	6 (5-6)	8 (5-11)
T6-T7	5 (2-7)	6 (6)	7 (4-11)
T7-T8	6 (3-8)	6 (3-8)	7 (4-11)
T8-T9	6 (3-8)	6 (4-7)	6 (6-7)
T9-T10	6 (3-8)	6 (4-7)	4 (3-5)
T10-T11	9 (4-14)	7 (3-10)	2 (2-3)
T11-T12	12 (6-20)	9 (4-13)	2 (2-3)
T12-L1	12 (6-20)	8 (5-10)	2 (2-3)

Flexion/extension of the thoracic spine is relatively limited, and is least between the segments T3 and T6 (2-5 degrees). White and Panjabi (1990) give the median value of the flexion/extension range of each segment as 4 degrees in the upper part and 6 degrees in the middle part. In the lowest segments, the median is 11-12 degrees. Loebl (1967) and White (1971) considered that spinal motion segments were more mobile into flexion than into extension, the latter motion accounting for 30-40 percent of the total sagittal motion. The removal of the posterior elements (the facet joints, the laminae, the ligaments and the spinous processes) resulted in significant increases in flexion/extension and in axial rotation (White and Hirsch, 1971).

Lateral flexion is in the range of 3-6 degrees at each interspace on average (White, 1971). The median range is 6 degrees in the upper segments and 8-9 degrees in the two lower segments. According to Grieve (1988) the range of lateral flexion is least between T5-T10.

White (1971) reported that rotation about the long axis is of the order of 2-6 degrees on average with some tendency towards less rotation in the more caudal regions. There are 8-9 degrees of motion of each segment in the upper half of the thoracic spine, reducing to 2 degrees for the lowest three segments (White and Panjabi, 1990).

In the thoracic region, the patterns of coupled movements have been studied in the cadaveric spine. White (1971) reported that in the upper portion of the thoracic spine there is a relatively marked and consistent coupling of axial rotation with lateral flexion. Right lateral flexion tends to be associated with right rotation and left lateral flexion is associated with left rotation. In the middle and lower regions of the thoracic spine, this same relationship continues. However, in these latter two regions it is neither as marked nor as consistently present as in the upper thoracic spine. The direction of the coupled axial rotation in the middle regions was noted in some cases to be the reverse of the pattern described for the upper region (White, 1969; 1971; White and Panjabi, 1990). White and Panjabi (1978) reported a coupling of primary lateral flexion with axial rotation towards the opposite side.

2.1.2 The Lumbar Spine

The massive vertebral bodies of the lumbar spine are developed to sustain greater stresses than the more superior regions. The lumbar spine is divided into the lumbar (L1-L5) and the lumbosacral (L5-S1) regions (Posner et al., 1982; White and Panjabi, 1990). The anatomy, kinematics, and kinetics of L5-S1 are different from the rest of the lumbar spine.

The facet joints of the lumbar spine are set chiefly in the sagittal plane, perhaps narrowing somewhat towards the posterior direction (Hall, 1991; Grieve, 1988; Bogduk and Twomey, 1991). The articular facets of the facet joints of the lumbar spine are biplanar in horizontal section, consisting of an anterior and coronally oriented third of the joint and a posterior and sagittally directed two-thirds of the joint. However, viewed from above, the articular facets vary both in the shape of their articular surfaces and in the direction they face [Figure 2.2]. Generally, the inward-facing concave facets of the superior articular process correspond to the inferior, convex and outward-facing facets of the vertebrae above.

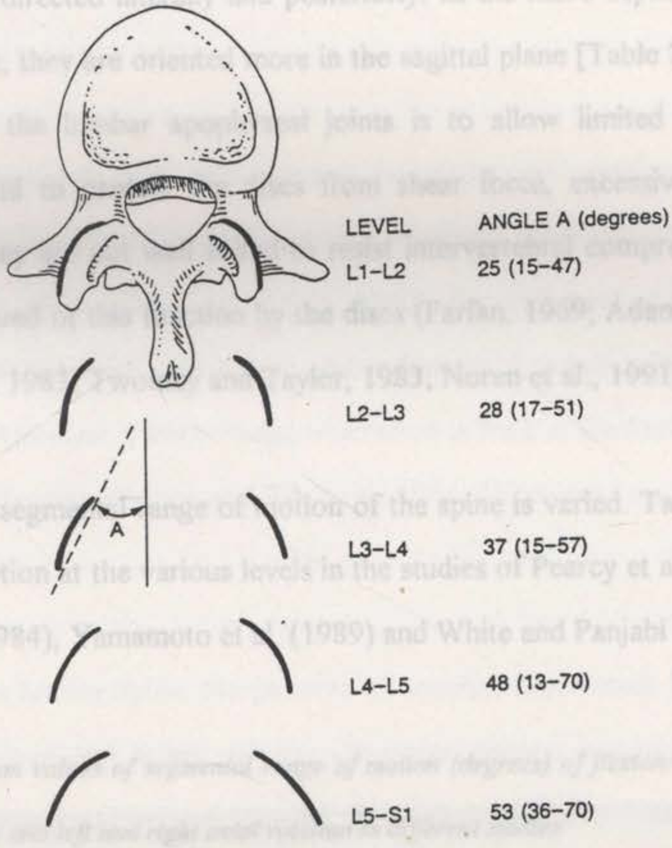


Figure 2.2 Shape and inclination of the facet joints of the lumbar spine. The diagram shows the gradual change in joint orientation from L1-L2 to L5-S1 (Taylor and Twomey, 1986; White and Panjabi, 1990).

Table 2.2 Average angles of apophyseal joints (degrees) to the sagittal plane in three studies.

Level	Van Schaik et al. (1985)	Taylor & McCornick (1987)	Noren et al. (1991)
L3-L4	37.1	36	39.6
L4-L5	48.2	47	48.4
L5-S1	53.1	51	53.9

The apophyseal joints at the L5-S1 level are oriented more in the frontal plane and may be directed laterally and posteriorly. In the more cephalad segments of the lumbar spine, they are oriented more in the sagittal plane [Table 2.2, Figure 2.2]. The function of the lumbar apophyseal joints is to allow limited movement between vertebrae and to protect the discs from shear force, excessive flexion, and axial rotation. They are not well suited to resist intervertebral compressive forces and are usually relieved of this function by the discs (Farfan, 1969; Adams and Hutton, 1983; Miller et al., 1983; Twomey and Taylor, 1983; Noren et al., 1991).

The segmental range of motion of the spine is varied. Table 2.3 demonstrates range of motion at the various levels in the studies of Pearcy et al. (1984), Pearcy and Tibrewal (1984), Yamamoto et al. (1989) and White and Panjabi (1990).

Table 2.3 Mean values of segmental range of motion (degrees) of flexion/extension, left and right lateral flexion and left and right axial rotation in different studies.

Level	Flexion/extension			Left and right lat. flexion			Left and right rotation		
	Pearcy	Yamamoto	White	Pearcy	Yamamoto	White	Pearcy	Yamamoto	White
L1-L2	13	10.1	12	10	9.8	12	2	4.2	4
L2-L3	14	10.8	14	11	14	12	2	5.2	4
L3-L4	13	11.2	15	10	11.4	16	3	5.2	4
L4-L5	16	14.5	16	6	11.4	12	3	4.4	4
L5-S1	14	17.8	17	3	11	6	2	2.6	2

In flexion/extension there is a cephalocaudal increase in the range of the lumbar motion segments as shown in Table 2.3. Adams et al. (1980) and Pearcy et al. (1984) have reported that, in the lumbar spine, the greatest range of forward flexion occurs at the L4-L5 level. Park (1980) reported total lumbar flexion/extension range as 70 degrees, with 40-50 degrees of the range occurring in the lower segments. An in vivo study of 14 adult males indicated that lumbar flexion accounts for approximately 60 degrees, further flexion from this point occurring at the hips (Farfan, 1975). Extension follows the reverse order, with the pelvis tilting backward and later, extension of the lumbar spine.

For lateral flexion, each segment has about the same range, except for the lumbosacral joint (L5-S1), which shows a relatively small amount of motion (Pearcy and Tibrewal, 1984; White and Panjabi, 1990). For unilateral axial rotation the range is considerably smaller, between 1 and 3 degrees for each segment from L1 to L5 (Pearcy and Tibrewal, 1984). Range of rotation is least at the lumbosacral joint, being from 0 to 2 degrees (Pearcy and Tibrewal, 1984; Yamamoto et al., 1989; White and Panjabi, 1990).

In the lumbar spine, the patterns of coupled movements have been studied in cadaveric spines and living subjects. Forward flexion involves a combination of anterior sagittal rotation and forward translation of approximately 1-3 mm. These primary movements are consistently associated with coupled rotation and lateral flexion each of about 1 degree (Pearcy et al., 1984). A small amplitude of vertical and lateral translation also occurs with forward flexion. Reciprocally, extension involves posterior sagittal rotation and posterior translation, with small amplitudes of coupled rotation and translation about and along the other two axes.

According to Pearcy and Tibrewal (1984) and Pearcy (1985) axial rotation and lateral flexion are coupled with one another and with sagittal plane movement, either forward flexion or extension. In segmental coupling patterns, rotation is variably coupled with forward flexion or extension but neither occurs consistently. Similarly, lateral flexion may be accompanied by either forward flexion or extension of the same joint, but extension occurs more frequently. The coupling between rotation and lateral flexion is a somewhat more consistent pattern. Rotation of the upper three lumbar joints is usually accompanied by lateral flexion to the opposite side, and lateral flexion is accompanied by contralateral rotation. In contrast, rotation of the L5-S1 joint is accompanied by lateral flexion towards the same side and lateral flexion of this joint is accompanied by ipsilateral rotation. The ranges of the associated movements in the L5-S1 are small compared to that of the L1-L5.

Few studies have measured dynamic back movements in three dimensions to determine the ranges and patterns of lumbar motion in normal subjects. More recent work, including that assessing total three-dimensional lumbar movements of normal subjects in a range of ages, has enabled a more precise evaluation of movement during flexion, extension, lateral bending and rotation (Hindle et al., 1990; Pearcy and Gill, 1987; Pearcy et al., 1987; Pearcy and Hindle, 1989; Thurston 1982; Thurston and Harris, 1983). These improvements are mainly due to advances in measurement technology. Television/computer systems, opto/electronic devices and electromagnetic systems have been used for this purpose.

In the studies which have been reported, the three-dimensional kinematic patterns of the lumbar spine were similar for all age groups, showing normals to have a consistent pattern of movement (Hindle et al., 1990). A general trend of decreasing mobility with age was also demonstrated. The results of these studies also showed that the range of flexion exceeds that of extension and that sagittal plane movements are associated with little or no accompanying axial rotation or lateral flexion. Lateral flexion is generally accompanied by extension and rotation. Axial rotation is accompanied by a few degrees of forward flexion or lateral flexion. However, no quantitative information on the amplitudes of the associated movements have been reported (Brown et al., 1976; Pearcy et al., 1987a; 1987b; Pearcy and Hindle, 1989; Hindle et al., 1990).

2.1.3 The Intervertebral Disc

The intervertebral disc consists of two components: the nucleus pulposus and the annulus fibrosus. The nucleus pulposus occupies approximately 40 percent of the cross-sectional area of the disc (DePalma and Rothman, 1970). The annulus fibrosus is strongly attached to both anterior and posterior longitudinal ligaments. Superiorly and inferiorly, the fibers attach to the bony endplates, and centrally they mesh with the hyaline cartilage endplates. In the unloaded human disc, the gelatinous nucleus contains water from 75 to 90 percent by weight depending on age (Markolf and Morris, 1974). The discs serve to allow greater motion between the vertebral bodies and also serve a shock-absorbing function during direct axial loading. More importantly, they distribute weight over a large extent of the vertebral body surface during bending movements rather than allowing concentration of the weight on the vertebral body edge towards which the spine is bent.

The lumbar intervertebral discs tend to be of greater height anteriorly than posteriorly, therefore, the lumbar lordotic curve is due to the shape of the disc. On the other hand, the thoracic kyphosis is due primarily to the shape of the vertebral body rather than to the shape of the disc. The discs in the thoracic region are of equal height anteriorly and posteriorly, however the vertebral bodies are of greater height posteriorly than anteriorly (DePalma and Rothman, 1970).

In the lumbar spine, the annulus tends to be thicker anteriorly than posteriorly, which may be one of the factors responsible for the predominance of posterior protrusion of the nucleus pulposus. Also, the laminated layers of the posterior portion of the annulus fibrosus are narrower and less numerous, and the fibres in the adjacent layers appear to be nearly parallel to one another (Markolf and Morris, 1974; Bernick et al., 1991). This leads to a weak point at the posterolateral part of the annulus fibrosus and is the most likely location for disc herniation.

In the intervertebral disc, the ageing process is accompanied by chemical changes in the disc's proteoglycan content and a reduction in water content (Bushell et al., 1977). The chronological ageing process irreversibly reduces the water-absorption capacity of the disc, with a concomitant decrease in shock-absorbing capability. The distinction between the nucleus pulposus and the annulus fibrosus is lost because the nucleus becomes more fibrous as water content lessens (Kirkaldy-Willis et al., 1978). These changes render the disc less capable of efficiently transmitting, distributing and dissipating axial loads in the vertebral column (Nachemson, 1976). As this normal degenerative change occurs, more of the compressive, tensile, and shear loads on the spine must be assumed by other structures, particularly the facets and joint capsules. With increasing age, the disc thickness is maintained and the principal change observed is the change in disc shape associated with an increase in the vertebral endplate concavity. The change in disc shape is accompanied by a marked increase in disc stiffness. The disc stiffness has been suggested as the major reason for the reduction in spinal movement in old age (Twomey and Taylor, 1984).

2.1.4 The Spinal Ligaments

The spinal ligaments help to maintain the configuration of the functional spinal unit. The ligaments consist of the anterior and posterior longitudinal ligaments, the ligamentum flavum, the supraspinous, interspinous, intertransverse, facet capsular and iliolumbar ligaments.

Braus (1921) reported that ligamentum flavum is the most pure elastin tissue in the human body (cited by White, 1971). The main function of ligamentum flavum is to provide a smooth dorsal covering for the spinal canal in all position of the vertebral column (Yong-Hing et al., 1976). In addition, the ligamenta flava and the facet joints have been shown experimentally to limit axial rotation in the normal thoracic spine (White, 1969). Adams et al. (1980) and Gunzburg et al. (1991) found that the facet capsular ligaments also restrict excessive motion. Forward flexion of a lumbar intervertebral joint is restricted primarily by the capsular ligaments of the apophyseal joints and by the intervertebral disc, with the ligamentum flavum and the interspinous and supraspinous ligaments making lesser contributions. The supraspinous and the interspinous ligaments are slack at small angles of forward flexion but are the first to become torn immediately after the limit of forward flexion is exceeded (Adams et al., 1980).

The iliolumbar ligaments are also important because they stabilize the lumbosacral junction and can restrict all directions of motion of that joint. However, they seem to be most effective in resisting lateral flexion (Leong et al., 1987; Yamamoto et al., 1989; 1990). Yamamoto et al. (1989) tested specimens with and without iliolumbar ligaments. Yamamoto et al. reported that, with intact iliolumbar ligament, the movements at L5-S1 decreased by about 5 degrees in flexion and extension and decreased about 1.5 degrees in bilateral side bending.

2.1.5 The Paraspinal Muscles

The back muscles consist of the erector spinae, interspinalis, intertransversus, iliocostalis lumborum, quadratus lumborum, lattissimus dorsi and multifidus (Gracovetsky and Farfan, 1986).

While the prime function of muscles is to bring about movement, it is also clear that the trunk muscles play an important role in the distribution of load to the vertebrae and intervertebral joints, and the attenuation of forward slip (spondylolisthesis) during lifting and carrying procedures (Bogduk and Twomey, 1991; Potvin et al., 1991; Twomey and Taylor, 1991). Moreover, the multifidus and interspinalis, being intersegmental muscles, play a greater role in maintaining spinal stability than the superficial muscle groups (Panjabi et al., 1989).

In summary, the complexity of structure of the spine allows motion in all three planes of movement. Although movement between adjacent vertebrae is small, spinal movements always involve a number of motion segments. The directions and ranges of motion of the individual motion segments vary according to the anatomical constraints in the different regions of the spine. Humphry (1858) pointed out that movements permitted in the spine are mainly due to the shape and position of the articulating processes of the diarthrodial joints (cited by White, 1971).

The present study was concerned with the kinematic characteristics of the lower thoracic spine and the lumbar spine. It would be expected that there are differences in the ranges and patterns of motion between the spinal segments because of the different orientations of the articular processes of the two levels. For example, the orientation of the lumbar facet joints will permit a greater freedom of movement in the sagittal plane compared to that of the lower thoracic spinal segments. The spinal ligaments also contributed to the mechanical resistance of the intervertebral joints during movements (White, 1969; Markolf, 1972; Adams et al., 1980; Twomey and Taylor, 1983; Gunzburg et al., 1991).

Markolf (1972) studied the effects of posterior structures on stiffness in the thoracic and lumbar intervertebral joints. The intervertebral joints were tested in forward flexion, extension, lateral flexion and torsion before and after removal of the posterior structures (the posterior structures were sawn off at the roots of the pedicles). Markolf found that removal of the posterior structures substantially reduced the extension stiffness of both the thoracic and the lumbar interspaces and markedly reduced the torsional stiffness of the lumbar joints. He also reported that removal of the articular processes and posterior elements did not affect the stiffness of forward flexion and lateral flexion either in the thoracic or lumbar intervertebral joints. These findings indicate that movements of forward flexion and lateral flexion of the thoracic and lumbar spine are not resisted by the posterior elements of the spine whereas axial rotation is restricted, particularly in the lumbar spine. The role of the facet joints of the lumbar spine in resisting axial rotation has been reported (Adams and Hutton, 1981; 1983; Goel et al., 1985). In the thoracic spine, the vertebral column is connected to the thoracic cage by multiple joints, and all the bony, cartilaginous and articular components of the cage play a role in orienting and limiting the movements of the thoracic spine. Additionally, in the living subjects, the intervertebral disc, spinal ligaments, intercostal muscles and paravertebral muscles play an important role in determining range of motion of the spine.

2.2 Measurement of Spinal Motion

There have been many attempts to measure spinal movements since the 1930s (cited by Pearcy, 1985). However, because of the relative inaccessibility of the spine and the complex nature of its movements, the results reported do not always agree. Currently, several methods are available to measure spinal range of motion, both simple and complex. Most of the techniques used clinically give single plane range of movement measurements using devices mounted on the surface of the subject's back i.e., plumb line, skin distraction measurement, goniometer, inclinometer and spondylometer (Hart et al., 1974; Lindahl, 1966; Loebl, 1967; Moll and Wright, 1971; Pearcy, 1986; Portek et al., 1983; Reynolds, 1975; Troup et al., 1968). There have been reports showing that these techniques are clinically accessible and easy to use. Macrae and Wright (1969) and Moll et al. (1972) used skin distraction and plumb line techniques to measure spinal flexion and extension respectively and compared these with the findings derived from radiological techniques. The results showed good correlation between the clinical and radiological techniques.

It has been reported that goniometry is a quick and easy alternative method of measuring spinal mobility (American Academy of Orthopeadic Surgeons, 1965; Fitzgerald et al., 1983). Fitzgerald et al. (1983), Million et al. (1982) and Reynolds (1975) have suggested a high degree of interobserver reliability for the measurement of spinal mobility in the sagittal and coronal planes using a goniometer. On the other hand, Portek et al. (1983) found that skin distraction and plumb line methods showed a significant difference between the measurements taken by two observers; these findings were similar to those reported by Reynolds (1975). Skin distraction methods were found difficult to reproduce, because of the variable mobility of the skin over the bony landmarks and the extensibility of the skin between the two points. Difficulty was also found with the plumb line technique, because accurate positioning of the skin marker under a freely hanging plumb line could not be achieved.

Although the clinician is able to record an index for the range of motion with the gonimeter, skin distraction and plumb line techniques, there is often very little correlation between these measurements and true spinal movement (Portek et al., 1983; Stokes et al., 1987). Besides, there is little evidence to show that the measurements give the clinician more information regarding restricted movement than would be the case with subjective observations (Pearcy and Hindle, 1989; Portek et al., 1983). The surface of the back has a variable relationship to the spine. Accurate measurement of the range of motion, therefore, is very difficult (Stokes et al., 1987).

Two-dimensional radiographic measurement of the primary movements of spinal flexion, extension, and lateral bending can be used clinically (Hanley et al., 1976), but these measurements will become inaccurate if out of plane movements occur (Benson et al., 1976; Stokes et al., 1987), and are liable to considerable error

(Benson et al., 1976). During motion in the coronal plane, associated sagittal and transverse plane motions may occur. Therefore, measurement confined to one plane does not give information concerning accompanying movement in other planes. Moreover, radiological measurements are expensive, require exposure of the subject to harmful radiation, and are not always accessible to the physiotherapist (Fitzgerald et al., 1983). There have been reports suggesting that the most accurate measurements in vivo rely upon radiography and may involve the insertion of Steinman pins into the spinous processes (Gregerson and Lucas, 1967; Lumsden and Morris, 1968), however such techniques are invasive, uncomfortable and poorly tolerated by subjects.

Although many methods giving one or two-dimensional measurements have been reported and are used clinically, the choice of an accurate and clinically feasible method of measuring spinal mobility is difficult. Nearly all the methods of measuring spinal mobility have some disadvantages (Einkauf et al., 1987; Pearcy et al., 1987; Portek et al., 1983). Since the spine is a complex structure exhibiting multi-axial motion, it should be expected to undertake complex movements in three dimensions (Hindle et al., 1990). The three-dimensional structure of the articulations between vertebrae, and the complexity of the associated ligamentous and muscular attachments, result in complex movements (Pearcy, 1985). Whatever the primary rotation about one axis, there are likely to be accompanying rotations about the two orthogonal axes. For example, when the spine is voluntarily bent laterally, individual intervertebral joints will exhibit some flexion or extension with axial rotation (Hindle et al., 1990; Pearcy et al., 1984; 1987; Thurston, 1982). Also, the differences in the orientation of spinal articulations in each trunk segment will result in different patterns of accompanying movement (Panjabi et al., 1989). Alterations to movements produced by a spinal disorder may not affect the total range of movement, but the overall pattern of the movement might be affected. Ideally a three-dimensional measurement system involving continuous monitoring of motion should be employed to describe the kinematic features of the spine (Hindle et al., 1990).

Despite a history of spinal movement analysis spanning over 60 years (Bakke, 1931), methodological requirements and major technological developments for measurement have been seen only during the last 20 years (Mellin, 1987). Most of the spinal kinematic data pertain to joint angle displacement which in themselves are not enough to define three-dimensional dynamic back movements. Although there is known to be varying contributions to spinal movement from the different regions, there has not been any study describing the kinematic characteristics of the lower thoracic spine, lumbar spine or the overall thoracolumbar segment in healthy subjects.

A description of normal movement in the spine is essential before an understanding of the pathological movement can be gained. Most researchers are interested in the range of motion of the spine and back movement characteristics in people suffering back pain. Marras and Wongsam (1986) studied range of motion and angular velocity of forward flexion at preferred and maximum speeds of motion in normals and in back pain subjects. They reported that significant decreases in range of motion and velocity were found in back pain group for both speeds. McIntyre et al. (1993) studied trunk motion against resistance set at 50% of the recorded maximum isometric torques in the preferred and maximum velocities in normal subjects. Their results showed that the preferred low-back movement characteristics were different from those in which a maximum effort was required.

No contemporary study has reported the effects of altered speed on the kinematic characteristics of the spine. Nor have there been any reports of the normal values of angular velocity of spinal movements in a diverse age range. Velocities achieved by elderly people in some sports-related activities have been reported as being less than those achieved by young skilled performers (Cunningham et al., 1986).

It might be expected that the elderly people would also decrease their speed for everyday motion compared to young adults.

2.3 Age-related Changes in Range and Speed of Motion

With advancing age, a general decline in spinal movement occurs as a result of increasing stiffness of the soft tissue elements. These changes in tissue compliance are associated with changes in the shape and structure of the intervertebral discs and the vertebral column itself (Twomey and Taylor, 1983). Age related changes within the connective tissue proteins, elastin and collagen, have been detected, with alterations in their physical properties, in particular, compressibility (Davies, 1983; LaBella and Paul, 1965). Most of the factors limiting joint motion have been shown to reside in the soft tissues; i.e., the muscles, tendons and joint capsule account for approximately 98 percent of the passive joint stiffness (Johns and Wright, 1962). There is an increase in crosslinking of the fibrous proteins with advancing age, leading to a reduction in mobility of the connective tissues (Chapman et al., 1972; Johns and Wright, 1962; LaBella and Paul, 1965). Alnaqeeb et al. (1984) have shown an increase in the stiffness of, and relative content of fibrous connective tissue in, the muscles of the elderly. Passive extensibility of the muscles is also reduced because of adaptive shortening of soft tissues and lack of functional use. These changes result in reduced compliance of the connective tissue (Saxon and Etten, 1978; Sharma, 1988).

Despite claims that ageing is accompanied by disc thinning, there are no studies that show a general reduction in the disc height in the elderly (Twomey and Taylor, 1991). With increasing age, the disc thickness is maintained and the principal change observed is in the disc shape associated with an increase in the vertebral endplate concavity (Twomey and Taylor, 1985a). The change in disc shape is accompanied by a marked increase in disc stiffness. It has been shown that removal of the posterior ligaments and zygapophyseal joints does not greatly increase the range of forward flexion (Twomey and Taylor, 1983). It appears that increased stiffness in the intervertebral disc is the major reason for the reduction in spinal movement in old people. This can be readily ascribed to the dehydration and fibrosis of older intervertebral discs (Nachemson et al., 1979; Twomey and Taylor, 1984; 1985; Bogduk and Twomey, 1991).

The ageing process usually brings about changes in the articular cartilage which causes the cartilage surface to become rough and irrigular in all joints, and the cartilage elasticity decreases and becomes more easily deformed. By the age of 65, 80 percent of the population has some articular disorder (Kolodny and Klipper, 1976), which leads to a reduced ability of the articular cartilage to recover from compression forces (Roche, 1966). Such changes in the cartilage lead to greater fatiguability and have been linked to an increased susceptibility to osteoarthritis (Radin, 1976; Weightman, 1976). In general, the pattern and the prevalence of joint changes in the elderly arise more frequently with advancing age and many joint disorders are chronic. Such factors might cause the joints to show reduced active and passive ranges of motion.

Similarly, increasing age is associated with a decline in the amount of habitual exercise activity (Twomey and Taylor, 1984). It has been reported that most elderly men and women live a sedentary life style after retirement (Shephard, 1987; Sidney and Shephard, 1977). There is a reduction of the activity patterns and physical capacity in elderly subjects (Twomey and Taylor, 1984; Sidney and Shephard, 1977). Sidney and Shephard (1977) found that both activity measurements and initial assessments of fitness indicated an inactive life style in elderly men and women aged 60 years and over. Smith and Mell (1987) indicated that more active subjects demonstrated less reduced range of motion compared to relatively inactive subjects. Furthermore, increased kyphosis and scoliosis may occur in the elderly population, particularly lumbar and thoracolumbar scoliosis (Robin et al., 1982) which contribute to reduced range. The reduction of daily activities, lack of exercise and poor posture in aged persons can cause adaptive shortening of soft tissues, and a partial loss of movement (McKenzie, 1981; Smith and Mell, 1987). Although most old people can manage everyday activities, back mobility is an important part of good back health (Bergstrom et al., 1985a, 1985b) and this may not be preserved in the elderly.

In order to withstand strains and maintain life at a high quality, the older person should engage in activities requiring greater range of motion and velocities than necessary for activities of daily living. Stress on bones is produced by muscle contraction. The stronger the contraction, the greater the stress; if stress on the bone is decreased, bone density may decrease. Disuse may be a major cause of age-related change in bone. Lack of rapid movement also reduces stress on the joints and may be implicated in the development of osteoarthritis. Due to a lack of fast movements by the elderly, there are no phasic muscle contractions, and fast-twitch muscles are not recruited leading to disuse atrophy in the type II muscle fibres (Rockstein, 1975; McCarter, 1978; Larsson et al., 1979).

In general, elderly people should be encouraged to use as full a range of joint motion as possible (Biegel, 1984) and also be advised not to maintain sustained postures which demand weight transmission through the spine (Twomey and Taylor, 1984). In addition, the preservation of a full range of joint motion will help to reduce the tendency towards adaptive shortening of periarticular connective tissues and muscles (Biegel, 1984; Chapman et al., 1972; Twomey and Taylor, 1984), minimising joint stiffening with increasing age. To maintain range of spinal motion and help prevent bone loss in the vertebrae, active spinal motion at a sufficiently high speed should also be encouraged.

Besides the reduction in range of motion, probably the main problem in older people is a decrease in speed of motion. Decline in muscle fibre cross-section and muscle mass will limit force production capability, movement speed, and reaction to rapid stimuli (Rockstein, 1975). With advancing age, decreases in mitochondrial enzymes lead to impairment of energy supply and tension development in muscles. Concomittant impairment of excitation-contraction coupling and membrane depolarisation result in decreased speed of muscle contraction (Ermini, 1976). Strength will thus be affected. Together with the muscular changes, the capability of the neuromuscular junction to sustain transmission of nerve impulses from the neuronal axon to the muscle fibre decreases. The amount of acetylcholine (ACh), the neurotransmitter at the neuromuscular junction, declines and the balance between nerve terminal growth and degeneration becomes less stable. These changes, which are characterised by their high variability (i.e., some neuromuscular junctions remain unaffected), are associated with altered membrane structure. Membrane alterations are manifested by reduced membrane potentials, lowered uptake of choline (the ACh precursor), and less uniform distribution of ACh receptors (Smith and Rosesheimer, 1984). Motor nerve conduction velocity is reduced in old age (Delbeke et al., 1978). With increasing age, the aforementioned changes at the neuromuscular junction may lead to the reduction in speed of active movement.

2.4 Summary of Research Problems

Most of the spinal kinematic data reported generally in the literature are reported in terms of maximum angular displacement without describing the characteristics of the movements, including their angular velocities. Due to the complexity of the structure of the spine, the kinematics of the spine could be better quantified and identified by an analysis of the relevant displacements over time and also need to take into account the patterns of displacement and velocity in three dimensions.

There is evidence that spinal range of motion decreases with increasing age. Most reported studies have been directed towards the age-related changes in range of lumbar spine motion. There are known to be different contributions to anatomical movements from the different regions of the spine, however there has been little research into age-related changes in the individual kinematic characteristics of the lower thoracic, lumbar or overall thoracolumbar spine in normal subjects.

A reduction in speed of motion may also be the main problem in older people and may affect the kinematics of the spine. There does not appear to have been any study reporting the effects of altered speed of movement on the kinematic characteristics of the spine nor any reports of the normal values of angular velocity of spinal movements in a diverse age range.

The present investigation was designed to describe the kinematic characteristics of the lower thoracic spine, the lumbar spine and the overall thoracolumbar spine in normal healthy subjects. The relationships between age, gender and speed of motion on the kinematic characteristics of the spine were also studied.

CHAPTER 3

METHODS

CONTENTS

METHODS

3.1 Introduction

The purpose of this study was to investigate the relationship between chronological age and the kinematic characteristics of the defined segments of the spine during movements at two different speeds. The speeds of movement in the present study were determined by the subject (e.g. preferred speed and a self-defined faster speed). The preferred speed motion was performed in order to simulate the normal activity during daily living. The fast speed was to explore any change in range of motion and patterns of movement which might occur. The identification of variables are reported in section 3.3. A sample of normal healthy subjects was assessed using a Motion Analysis™ (ExpertVision) system while they performed a number of anatomical movements and a functional movement (lifting simulation). This study is concerned with the kinematics of the relatively mobile part of the thoracic and the lumbar spine extending from the 6th thoracic vertebra to the 5th lumbar vertebra. The overall thoracolumbar spine (T6-L5) was measured as a composite functional unit and subdivided into the lower thoracic spine (T6-T12) and the lumbar spine (T12-L5).

The kinematic characteristics studied were:-

- Range of motion
- Angular velocity
- Patterns and ranges of associated movements

3.2 Identification of Variables

3.2.1 Anatomical Movements

The mean and standard deviation of the following parameters were calculated for male and female groups at both the preferred and the fast speeds of motion for the overall thoracolumbar, lower thoracic and lumbar spine:-

1.1 Range of motion (degrees)

- Maximum range of motion (ROM) of forward flexion, lateral flexion to the left and right, axial rotation to the left and right.
- Range of forward flexion from the starting to the final positions (absolute range of forward flexion).
- Sum of the maximum ROM of left and right lateral flexion.
- Sum of the maximum ROM of left and right axial rotation.

1.2 Angular velocity (degrees/second)

- Average angular velocity of forward flexion, lateral flexion and axial rotation.
- Peak angular velocity of forward flexion, extension (from the flexed position), lateral flexion, rotation from left to right and rotation from right to left.

1.3 Range of motion of the associated movements (degrees)

- ROM of the associated lateral flexion and axial rotation during the primary movement of forward flexion.
- ROM of the associated forward flexion and axial rotation during the primary movement of lateral flexion.
- ROM of the associated forward flexion and lateral flexion during the primary movement of axial rotation.

3.2.2 Seated Lift

The mean and standard deviation of the following parameters were calculated for male and female groups at both the preferred and the fast speeds of motion for the thoracolumbar and the lumbar spine:-

2.1 Range of motion (degrees) of forward flexion, lateral flexion and axial rotation.

2.2 Time to maximum displacement of the primary movements (recorded as a percentage of the cycle of movement).

2.3 Peak angular velocity (degrees/second) of the primary movements.

3.3 Subjects

Subjects were voluntary participants from the academic and non-academic staff and the students of the University of Sydney and also from the local community, e.g. golf club, bowling club and community centre, etc. None of these subjects had experienced back or lower limb pain during the preceding six months nor had they any history of spinal or hip joint surgery. Subjects with pain or stiffness of the shoulder joints were excluded from this study as were those regularly taking medication likely to affect muscle function or control of balance. Such physical impairments would have compromised the normative data of the present study.

Forty-six male and fifty-four female volunteers aged over 20 years were included. Subjects were allocated to one of three age groups: 20 to 35 (young group), 36 to 59 (middle-aged group) and 60 years and over (elderly group). Each group contained 15-20 subjects. Details of the ages, weight and height of subject groups are presented in Table 3.1. The reasons in dividing the subjects into three age groups will be discussed in section 5.2.

Subjects were informed of the nature of the test (see Appendix A) and were at liberty to withdraw from the test at any time. A form indicating the subject's informed consent to the test was signed by each subject (see Appendix B). Subjects were interviewed by the researcher to categorize the level of activities of daily living and general health (see Appendix C). A questionnaire modified from that used by the Australian Heart Association was applied to assess activity level of the subjects over 60 years. On the basis of the criteria used in the questionnaire, elderly subjects in this study were physically active and lived independently.

Table 3.1 Means (and standard deviations) of study group profile.

Gender	Group	N	Age (years)	Weight (kg)	Height (cm)
Male	Young	15	27.1(4.3)	75.9(12.5)	177.0(8.6)
	Middle-aged	15	44.3(6.6)	72.9(10.5)	171.4(9.9)
	Elderly	16	70.0(7.1)	73.1(8.7)	169.6(5.0)
Female	Young	20	27.1(5.1)	58.7(11.3)	163.6(6.5)
	Middle-aged	18	43.1(7.8)	60.3(10.7)	161.4(7.8)
	Elderly	16	68.3(5.7)	61.1(9.3)	158.6(7.0)

3.4 Instrumentation

The Motion Analysis ExpertVision™ system is an automated three-dimensional motion tracking (digitising) and analysis system. The system can track up to 30 individual reflective markers applied to a subject, therefore the kinematics of multiple trunk segments can be measured at the same time. The principal components of the system are:

1) Camera system with or without a set of VHS video recorders

2) A video processor (Motion Analysis Corporation)

3) A minicomputer (SUN workstation)

For this study, four video cameras (NEC model T1-23A CCD camera, lens 12.5-75 mm. zoom) were used to record the images from the markers at a sampling frequency of 60 frames per second. The cameras were positioned approximately 3.5 meters away from the subjects and placed at approximately 50 degrees to each other [Figure 3.1]. Cameras number one and four were 2.5 meters above the floor height, whereas the other two cameras (cameras number two and three) were 1.8 metres above the level of the floor. The cameras were positioned such that the visibility of all markers in at least two cameras during the whole trial was ensured, and that potential merging of marker images was avoided. 75 watt spot lamps were mounted next to each camera.

The video processor (Motion Analysis Corporation VP320) accepts synchronised simultaneous video images from four cameras. The system automatically digitises the marker outlines which are stored in memory as pixel positions corresponding to the outline of each marker. The digitised data was transferred to a Sun graphics workstation and stored in files on the hard disc. These data are time-synchronised and thus suitable for use with the 3D ExpertVision tracking and analysis system. The files of pixel position were used to identify each marker and its centroid (by the tracking process). The 3D-path of each marker centroid was determined and checked for missing or crossed paths and the resulting position-time data files stored. The coordinate values were available for further mathematical manipulation.

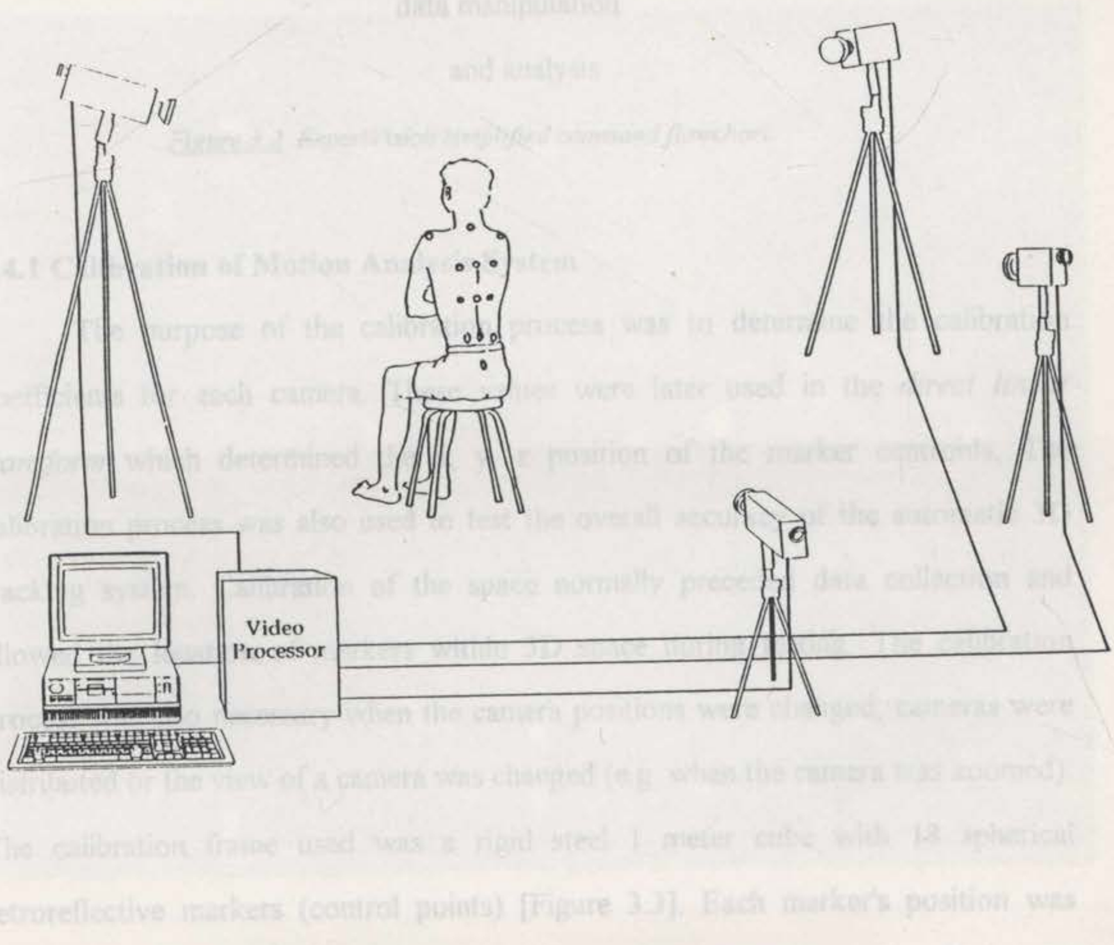


Figure 3.1 Schematic of camera placement.

video input

↓

video processor

(automatic digitisation)

↓

digitised video data files

(stored in the computer)

↓

tracking processes

(marker identification and centroid calculation)

↓

realisation of 3D coordinates (x,y,z)

and path for each marker

↓

data manipulation

and analysis

Figure 3.2 ExpertVision simplified command flowchart.

3.4.1 Calibration of Motion Analysis System

The purpose of the calibration process was to determine the calibration coefficients for each camera. These values were later used in the *direct linear transform* which determined the x, y, z position of the marker centroids. The calibration process was also used to test the overall accuracy of the automatic 3D tracking system. Calibration of the space normally preceded data collection and allowed the location of markers within 3D space during testing. The calibration process was also necessary when the camera positions were changed, cameras were distributed or the view of a camera was changed (e.g. when the camera was zoomed). The calibration frame used was a rigid steel 1 meter cube with 18 spherical retroreflective markers (control points) [Figure 3.3]. Each marker's position was certified by the Surveying Measurement Laboratory, School of Surveying, University of New South Wales. The calibration frame was painted matt black to minimise reflection and was placed in the field of view of all cameras.

Data were collected for one second at 60 Hz. Digitised video images of the static calibration cube for 60 frames were obtained. These digitised image data were fed directly into the 3D calibration software. The calibration coefficients together with the positions of each camera in xyz-space were calculated with respect to the zero reference point of the calibration frame, displayed and saved to an "environment" file. The overall accuracy of the calibration process and the accuracy of identification of the correct marker was represented in terms of the "norm of residuals". No further adjustment or relocation of the cameras occurred after calibration. If any camera was moved accidently, the system was recalibrated.

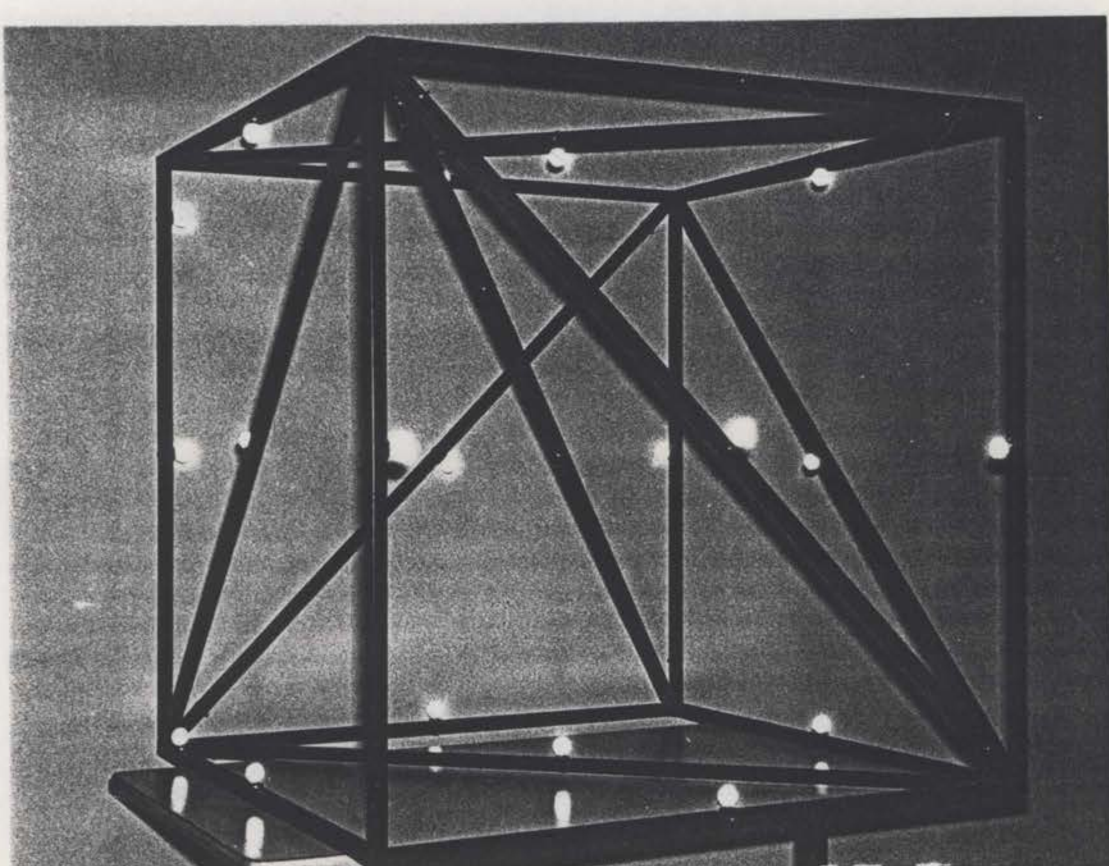


Figure 3.3 Calibration frame.

The "norm of residuals" is a criterion of the accuracy of the calibration and tracking process and is used to determine whether two images of an object belong to that object. The norm of residuals is the square root of the sum of squares of the (perpendicular) distances between the (x,y,z) location to the ray of each camera divided by (n/2) where n is the number of cameras. For this study the norm of residuals values obtained in each test were between 0.1 and 0.3 which, according to the manufacturer specification, were in the acceptable range. [The manufacturer's acceptable value is less than 1.0]. Factors that can decrease the accuracy of the resulting 3D coordinates include imprecise focussing, lens distortion and marker imperfections. In addition, if the marker is not seen by the camera as a sphere, or there is a merging of markers in one or more of the camera views, the estimation of the centre of the sphere may be offset or the centroid of the markers may shift, leading to an apparent movement of the marker.

3.4.2 Accuracy and Reliability of Motion Analysis System

The manufacturers of the Motion Analysis system report high accuracy and precision of the ExpertVision™ three dimensional four camera 60 Hz system. The calibration frame used by the manufacturer was a rigid steel cube approximately 30cm X 30cm X 30cm in dimensions with eight spherical retroreflective markers. The accuracy and precision test results were :

3D Static :

Accuracy : 1 part in 6000 of the field of view.

Precision : 1 part in 4250 of the field of view.

3D Dynamic :

Accuracy : 1 part in 2000 of the field of view.

Precision : 1 part in 2000 of the field of view.

Linden et al. (1992) demonstrated high accuracy and reproducibility of angles calculated from spherical reflective markers by use of the Motion Analysis video system with two cameras using a standard goniometer at three positions. The intraclass correlation coefficient for each location tested was 0.99. Average within-trial variability was less than 0.4 degrees at all locations.

Therefore, when the length of the calibrated volume is 200 cm, it could be expected that the coordinates of a reflective marker could be located to within 1 millimeter of the marker's actual location. Although data relating to the accuracy of the system is provided by the manufacturer, the accuracy of measurement should be established for each experiment. For this study, the accuracy and reliability of the Motion Analysis™ (ExpertVision) four camera system were evaluated under static conditions to determine the measurement error of the system (see Experiment I; Appendix D.). The results of this test indicated that the system was highly accurate in measuring the position of markers in a calibrated volume of 1m X 1m X 1m. The average measurement error in each of the three coordinate axes was approximately 1 millimetre. For a camera view of 2 metres, the percentage of average measurement errors were 0.05% for x and y coordinates and 0.01% for z coordinates.

3.5 Experimental Procedure

Subjects wore either a swimsuit or shorts and a singlet for the test. Subjects were fitted with lightweight adhesive body markers consisting of 2.5 cm-diameter hollow spherical reflective targets using double side adhesive tape and hypoallergenic adhesive backing. Thirteen body markers were attached to the subject's back [Figure 3.4]. In order to minimise motion of markers on the skin, the position of each marker was checked between tests and at the conclusion of the test session by the researcher.

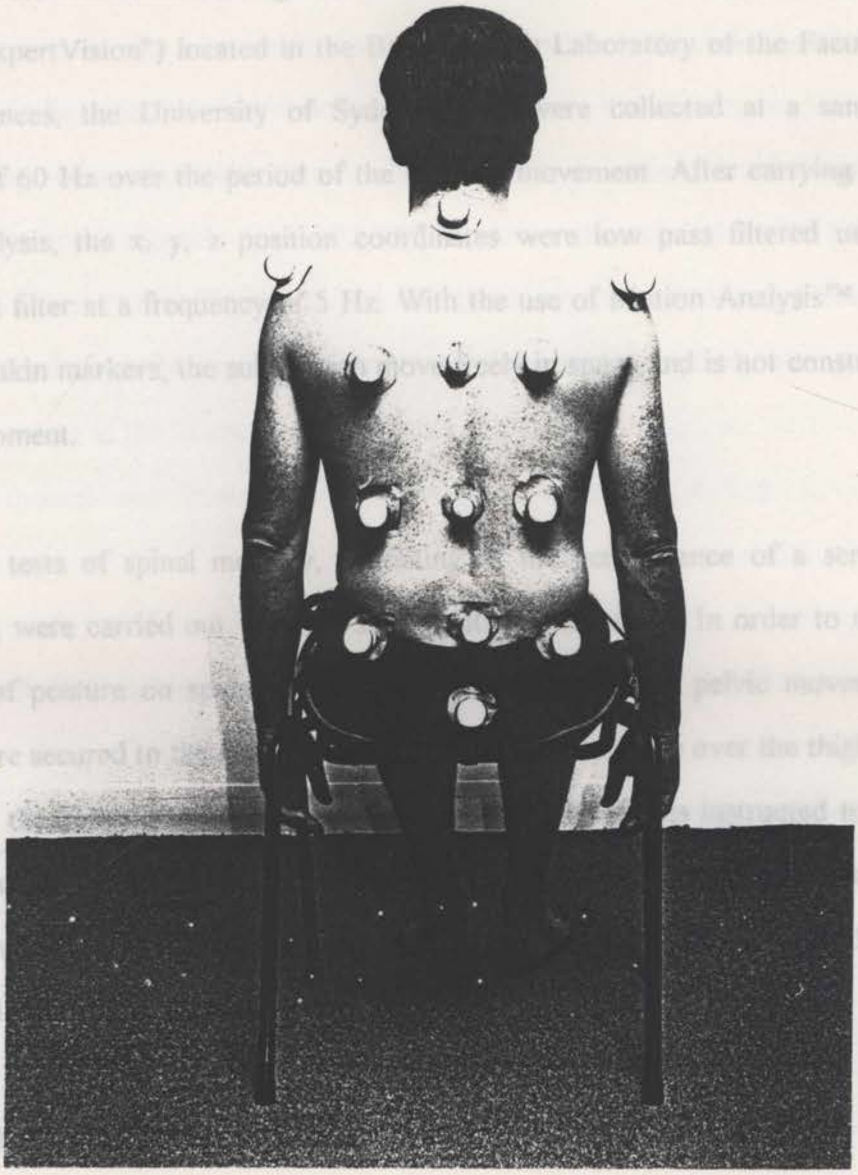


Figure 3.4 *Positions of the thirteen body markers: 1.Left acromion process. 2.Spinous process of 7th cervical vertebra. 3.Right acromion process. 4.Left medial border of scapula at the level of 6th thoracic vertebra (inferior angle of scapula). 5.Spinous process of 6th thoracic vertebra. 6.Right medial border of scapula at the level of 6th thoracic vertebra (inferior angle of scapula). 7.Left lateral border of erector spinae muscles at the level of 12th thoracic vertebra. 8.Spinous process of 12th thoracic vertebra. 9.Right lateral border of erector spinae muscles at the level of 12th thoracic vertebra. 10.Left posterior superior iliac spine. 11.Spinous process of 5th lumbar vertebra. 12.Right posterior superior iliac spine. 13.Sacrum.*

Subjects were filmed using a four camera automated video system (Motion Analysis "ExpertVision") located in the Biomechanics Laboratory of the Faculty of Health Sciences, the University of Sydney. Data were collected at a sampling frequency of 60 Hz over the period of the relevant movement. After carrying out a Fourier analysis, the x, y, z position coordinates were low pass filtered using a Butterworth filter at a frequency of 5 Hz. With the use of Motion Analysis™ video system and skin markers, the subject can move freely in space and is not constrained by any equipment.

The tests of spinal mobility, consisting of the performance of a series of movements, were carried out with the subject sitting on a stool. In order to reduce the effect of posture on spinal motions and eliminate hip and pelvic movements, subjects were secured to the stool by two broad nylon straps, one over the thighs and one around the pelvis. During the measurement, the subject was instructed to keep both feet flat on the floor. Each movement was practised three times and the subject was asked to move through range at his/her preferred speed and also at a self-defined faster speed. The order of testing was randomised.

Each subject performed three anatomical movements, forward flexion, lateral flexion and rotation, and a lifting simulation, starting and ending in a relaxed upright posture seated on the stool. Each of the movements was performed four times.

3.6 Data Reduction

The process of reduction of data obtained in this study was organized in the following order:-

- Transformation of marker centroids to coordinate system locations
- Normalisation of data
- Derivation of Euler angles
- Computation of angles and angular velocities

3.6.1 Transformation of Marker Centroids to Coordinate System Locations

The purpose of a coordinate system is to allow the relative position between two bodies to be specified. The description of motion is the characterisation of the relative change of position with time. In this study, the trunk was divided into three segments, the upper thoracic spine (C7-T6), the lower thoracic spine (T6-T12) and the lumbar spine (T12-L5). Figure 3.4 demonstrates the positions of the body markers. To calculate the angular displacement of the spine, the body markers were used to formulate of the following 4 coordinate systems:-

- the upper thoracic coordinate system was formed by markers 2, 4, 5, 6

      2
4   5   6

- the lower thoracic coordinate system was formed by markers 5, 7, 8, 9

      5
7   8   9

- the lumbar coordinate system was formed by markers 7, 8, 9, 11

7   8   9
      11

- the pelvis coordinate system was formed by markers 10, 11, 12, 13

10   11   12
       13

In this study, the x axis of the laboratory reference system is the anterior-posterior axis, the y axis is the medial-lateral axis and the z axis is the vertical axis. Subjects were positioned facing the direction of the positive x axis, with the positive y axis directed towards their left side.

The segmental embedded axes were determined as follows. The first axis, caudo-cephalic, was defined by a unit vector parallel to the spinous process markers. The provisional second axis was defined as a vector determined by the lateral markers. The third posteroanterior axis was defined as the cross product of the first (vertical) and provisional second axes. The true second axis was then defined as the cross product of the vertical and posteroanterior axes.

3.6.2 Normalisation of Data

In each movement tested, the four repeated movements were time normalised and averaged for one cycle of movement using the ExpertVision software. To compute the starting and ending points of the cycle of movement, data were resolved into the components along each of the three axes. The onset of forward flexion and of the lifting simulation was identified by the commencement of displacement of marker 2 (at the spinous process of the 7th cervical vertebra) along the anteriorly directed x axis and the completion of the cycle by the end of that displacement [Figures 3.5 and 3.6]. Similarly, the cycle of lateral flexion was identified by the commencement of motion of marker 2 along the laterally directed y axis and the completion of that cycle by the beginning of the next movement [Figure 3.7].

Rotation occurred around the vertical axis. Therefore, the movement of markers placed over the spinous processes could not be used to indicate the starting or the ending point of the movement [Figure 3.8]. Movement of the right or left acromion marker, which was stable relative to the trunk because the arms were crossed, was therefore used to identify the cycle of rotation. However, the left and right shoulders did not consistently pass the neutral position (starting position) at the same time. The cycle of movement of the two shoulder markers, therefore, was not always symmetrical, leading to difficulty in identifying the neutral position. To compensate for the asymmetry, the peak of rotation was chosen to define the commencement of the cycle of rotation. The peak occurred at the same time for both left and right shoulders. One cycle, therefore, was defined as being from maximum left rotation to the next maximum left rotation.

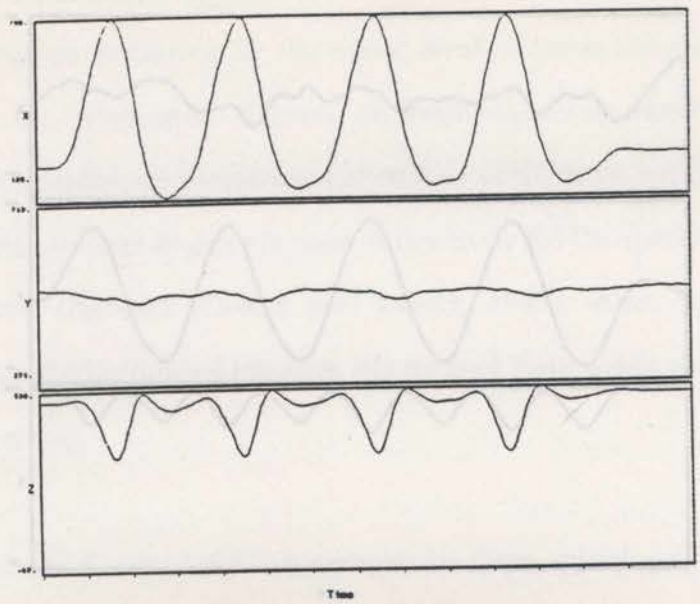


Figure 3.5 Displacement data of four repeated movements of ***forward flexion*** in x, y and z directions of marker 2 at the 7th cervical vertebra. [Horizontal axis represents time in seconds, vertical axis represents marker displacement in millimetres].

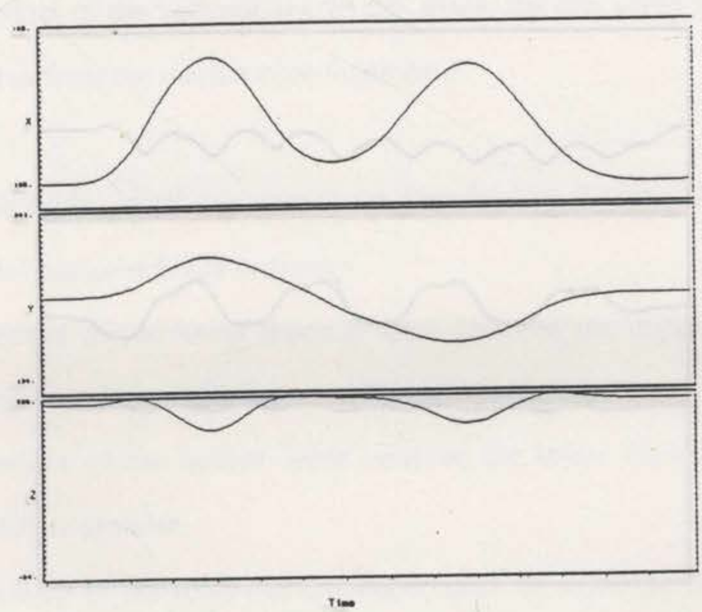


Figure 3.6 Displacement data of the ***lifting simulation*** in x, y and z directions of marker 2 at the 7th cervical vertebra. [Horizontal axis represents time in seconds, vertical axis represents marker displacement in millimetres].

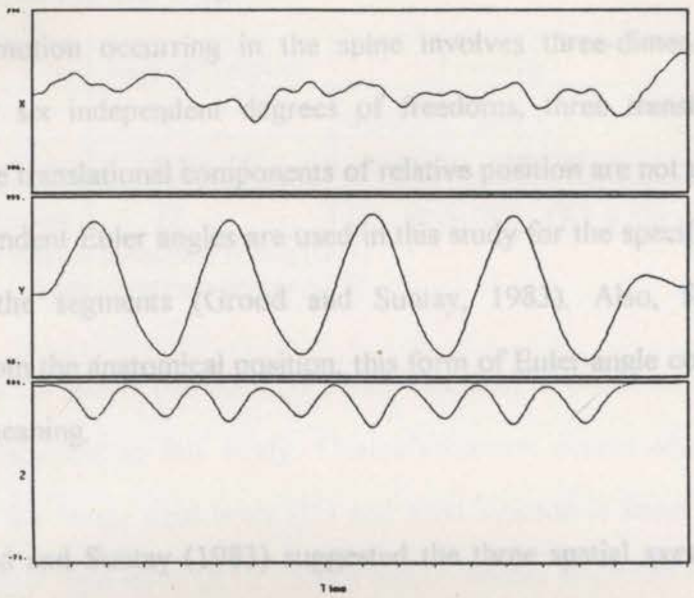


*Figure 3.7 Displacement data of four repeated movements of **lateral flexion** in x, y and z directions of marker 2 at the 7th cervical vertebra. [Horizontal axis represents time in seconds, vertical axis represents marker displacement in millimetres].*

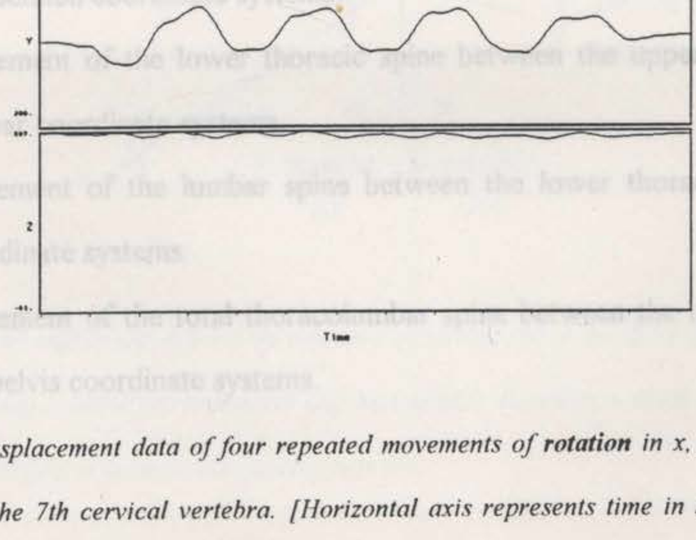


*Figure 3.8 Displacement data of four repeated movements of **rotation** in x, y and z directions of marker 2 at the 7th cervical vertebra. [Horizontal axis represents time in seconds, vertical axis represents marker displacement in millimetres].*

3.6.3 Derivation of Euler Angles

The motion occurring in the spine involves three-dimensional movement described by six independent degrees of freedoms, three translations and three rotations. The translational components of relative position are not used in this study. Order independent Euler angles are used in this study for the specification of relative attitude of the segments (Grood and Suntay, 1983). Also, for small angular deviations from the anatomical position, this form of Euler angle computation retains anatomical meaning.

Grood and Suntay (1983) suggested the three spatial axes about which the corresponding rotational motions occur. Two pairs of axes, the body fixed axes, are embedded in each of the two bodies whose relative motion is to be described. Their direction is specified by unit vectors. The fixed axes move with the bodies so that the spatial relationship between them changes with the motion. The third axis is the common perpendicular to the body fixed axes, therefore, its orientation is given by the cross product of the unit vectors. In this study, the unit vectors of each segment were calculated from the marker coordinate data.

In this study, spinal movements are described by the relative motion between two locally defined coordinate systems:-

- movement of the lower thoracic spine between the upper thoracic and the lumbar coordinate systems.
- movement of the lumbar spine between the lower thoracic and the pelvis coordinate systems.
- movement of the total thoracolumbar spine between the upper thoracic and the pelvis coordinate systems.

Table 3.2 Calculation of angles between coordinate systems 1 and 2 using Euler angles.

Angle	Axis of rotation	Formula
Rotation	K1	acos (J1 . (K1 x J2)) - 90
Lateral flexion	K1 x J2	acos (K1 . J2) - 90
Forward flexion	J2	90 - acos (K2 . (K1 x J2))

Note: system 1 is upper coordinate system (UCS)
system 2 is lower coordinate system (LCS)

Table 3.2 shows the standard vector notation formulae used to calculate the angular displacement in this study. Flexion/extension occurs about the horizontal fixed axis of the lower rigid body (J2) and axial rotation is about the vertical fixed axis of the upper rigid body (K1). Lateral flexion occurs about the floating axis which is K1xJ2 [Figure 3.9].

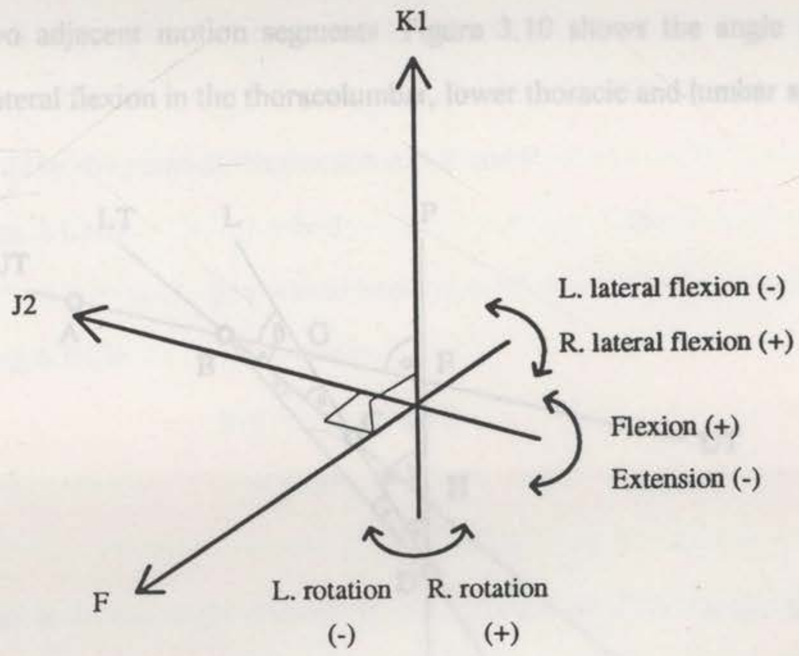


Figure 3.9 Joint angles are defined by rotations occurring about the three joint coordinate axes. Flexion/extension is about the horizontal (J2) axis of LCS. Rotation is about the vertical (K1) axis of UCS. Lateral flexion is about the floating axis (F).

For example, the relative motion between the lower thoracic spine and the pelvis is referred to in this study as movement of the lumbar spine. The axis of forward flexion is the horizontal fixed axis of the pelvis coordinate system. The axis of rotation is the vertical fixed axis of the lower thoracic coordinate system. The axis of lateral flexion is the floating axis which is the cross product of the unit vectors of the two fixed axes.

The biomechanical model used in this study treats the defined segments as rigid links (see Figure 3.10) and ignores the fact that the movement of each trunk segment would include movement of shared vertebral bodies of the adjacent segments. This was accepted as one of the limitations of the study. In addition, the sum of the lower thoracic and lumbar spine range of motion will not necessarily equal the range of the total thoracolumbar spine because there is an overlap of the angle between two adjacent motion segments. Figure 3.10 shows the angle of forward flexion or lateral flexion in the thoracolumbar, lower thoracic and lumbar spine.

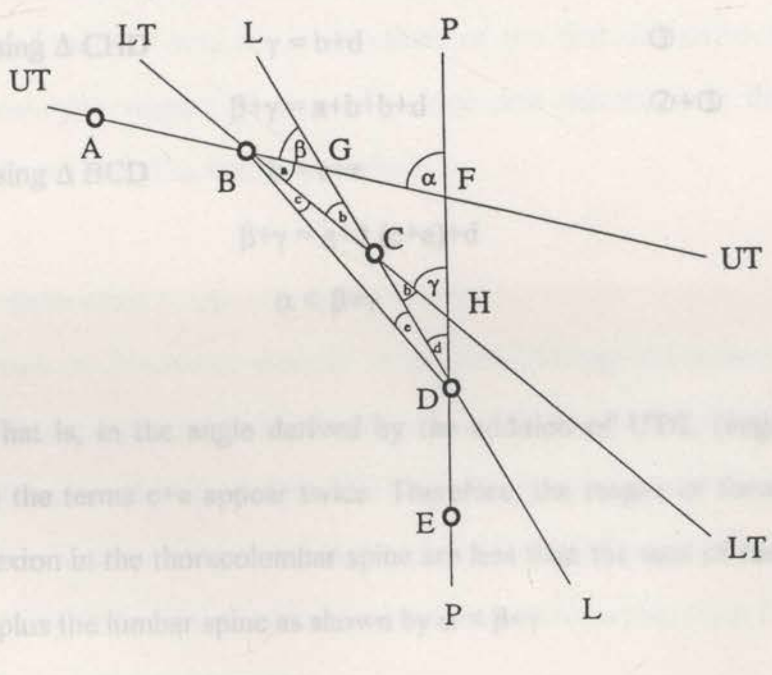


Figure 3.10 Geometrical representation of angulation in the thoracolumbar (α), lower thoracic (β) and lumbar spine (γ) in forward flexion or lateral flexion.

The line, UT, joining markers at C7 (A) and T6 (B) represents the vector of the upper thoracic segment. The line, LT, joining markers at T6 (B) and T12 (C) represents the vector of the lower thoracic segment. The line, L, joining markers at T12 (C) and L5 (D) represents the vector of the lumbar segment. The line, P, joining markers at L5 (D) and sacrum (E) represents the vector of the pelvic segment. The angle of the thoracolumbar spine (α) is the angle between UT and P. The angle of the lower thoracic spine (β) is the angle between UT and L. The angle of the lumbar spine (γ) is the angle between LT and P. Figure 3.10 demonstrates the overlapping of the angle b at the intersection of the vectors representing the long axes of the lower thoracic (LT) and lumbar (L) segments as shown by the following equations.

Let F be the point of intersection of UT and P

using Δ BFD $\quad \alpha = a+c+d+e \quad$ ①

Let G be the point of intersection of UT and L

using Δ BGC $\quad \beta = a+b \quad$ ②

Let H be the point of intersection of LT and P

using Δ CHD $\quad \gamma = b+d \quad$ ③

$\beta+\gamma = a+b+b+d \quad$ ②+③

using Δ BCD $\quad b = c+e$

$$\beta+\gamma = a+2\,(c+e)+d$$

$$\therefore \quad \alpha < \beta+\gamma$$

That is, in the angle derived by the addition of UT/L (angle β) and LT/P (angle γ) the terms c+e appear twice. Therefore, the ranges of forward flexion and lateral flexion in the thoracolumbar spine are less than the sum of range in the lower thoracic plus the lumbar spine as shown by $\alpha < \beta+\gamma$.

3.6.4 Computation of Angles and Angular Velocities

The ExpertVision software produces three dimensional angles as the absolute angle between two vectors, and the direction cosines between a single vector and three orthogonal axes of the frame of reference. These angles do not represent the orientation of the joint motion in the anatomical meaning i.e., forward flexion, lateral flexion or rotation. Therefore, the angles computed by ExpertVision were not used in this study. In the present study, the relative motion between the spine and pelvis was computed on the basis of the definitions of flexion/extension, lateral flexion and axial rotation.

The marker x, y, z values were read, embedded axes were constructed for each segment, joint coordinate systems were determined and the time series relative attitude of the segments calculated using a programme written in the ASYST language (A Scientific System, 1990) by West (1992). The average and peak angular velocities for each movement were also calculated. Average angular velocity was calculated as the total angular displacement divided by time taken for that movement. Peak angular velocity was the peak values of the first derivative of the angular displacement with respect to time. The kinematic results were then stored and subsequently subjected to statistical analysis.

3.7 Error Reduction

Errors in kinematic analysis in studies utilizing computerized movement analysis systems and skin markers have been reported as a common problem (Wood, 1982; Lafortune and Lake, 1991). The method used in this study involved possible sources of error associated with data processing and movement of markers and skin. The efforts made by the researcher to reduce or compensate for these errors are reported in the following sections.

3.7.1 Data Processing Errors

Analysis systems that require hand-digitisation of data are subject to errors associated with the visual identification of joint centres or marker centres on film. The Motion Analysis™ system is computerised and joint centres are digitised automatically, presumably reducing a potential source of error from manual digitisation (Linden et al., 1992).

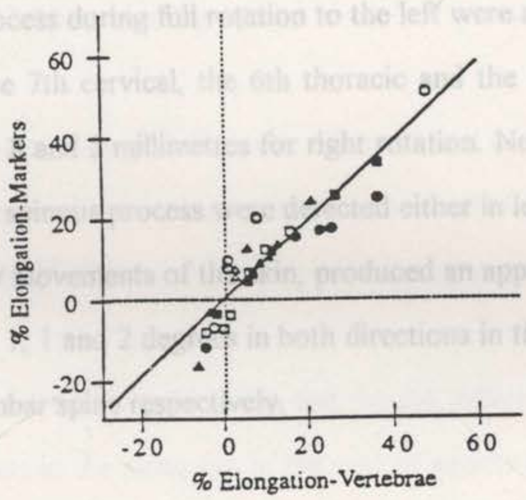
Reliability in the digitisation process is threatened when markers are placed too close together or when their trajectories overlap. In this study, the close proximity of markers at the 6th thoracic vertebra and left and right medial border of scapula (markers number 4 to 6) resulted in occasional coalescence and exchange of the marker trajectories during the process of marker identification (tracking process). The ExpertVision™ software programme allowed for manual correction of the error before continuing with the tracking process. The 3D-path of each marker was also checked and edited by the researcher for missing or crossed paths.

The selection of camera locations was important to minimise the coalescing of marker trajectories. Care was taken to ensure that each marker was seen by at least two cameras during data collection.

3.7.2 Marker and Skin Movements

The use of adhesive body markers introduces a potential source of error due to positional changes of the markers resulting from skin or soft tissue movements (Lafortune and Lake, 1991). In order to minimise this error, Atha (1984) suggested that skin markers should be placed in areas where the skin is firmly anchored. In this study, the markers were placed over the spinous processes of the vertebrae as there is very little overlying soft tissues.

The method used to compute angles required two lateral markers which were located at the lateral border of the erector spinae muscles at the same level of the marker over the spinous process. These two markers may then introduce an error due to soft tissue movement. In order to compensate for this error, a provisional direction vector was defined by these markers and subsequently corrected to be orthogonal to the vector defined by the spinous process markers.



<u>Figure 3.11</u> Correlation between the relative elongation calculated from the position of the markers and the spinous processes in forward flexion (Gracovetsky et al., 1990).

Gracovetsky et al. (1990) studied the relationship between the movement of markers on the skin and the movement of the lumbar spine in forward flexion and lateral flexion as measured directly from radiographs. A high correlation between the elongation as measured from the markers and the true elongation of the spine was reported [Figure 3.11]. The average difference between the angles measured from the markers and the spine was about two degrees in both directions.

The movement of markers on the skin was minimised by using double-sided adhesive tape with a hypoallergenic backing. The position of each marker was checked between tests and at the conclusion of the test by the researcher.

As the subject's spine moves, so does the overlying skin. Therefore, the relationship between the motion of the markers and the kinematics of the spine may be affected by the motion of the skin. During rotation, the skin was drawn across the back, displacing the marker from the central line leading to an apparent movement of the marker over the spinous process. In order to estimate the error introducing by skin movement, distances of the skin moving across the spine during rotation were measured in 10 subjects (see Experiment III; Appendix D). Movements of the skin over the spinous process during full rotation to the left were approximately 10, 9 and 6 millimetres for the 7th cervical, the 6th thoracic and the 12th thoracic vertebrae respectively and 10, 8 and 5 millimetres for right rotation. No movements of the skin over the 5th lumbar spinous process were detected either in left or right rotation. The error, introduced by movements of the skin, produced an approximate apparent angle of lateral flexion by 1, 1 and 2 degrees in both directions in the upper thoracic, lower thoracic and the lumbar spine respectively.

Movements of the skin over the spinous processes during spinal motion indicated that the errors of forward flexion and lateral flexion were about 2 degrees (Gracovetsky et al., 1990) and of rotation also approximately 2 degrees. The evidence supports the use of skin markers to track the motion of the spine. Additionally, with the use of Motion Analysis™ video system and skin markers, the subject can move freely in space and is not constrained by any equipment.

3.8 Statistical Analysis

The statistical analysis of data was performed using the SPSS^X programme (SPSS Inc. Chicago, IL 60611) and Minitab Statistical Software (Ryan, Joiner and Ryan, 1985) both of which are comprehensive tools for managing, analysing and displaying information without extensive manipulation of the data.

Multivariate Analysis of Variance procedures (MANOVA) and correlational regression were used to test for significant associations in the results of this study as shown by the following details:-

- MANOVA was used to test for significant differences in the mean values of range of motion and of angular velocity with respecÛ¥-+@ he age effects, gender effects and speed effects in the lower thoracic, lumbar and the overall thoracolumbar spine.

- Schéffé multiple comparison of pairs was used as a post-hoc procedure to test for the differences between age groups in the case of significant age effects as shown by MANOVA.

- An independent t-test was used to test for the differences between male and female subjects in the same age in the case of gender effects demonstrated by MANOVA.

- A paired t-test was used to test for the differences between the fast and the preferred speeds in each age group in the case of speed effects demonstrated by MANOVA.

- Correlational regression statistics were constructed to analyse the relationship between age and range of motion, and age and angular velocity for each movement. The MSE/MSR ratio less than 20% helped to indicate the strong relationship between age and range of motion, and age and angular velocity for each movement.

- Experimental lack of fit tests were used to test the linearity of the relationships between age and range of motion, and age and angular velocity for each movement. A *p* value of more than 0.05 indicated the linearity of the relationship, permitting a simple linear regression to be applied to the data.

- Pearson product moment correlation coefficients were constructed to analyse the relationships between the primary movement and its associated movements.

CHAPTER 4

RESULTS-ANATOMICAL MOVEMENTS

CONTENTS

RESULTS-ANATOMICAL MOVEMENTS

Introduction

The three dimensional kinematics of the spine were investigated in the three anatomical movements: forward flexion, lateral flexion and rotation [Figures 4.1 to 4.3]. This part of the study was concerned with the overall thoracolumbar spine both as a composite functional unit and subdivided into the lower thoracic and the lumbar spinal segments. (These segments were defined in section 3.1). This part of the study attempts to clarify the separate contributions of the segments to motion. The purposes of this part of the study were:-

- to investigate the relationships between age, gender and speed of motion with respect to the characteristics of the movements, including range of motion, angular velocity and patterns of movement.

- to determine the kinematic patterns of the following primary movements and the associated movements about the two orthogonal axes for the overall thoracolumbar, lower thoracic and lumbar spine:

: forward flexion with associated lateral flexion and rotation

: lateral flexion with associated forward flexion and rotation

: rotation with associated forward flexion and lateral flexion

Forward flexion commenced with the subject sitting upright on a stool with both arms hanging relaxed by the sides, the subject was asked to bend his/her head and trunk forward as far as possible, within comfortable limits and then return to the starting position, while reaching up with both arms [Figure 4.1].

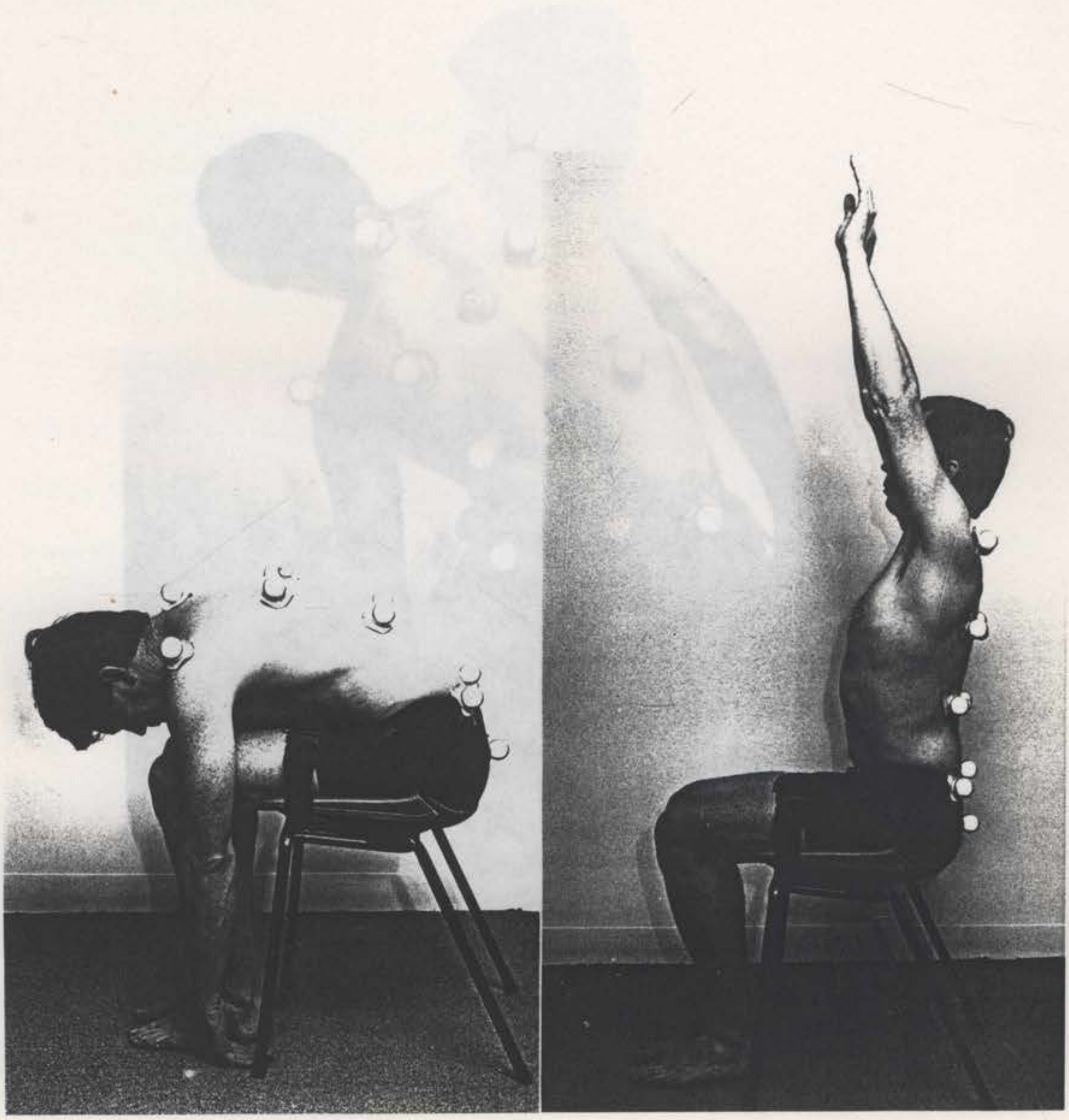
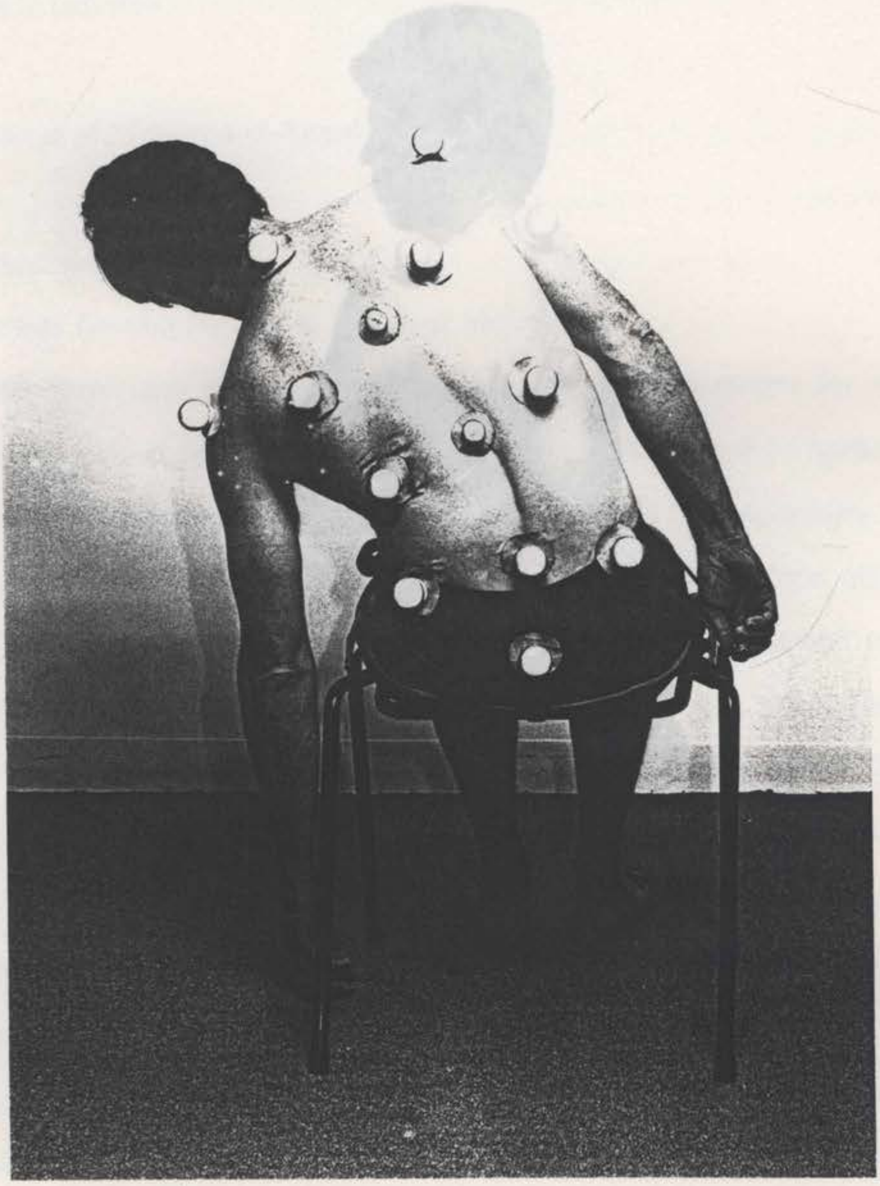


Figure 4.1 Forward flexion.

Left and right lateral flexion commenced with the subject sitting upright on a stool with both arms hanging relaxed, he/she was asked to bend towards the side as far as possible reaching towards a reference point on the ground. The procedure started towards the left then continued to the right [Figure 4.2].



<u>Figure 4.2</u> Lateral flexion.

Left and right rotation commenced with the subject sitting upright on a stool with both arms crossed over his/her chest, he/she was asked to turn the head and trunk together as far as possible to the left then to the right [Figure 4.3].

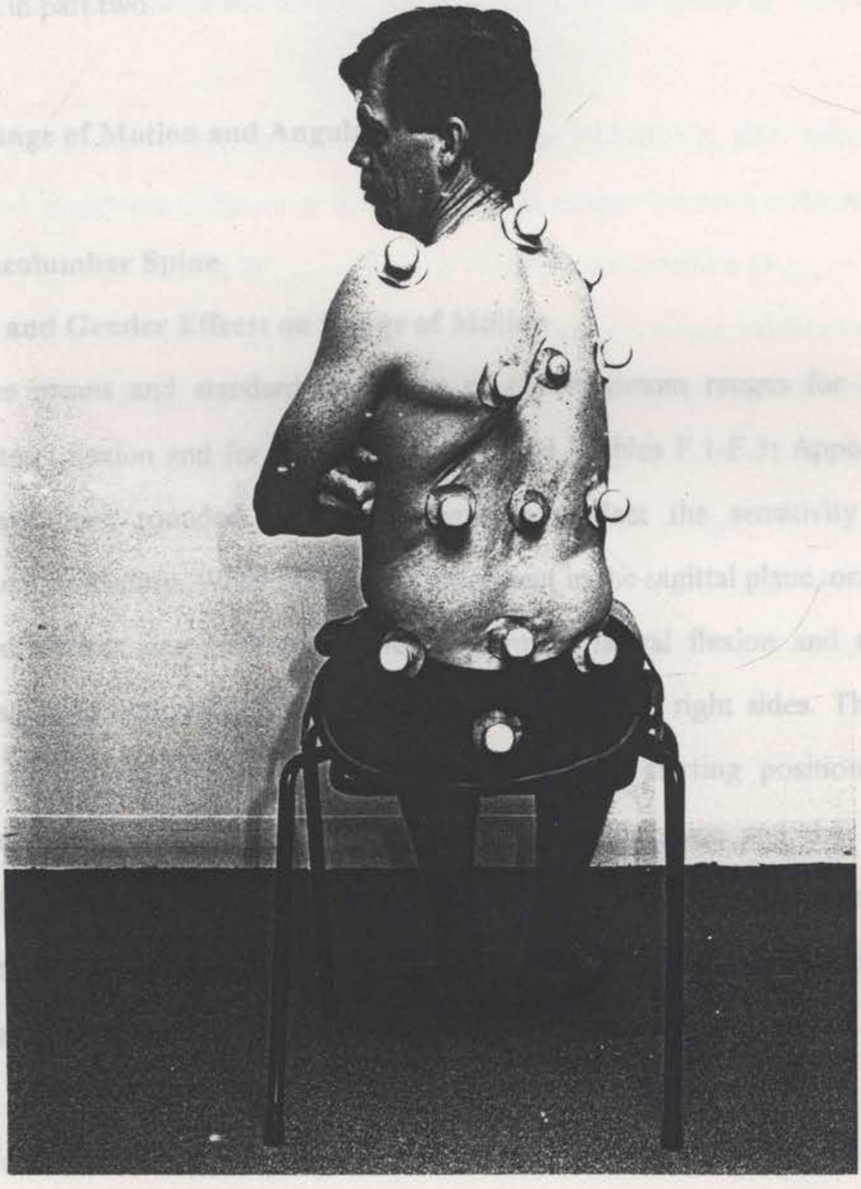


Figure 4.3 Rotation.

Results

The results of this section are presented in terms of range of motion (deg), angular velocity (deg/s) and patterns of movement for forward flexion, lateral flexion and for rotation and are partitioned according to age of the subject. The results are presented in 2 parts; range of motion and angular velocity in part one and patterns of movement in part two.

Part I: Range of Motion and Angular Velocity

4.1 Thoracolumbar Spine

4.1.1 Age and Gender Effects on Range of Motion

The means and standard deviations of the maximum ranges for forward flexion, lateral flexion and for rotation are presented [Tables F.1-F.3; Appendix F]. Values have been rounded to nearest degree to reflect the sensitivity of the measurement procedure. When performing movement in the sagittal plane, only range of forward flexion was measured. When performing lateral flexion and rotation, individuals varied with respect to the ranges to the left and right sides. There is a potential problem in identifying the zero value for the starting position of the movement which could vary due to the curvature of the spine and the subject's posture. Therefore, lateral flexion and rotation are presented as the sum of the movements to the left and right. The group mean values of maximum range of motion are illustrated in Figure 4.4. The decline is seen at both speeds of movement.

Multivariate Analysis of Variance demonstrated significant differences ($p < 0.001$) in the range of motion between the age groups: forward flexion ($F_{2,94} = 14.60$), lateral flexion ($F_{2,94} = 22.34$) and rotation ($F_{2,94} = 22.70$). Table 4.1 shows the results of Schéffé's multiple comparisons between the age groups. There were significant differences in the young/middle-aged male groups compared to the elderly male and female groups for the range of forward flexion whereas no significant differences were detected among the female groups. Differences between young males and middle-aged females were also seen in forward flexion at both speeds of motion. For lateral flexion, significant differences were demonstrated between the young/middle-aged groups and the elderly group for both genders and at both speeds of motion. Differences were also found in the ranges of rotation between the young/middle-aged males and females and the elderly female group ($p < 0.01$).

The between-subjects effects tested by the MANOVA also indicated that there were significant differences in the maximum ranges between male and female groups for forward flexion ($F_{1,94} = 10.38$, $p = 0.002$) and rotation ($F_{1,94} = 5.67$, $p = 0.019$). Young and middle-aged females demonstrated a reduced maximum range of forward flexion compared to male subjects in the same age group. Elderly females showed a marked reduction in the range of rotation as shown in Figure 4.4. The range of lateral flexion showed smaller differences between the genders ($F_{1,94} = 0.16$, $p = 0.693$). No significant differences in gender-age combination effects were detected for any movement, thus there was no difference in the decreasing trend between male and female subjects across age groups.

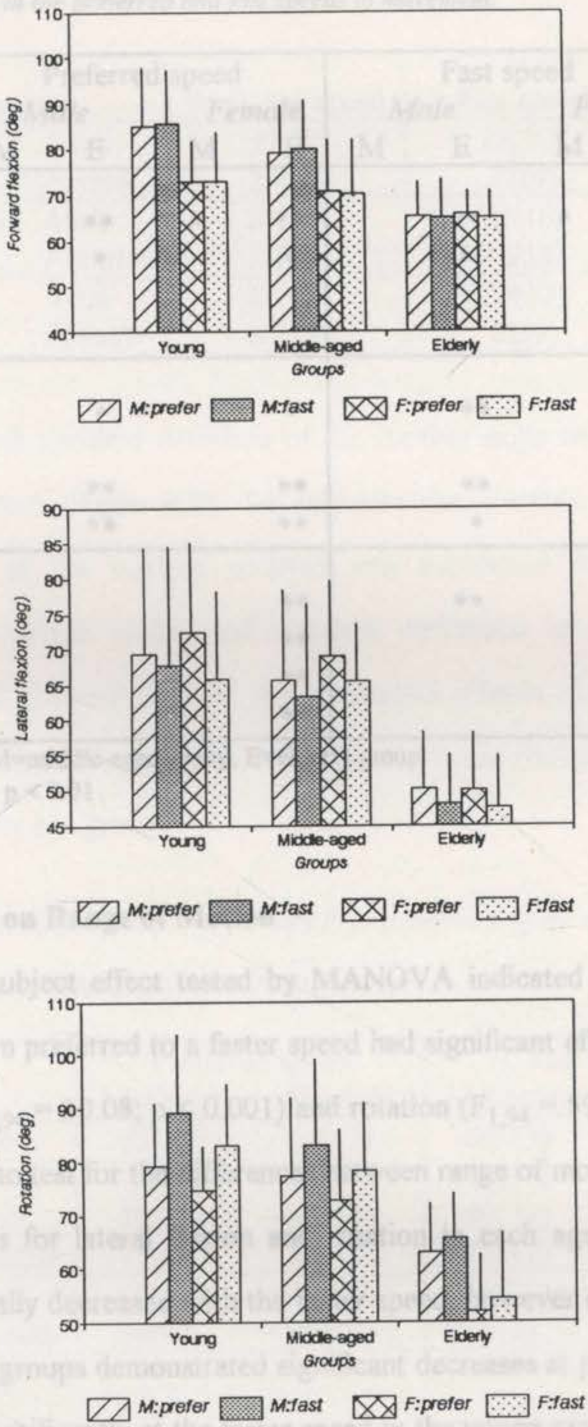


Figure 4.4 *Range of forward flexion, lateral flexion and rotation in the thoracolumbar segment for male and female groups at the preferred and the fast speeds; M=male, F=female, prefer=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].*

Table 4.1 Tests for significance of multiple comparison for range of motion between age groups in the thoracolumbar spine in the preferred and fast speeds of movement.

Movements		Preferred speed				Fast speed			
		Male		*Female*		*Male*		*Female*	
		M	E	M	E	M	E	M	E
Flexion									
Male	Y		**	*	**		**	*	**
	M		*		*		*		*
Female	Y								
	M								
Lat. flexion									
Male	Y		*		*		**		**
	M								*
Female	Y		**		**		**		**
	M		**		**		*		**
Rotation									
Male	Y				**		**		**
	M				**				**
Female	Y				**				**
	M				**				**

Note: Y=young group, M=middle-aged group, E=elderly group.
$* = p < 0.05, ** = p < 0.01$

4.1.2 Speed Effects on Range of Motion

The within-subject effect tested by MANOVA indicated that changing the speed of motion from preferred to a faster speed had significant effects on the ranges of lateral flexion ($F_{1,94} = 30.08$; $p < 0.001$) and rotation ($F_{1,94} = 59.04$; $p < 0.001$). A pair t-test was used to test for the differences between range of motion at the fast and the preferred speeds for lateral flexion and rotation in each age group. Range of lateral flexion generally decreased with the faster speed, however only the young and middle-aged female groups demonstrated significant decreases at $p < 0.05$. Ranges of rotation increased significantly at the faster speed in the young and middle-aged male and female groups ($p < 0.05$).

Table 4.2 Mean values (S.D) in degrees of angulation of the thoracolumbar segment at the starting position for forward flexion at the preferred and fast speeds of motion.

Subject groups		Preferred speed	Fast speed
Young	*Male*	22(7)	22(10)
	Female	10(9)	12(9)
Middle-aged	*Male*	24(11)	23(10)
	Female	12(12)	12(11)
Elderly	*Male*	21(12)	20(12)
	Female	20(13)	21(9)

The mean and standard deviation of the starting angle of the thoracolumbar segment are presented [Table 4.2]. To calculate the absolute range of forward flexion, the angle at the starting position was subtracted from the maximum displacement value. Mean values and standard deviations of the maximum and absolute ranges of forward flexion are presented [Table 4.3]. No significant differences in the absolute range of forward flexion were found between male and female subjects in any age group.

Table 4.3 Maximum and absolute ranges of forward flexion (degrees) of the thoracolumbar segment of male and female groups at the preferred and fast speeds.

Subject groups		Preferred speed		Fast speed	
		Maximum	Absolute	Maximum	Absolute
Young	*Male*	85(14)	63(13)	86(13)	64(10)
	Female	73(8)	63(10)	73(11)	61(10)
Middle-aged	*Male*	79(11)	55(17)	80(12)	57(15)
	Female	71(12)	58(11)	70(12)	58(12)
Elderly	*Male*	65(10)	44(12)	65(11)	45(13)
	Female	66(6)	46(11)	65(7)	43(9)

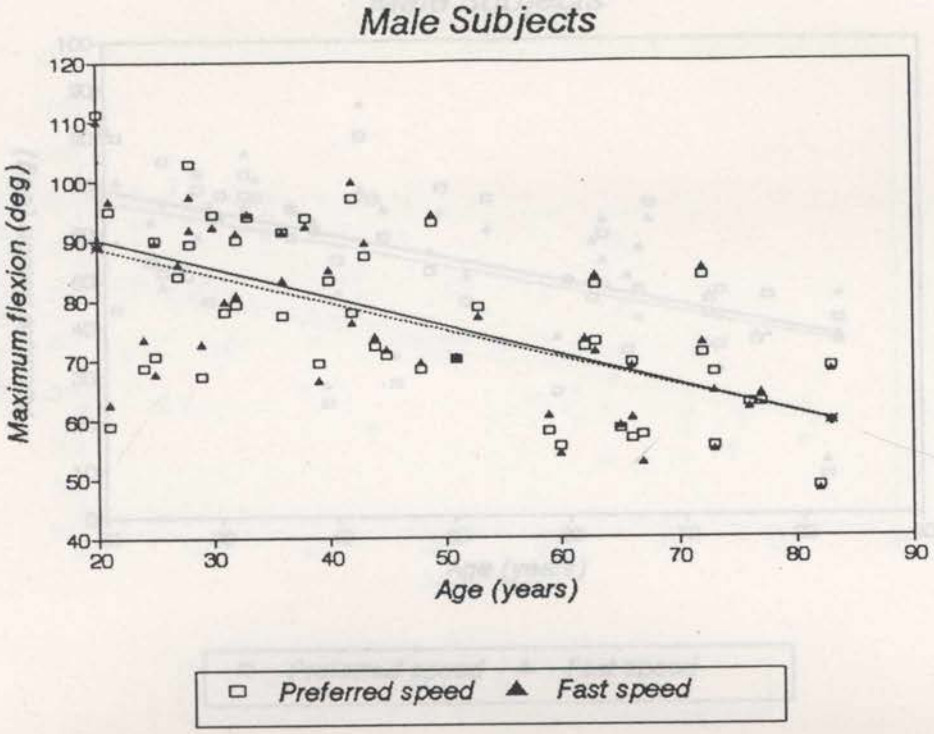
The relationships between range of motion of forward flexion, lateral flexion and rotation and age are illustrated [Figure 4.5]. The experimental lack of fit tests were used to test the linearity of the relationship for each movement. A p value of more than 0.05 would indicate linearity of the relationship. The random distribution of the plotted residuals for each movement over age was also used to indicate the linearity of the relationship. No evidence of lack of fit for linearity was detected in any movement ($p > 0.1$). Significant negative correlations were found between age and the maximum ranges of the three motions in both genders at both the preferred and fast speeds [Table 4.4]. Female subjects demonstrated poor correlations between age and maximum forward flexion values at both speeds. However, age and absolute range of forward flexion in these subjects were strongly negatively correlated at both the preferred and fast speeds. The negative coefficients indicated a reduction of the ranges of forward flexion, lateral flexion and rotation with advancing age in the thoracolumbar segment.

Table 4.4 Correlation coefficients and regression equations for age and range of motion in forward flexion, lateral flexion and rotation at the thoracolumbar segment in preferred (P) and fast (F) speeds of motion.

Movement		Male (n=46)		Female (n=54)	
		r	Equation	r	Equation
Maximum flexion	P	-0.611**	y=89.0-0.47x	-0.341*	y=74.7-0.18x
	F	-0.639**	y=90.1-0.49x	-0.363**	y=75.1-0.22x
Absolute flexion	P	-0.561**	y=66.6-0.48x	-0.583**	y=66.6-0.42x
	F	-0.613**	y=68.6-0.49x	-0.632**	y=66.0-0.44x
Lateral flexion	P	-0.567**	y=75.1-0.49x	-0.615**	y=78.2-0.55x
	F	-0.555**	y=72.9-0.49x	-0.581**	y=71.5-0.46x
Rotation	P	-0.537**	y=85.6-0.46x	-0.601**	y=81.0-0.56x
	F	-0.588**	y=95.7-0.60x	-0.638**	y=90.1-0.70x

Note * = $p < 0.05$, ** = $p < 0.01$, y = range of motion (deg), x = age-20 (years)
r = Pearson product moment correlation coefficient.

The decrease in range of motion was approximately 1 degree every 2 years for all movements in both genders, except for the movement of maximum forward flexion in female subjects which was 1 degree every 5 years.



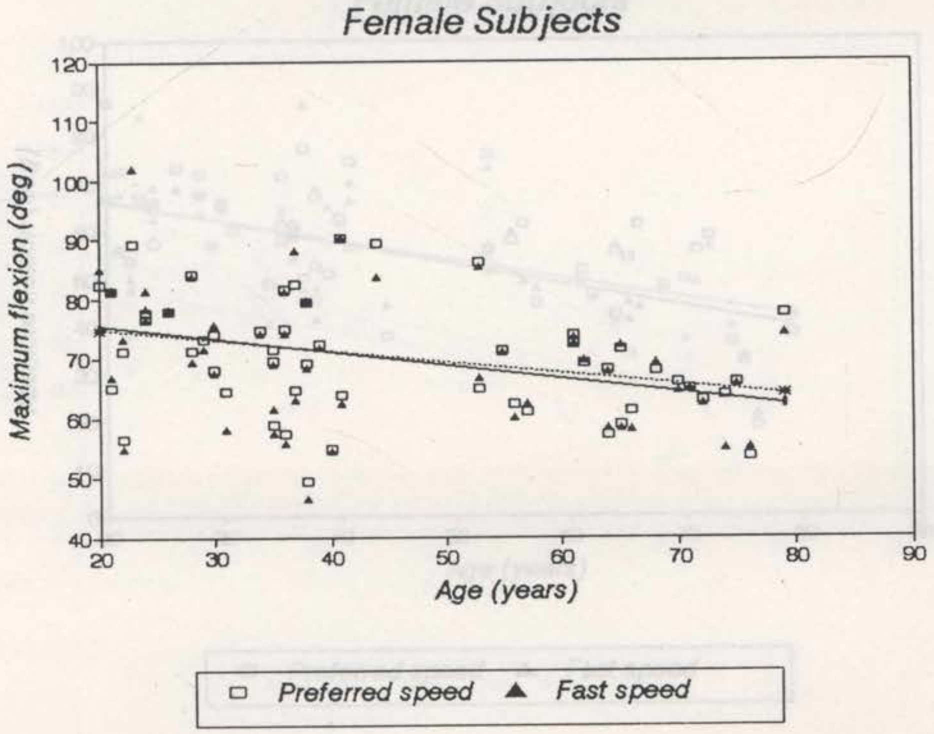
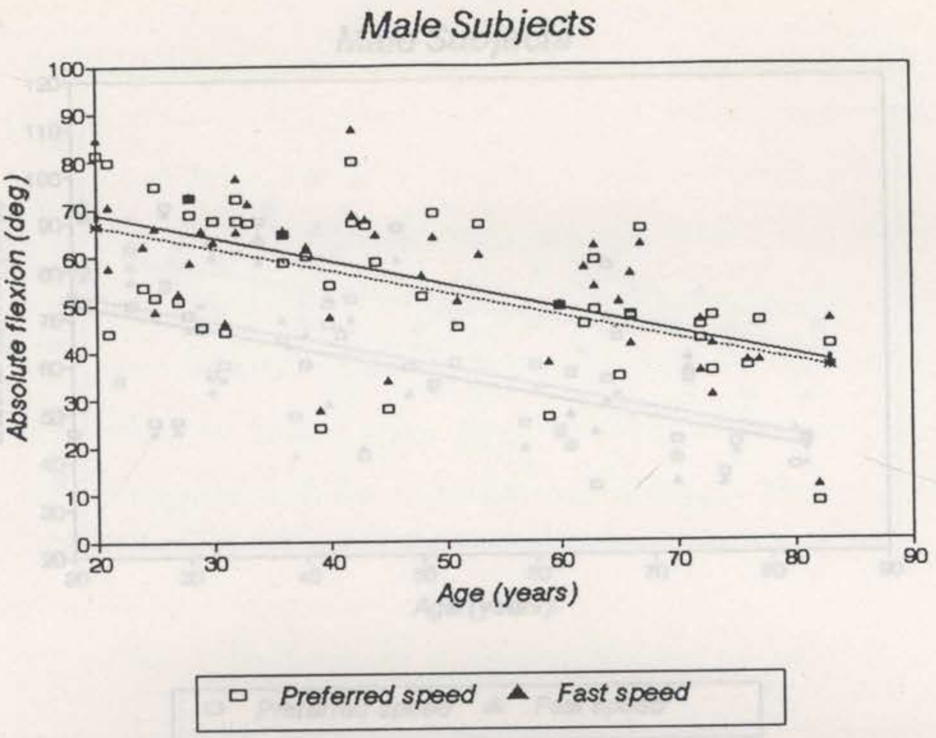


Figure 4.5a Relationships between age and maximum range of forward flexion in the thoracolumbar segment in male and female subjects for both speeds of motion (---- preferred speed, —— fast speed).



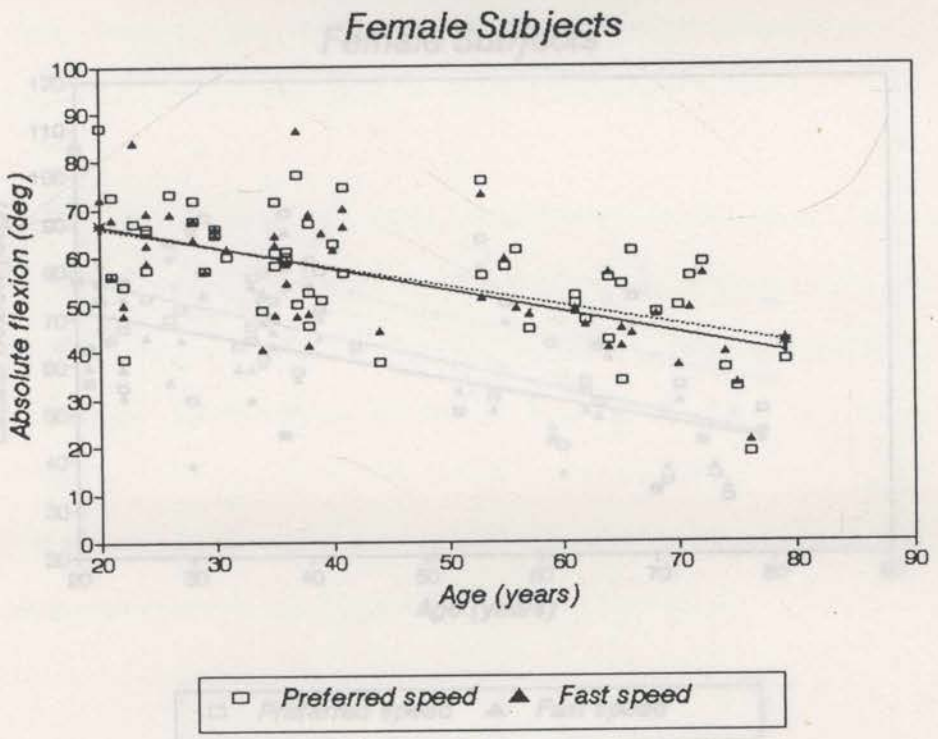
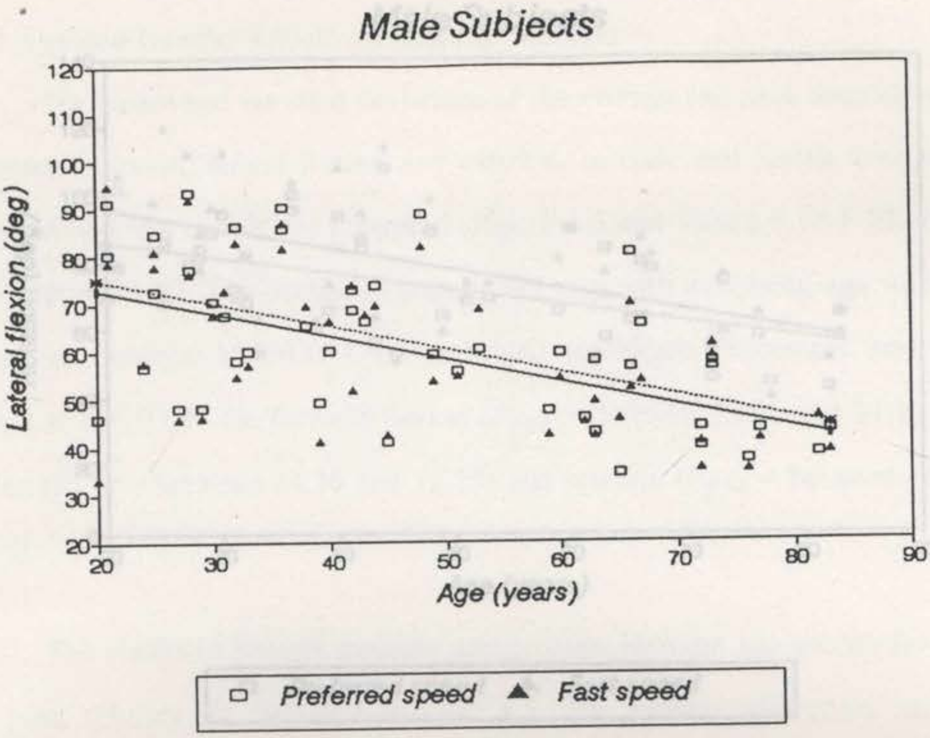


Figure 4.5b Relationships between age and absolute range of forward flexion in the thoracolumbar segment in male and female subjects for both speeds of motion (---- preferred speed, —— fast speed).



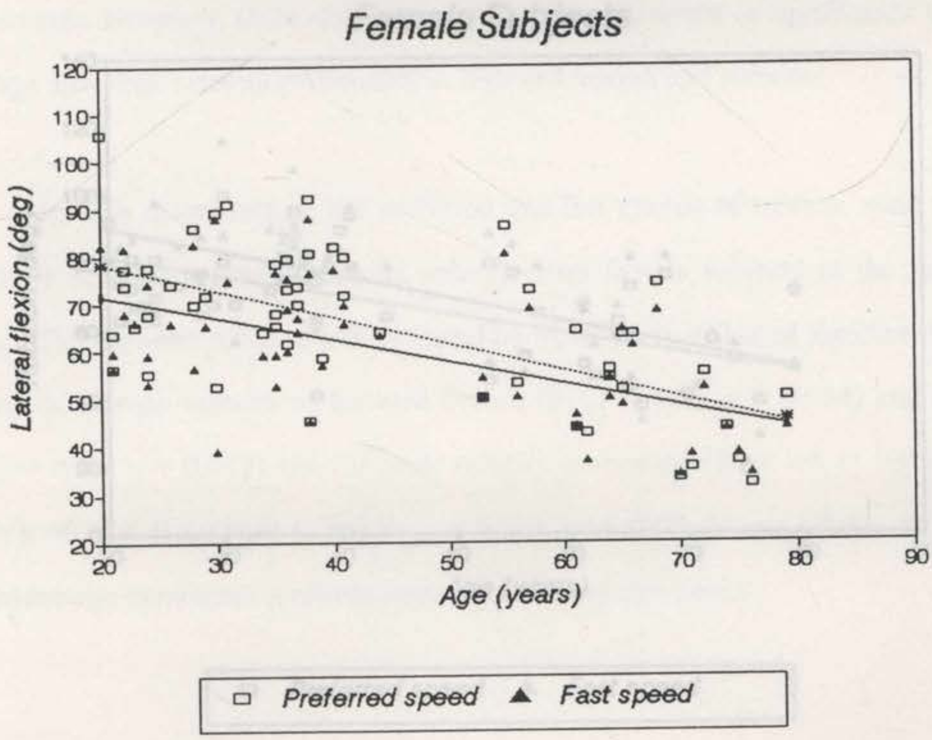
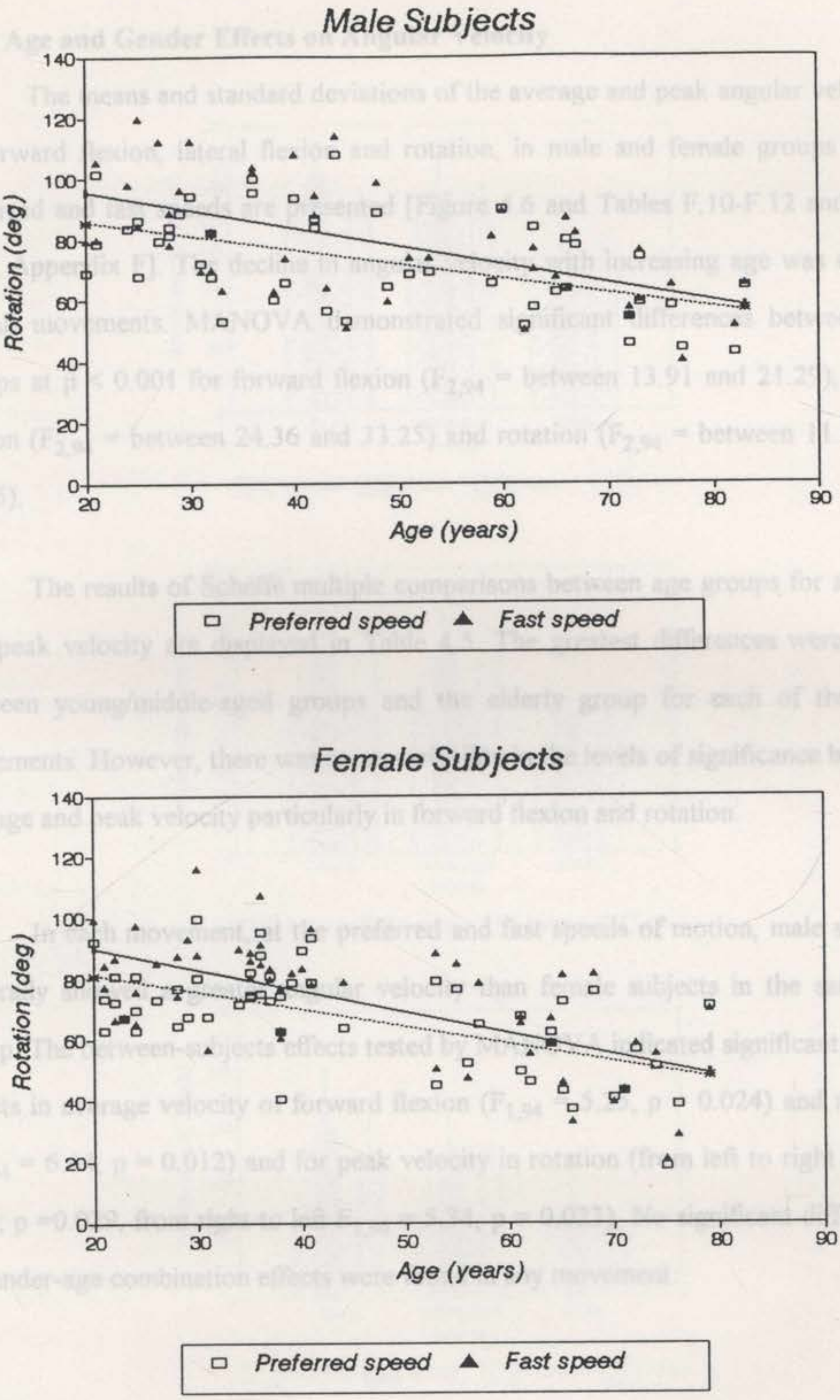


Figure 4.5c Relationships between age and range of lateral flexion in the thoracolumbar segment in male and female subjects for both speeds of motion (---- preferred speed, —— fast speed).



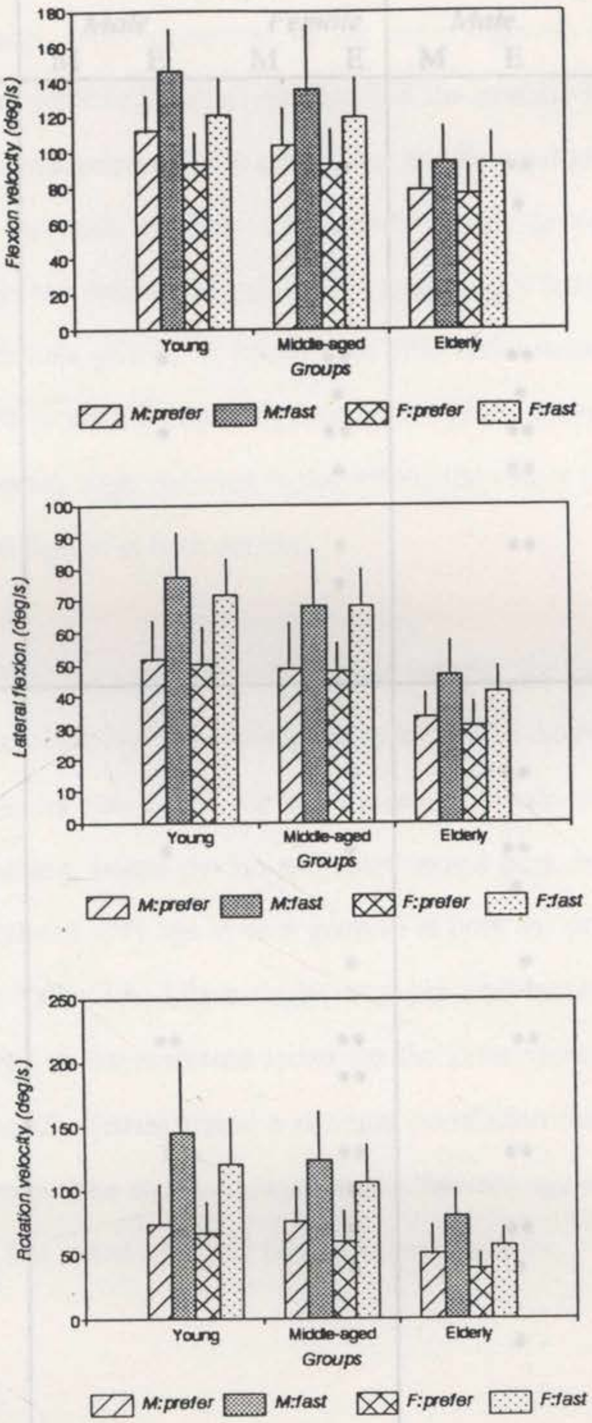
<u>Figure 4.5d</u> Relationships between age and range of rotation in the thoracolumbar segment in male and female subjects for both speeds of motion (---- preferred speed, —— fast speed).

4.1.3 Age and Gender Effects on Angular Velocity

The means and standard deviations of the average and peak angular velocities of forward flexion, lateral flexion and rotation, in male and female groups at the preferred and fast speeds are presented [Figure 4.6 and Tables F.10-F.12 and F.19-F.23; Appendix F]. The decline in angular velocity with increasing age was evident for all movements. MANOVA demonstrated significant differences between age groups at $p < 0.001$ for forward flexion ($F_{2,94}$ = between 13.91 and 21.29), lateral flexion ($F_{2,94}$ = between 24.36 and 33.25) and rotation ($F_{2,94}$ = between 11.50 and 16.95).

The results of Schéffé multiple comparisons between age groups for average and peak velocity are displayed in Table 4.5. The greatest differences were found between young/middle-aged groups and the elderly group for each of the three movements. However, there was some variability in the levels of significance between average and peak velocity particularly in forward flexion and rotation.

In each movement, at the preferred and fast speeds of motion, male subjects generally showed a greater angular velocity than female subjects in the same age group. The between-subjects effects tested by MANOVA indicated significant gender effects in average velocity of forward flexion ($F_{1,94} = 5.25$, $p = 0.024$) and rotation ($F_{1,94} = 6.64$, $p = 0.012$) and for peak velocity in rotation (from left to right $F_{1,94} = 4.94$; $p = 0.029$, from right to left $F_{1,94} = 5.34$; $p = 0.023$). No significant differences in gender-age combination effects were found in any movement.



<u>Figure 4.6</u> Average angular velocity of forward flexion, lateral flexion and rotation in the thoracolumbar segment for male and female groups at the preferred and the fast speeds; M=male, F=female, prefer=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].

Table 4.5 Tests for significance of multiple comparison for angular velocity between age groups in the thoracolumbar segment.

Movements		Preferred speed				Fast speed			
		Male		*Female*		*Male*		*Female*	
		M	E	M	E	M	E	M	E
Average velocity									
Flexion									
Male	Y		*		*		**		**
	M						*		*
Female	Y								
	M								
Lat.flexion									
Male	Y		*		**		**		**
	M				*		*		**
Female	Y		*		**		**		**
	M				*		**		**
Rotation									
Male	Y				*		**		**
	M				*				**
Female	Y								**
	M								
Peak velocity									
Flexion									
Male	Y				*		**		**
	M								*
Female	Y		*		*		**		**
	M						*		**
Extension									
Male	Y				*		*		**
	M								
Female	Y		**		**		**		**
	M				**				*
Lat. flexion									
Male	Y		*		**		**		**
	M				*				**
Female	Y				*		**		**
	M				*		*		**
Rotation L-R									
Male	Y						*		**
	M								*
Female	Y								*
	M								
Rotation R-L									
Male	Y						*		**
	M								**
Female	Y								**
	M								*

Note: Y = young group. M = middle-aged group. E = elderly group. * = $p < 0.05$. ** = $p < 0.01$

The young and middle-aged male and female subjects demonstrated a greater capability to increase angular velocity from the preferred to the fast speed of motion, particularly in rotation, when compared to the elderly groups [Figure 4.6]. The differences in angular velocity between the fast and the preferred speeds of motion (differential values) were greater in the young and middle-aged groups compared to the elderly groups for both genders. The elderly female group demonstrated a significant decrease in the differential values for rotation ($p < 0.01$) compared to the young/middle-aged female groups. A decrease in differential values for rotation was also found in the elderly male group compared to the young male group ($p < 0.01$). No significant differences were detected in the differential values between age groups for forward or lateral flexion in both genders.

The relationship between age and angular velocity for each movement was linear as confirmed statistically. No evidence of lack of fit in the relationship between age and angular velocity was found for any movement. Peak and average velocity values of forward flexion, lateral flexion and rotation and peak velocity of extension were negatòely correlated with age in both genders at both the preferred and the fast speeds as shown in Table 4.6. Interestingly, stronger correlations were seen in the fast motion compared to the preferred speed for the same movement. Additionally, female subjects generally demonstrated a stronger correlation than male subjects for each of the movements. The strongest relationship between age and angular velocity was detected at the fast speed of lateral flexion in both genders.

Table 4.6 Correlation coefficients and regression equations for age and angular velocity of forward flexion, lateral flexion and rotation in the thoracolumbar segment in male and female subjects at both speeds of motion.

Angular velocity	Preferred speed r	Preferred speed Equation	Fast speed r	Fast speed Equation
Male(n=46)				
Average velocity				
Forward flexion	-0.463**	y=118-0.74x	-0.559**	y=157-1.17x
Lateral flexion	-0.524**	y=56.9-0.46x	-0.642**	y=84.1-0.74x
Rotation	-0.330*	y=83.1-0.60x	-0.555**	y=160-1.60x
Peak velocity				
Forward flexion	-0.453**	y=135-0.97x	-0.556**	y=187-1.58x
Extension	-0.423**	y=155-1.02x	-0.536**	y=196-1.38x
Lateral flexion	-0.473**	y=108-0.83x	-0.548**	y=150-1.24x
Rotation L - R	-0.235#	y=144-0.72x	-0.502**	y=279-2.40x
Rotation R - L	-0.177#	y=137-0.59x	-0.458**	y=261-2.03x
Female(n=54)				
Average velocity				
Forward flexion	-0.308*	y=99-0.44x	-0.400**	y=128-0.64x
Lateral flexion	-0.555**	y=54.2-0.43x	-0.687**	y=78.5-0.69x
Rotation	-0.459**	y=71.4-0.62x	-0.561**	y=131-1.40x
Peak velocity				
Forward flexion	-0.526**	y=137-1.00x	-0.627**	y=183-1.60x
Extension	-0.633**	y=171-1.49x	-0.676**	y=204-1.67x
Lateral flexion	-0.444**	y=97.0-0.67x	-0.600**	y=145-1.26x
Rotation L - R	-0.366**	y=132-0.83x	-0.497**	y=235-2.22x
Rotation R - L	-0.385**	y=128-0.89x	-0.535**	y=230-2.21x

Note: * = $p < 0.05$, ** = $p < 0.01$, y = angular velocity (deg/s), x = age-20 (years)
r = Pearson product moment correlation coefficient. # = MSE/MSR ratio > 20%

Average velocity in the preferred speed decreased approximately 1 deg/s and in the fast speed 3 deg/s every 2-3 years. The decrease in peak velocity with the preferred speed was approximately 2 deg/s and with the fast speed 4 deg/s every 2-3 years. The greatest decrease in angular velocity in the preferred speed occurred at peak extension velocity and in the fast speed at peak rotation velocity for both genders. For example, if a 20 year old man had a peak extension velocity of 155 deg/s, at 60 years old he would peak at 115 deg/s. Thus, the reduction in peak extension velocity was 26 %.

4.2 Lower Thoracic Spine

4.2.1 Age and Gender Effects on Range of Motion

Ranges of motion for forward flexion, lateral flexion and for rotation are presented [Tables F.4-F.6; Appendix F]. The group mean values of the ranges are illustrated [Figure 4.7]. The decline in the ranges of forward flexion, lateral flexion and of rotation with increasing age is evident.

Multivariate Analysis of Variance (MANOVA) indicated significant differences between the age groups for each of the three movements (forward flexion $F_{2,94} = 7.60$, $p \ \ 0.001$; lateral flexion $F_{2,94} = 26.41$, $p < 0.001$; rotation $F_{2,94} = 38.89$, $p < 0.001$). The results of the Schéffé comparisons of pairs is presented in Table 4.7. The obvious trend was a decrease in the ranges of lateral flexion and rotation with age. The greatest differences were found between the young/middle-aged and the elderly groups in both genders. The MANOVA indicated no significant gender-age combination effect in any movement (forward flexion $F_{2,94} = 0.94$, $p = 0.396$; lateral flexion $F_{2,94} = 0.31$, $p = 0.737$; rotation $F_{2,94} = 1.37$, $p = 0.260$), thus there was no difference in the decreasing trend of range of motion between male and female subjects across age groups.

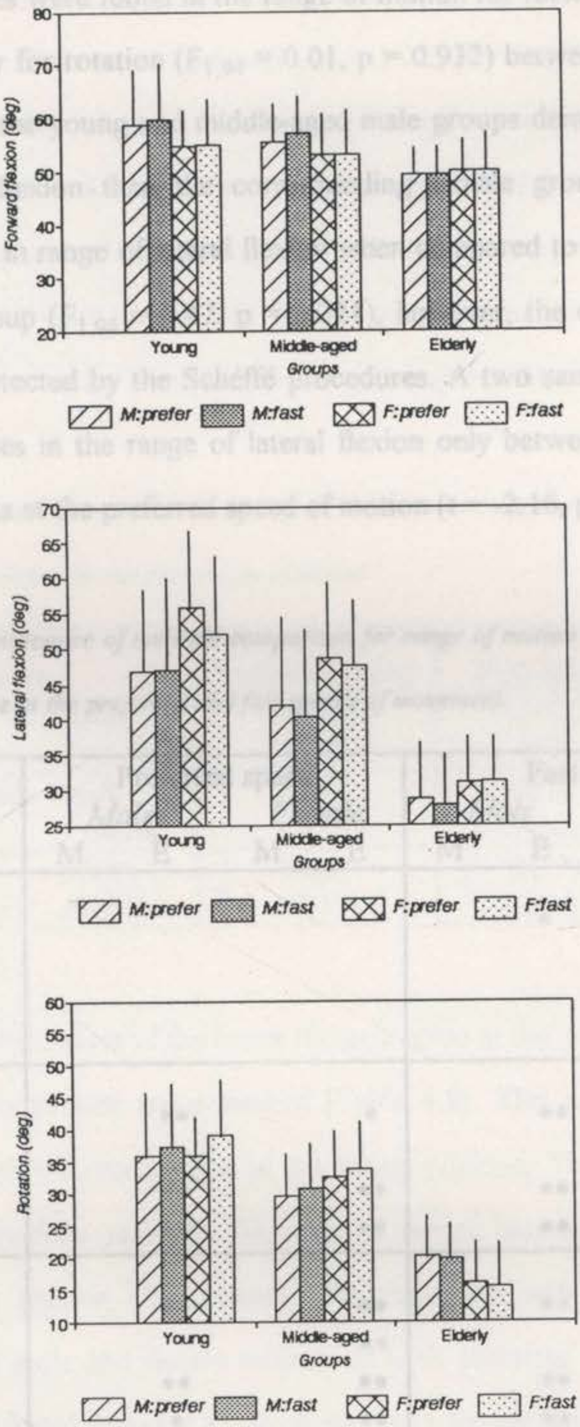


Figure 4.7 *Range of forward flexion, lateral flexion and rotation in the lower thoracic spine for male and female groups at the preferred and the fast speeds; M=male, F=female, prefer=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].*

The between-subjects effects tested by the MANOVA indicated that no significant differences were found in the range of motion for forward flexion ($F_{1,94}$ = 2.08, p = 0.153) nor for rotation ($F_{1,94}$ = 0.01, p = 0.932) between male and female subjects. However, the young and middle-aged male groups demonstrated a greater range of forward flexion than the corresponding female groups. Male subjects showed a reduction in range of lateral flexion when compared to the female subjects in the same age group ($F_{1,94}$ = 5.47, p = 0.021), however, the differences between groups were not detected by the Schéffé procedures. A two sample t-test indicated significant differences in the range of lateral flexion only between young male and young female groups at the preferred speed of motion (t = -2.16, p = 0.039).

Table 4.7 Tests for significance of multiple comparison for range of motion between age groups in the lower thoracic spine in the preferred and fast speeds of movement.

Movements		Preferred speed				Fast speed			
		Male		*Female*		*Male*		*Female*	
		M	E	M	E	M	E	M	E
Flexion									
Male	Y						*		
	M								
Female	Y								
	M								
Lat. flexion									
Male	Y		**		*		**		*
	M								
Female	Y		**		**		**		**
	M		**		**		**		*
Rotation									
Male	Y		**		**		**		**
	M				**				**
Female	Y		**		**		**		**
	M		*		**		**		**

Note: Y=young group, M=middle-aged group, E=elderly group. *= p<0.05, **= p<0.01

4.2.2 Speed Effects on Range of Motion

Changing the speed of motion from preferred to a faster speed had no clear effect on the ranges of forward flexion ($F_{1,94} = 3.21$, $p = 0.077$) or lateral flexion ($F_{1,94} = 4.36$, $p = 0.04$) whereas significant speed effects were shown in rotation ($F_{1,94} = 6.71$, $p = 0.011$). Although there was a general trend for increasing range of rotation in the young and middle-aged groups with the faster speed in both genders, significant differences were found only in the range of motion between fast and preferred speed of motion for the young female group ($t = 2.83$, $p = 0.011$).

Table 4.8 Mean (S.D) in degrees of angulation of the lower thoracic spine at starting position for forward flexion at the preferred and fast speeds of motion.

Subject groups		Preferred speed	Fast speed
Young	*Male*	16(10)	15(12)
	Female	6(9)	7(9)
Middle-aged	*Male*	22(11)	20(10)
	Female	10(10)	9(10)
Elderly	*Male*	22(8)	21(9)
	Female	22(11)	22(10)

The angulation values of the lower thoracic spine at the starting position prior to trunk forward movement are presented [Table 4.8]. This angle equates to the curvature of the lower thoracic spine in the sitting position. The absolute range of forward flexion, therefore, refers to the range of motion between the starting angle and the maximum angular displacement. The maximum and absolute ranges of forward flexion, of male and female subjects at both preferred and fast speeds are presented [Table 4.9 and Figure 4.8]. Both male and female groups demonstrated a decreased range of forward flexion with increasing age. This finding was expected given the increasing kyphotic curvature of the thoracic spine associated with advancing age.

Table 4.9 Maximum and absolute range of forward flexion (degrees) in the lower thoracic spine of male and female groups at the preferred and fast speeds of motion.

Subject groups		Preferred speed		Fast speed	
		Maximum	Absolute	Maximum	Absolute
Young	*Male*	59(10)	43(13)	60(10)	44(11)
	Female	55(6)	48(9)	55(8)	48(10)
Middle-aged	*Male*	56(7)	34(13)	57(7)	37(11)
	Female	53(9)	42(8)	53(10)	44(9)
Elderly	*Male*	49(7)	27(9)	49(7)	28(10)
	Female	50(7)	28(9)	50(8)	28(9)

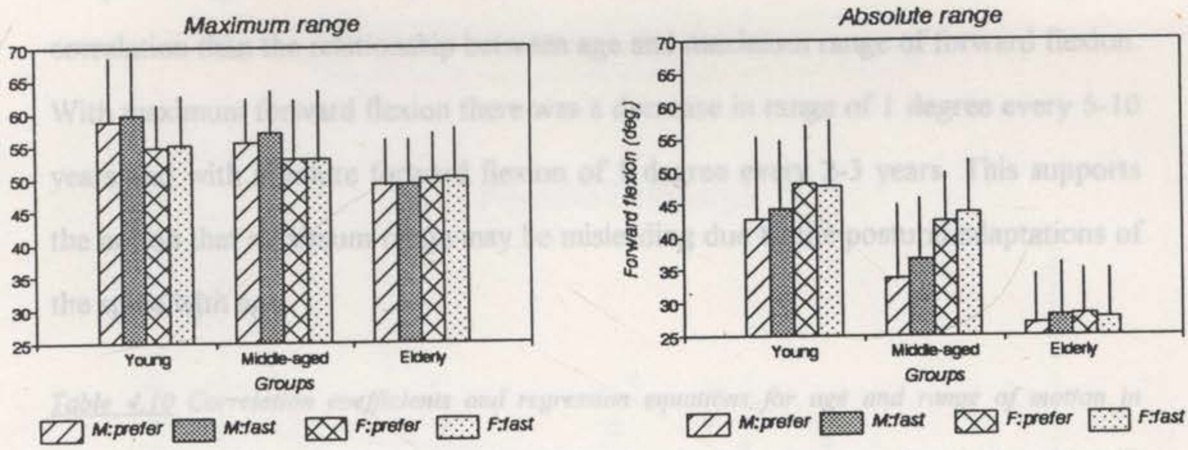


Figure 4.8 Mean values and standard deviations of maximum and absolute range of forward flexion in the lower thoracic spine in the young, middle-aged and elderly male and female groups at the preferred and fast speeds; M=male, F=female, prefer=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].

The ranges of motion of forward flexion, lateral flexion and rotation are plotted against age [Figure 4.9]. Although there was some variation between subjects in each age group, no evidence of lack of fit was found in any movement ($p > 0.1$). Linear regression, therefore, can be applied to the relationships between age and range of motion for both genders and at the preferred and fast speeds of motion.

Significant negative correlations were found between age and ranges of motion in both genders at both the preferred and the fast speeds of motion (Table 4.10 and Figure 4.9). The decrease in range of lateral flexion and rotation was approximately 1 degree every 2-3 years. It is interesting to note that the regression analysis of age and absolute range of forward flexion indicated a stronger negative correlation than the relationship between age and maximum range of forward flexion. With maximum forward flexion there was a decrease in range of 1 degree every 5-10 years and with absolute forward flexion of 1 degree every 2-3 years. This supports the notion that maximum range may be misleading due to the postural adaptations of the spine with age.

<u>Table 4.10</u> Correlation coefficients and regression equations for age and range of motion in forward flexion, lateral flexion and rotation at the lower thoracic spine in preferred (P) and fast (F) speeds of motion.

Movement		Male (n=46)		Female (n=54)	
		r	Equation	r	Equation
Maximum flexion	P	-0.391**	y=59.6-0.19x	-0.263#	y=55.5-0.11x
	F	-0.452**	y=61.2-0.22x	-0.282*#	y=56.2-0.14x
Absolute flexion	P	-0.554**	y=44.9-0.38x	-0.682**	y=51.7-0.46x
	F	-0.631**	y=47.4-0.41x	-0.675**	y=52.2-0.47x
Lateral flexion	P	-0.563**	y=51.1-0.44x	-0.636**	y=60.0-0.56x
	F	-0.584**	y=50.9-0.46x	-0.625**	y=56.5-0.49x
Rotation	P	-0.635**	y=39.1-0.39x	-0.741**	y=41.1-0.50x
	F	-0.682**	y=40.8-0.42x	-0.749**	y=44.5-0.57x

Note * = $p < 0.05$, ** = $p < 0.01$, y = range of motion (deg), x = age-20 (years)
r = Pearson product moment correlation coefficient. # = MSE/MSR ratio > 20%

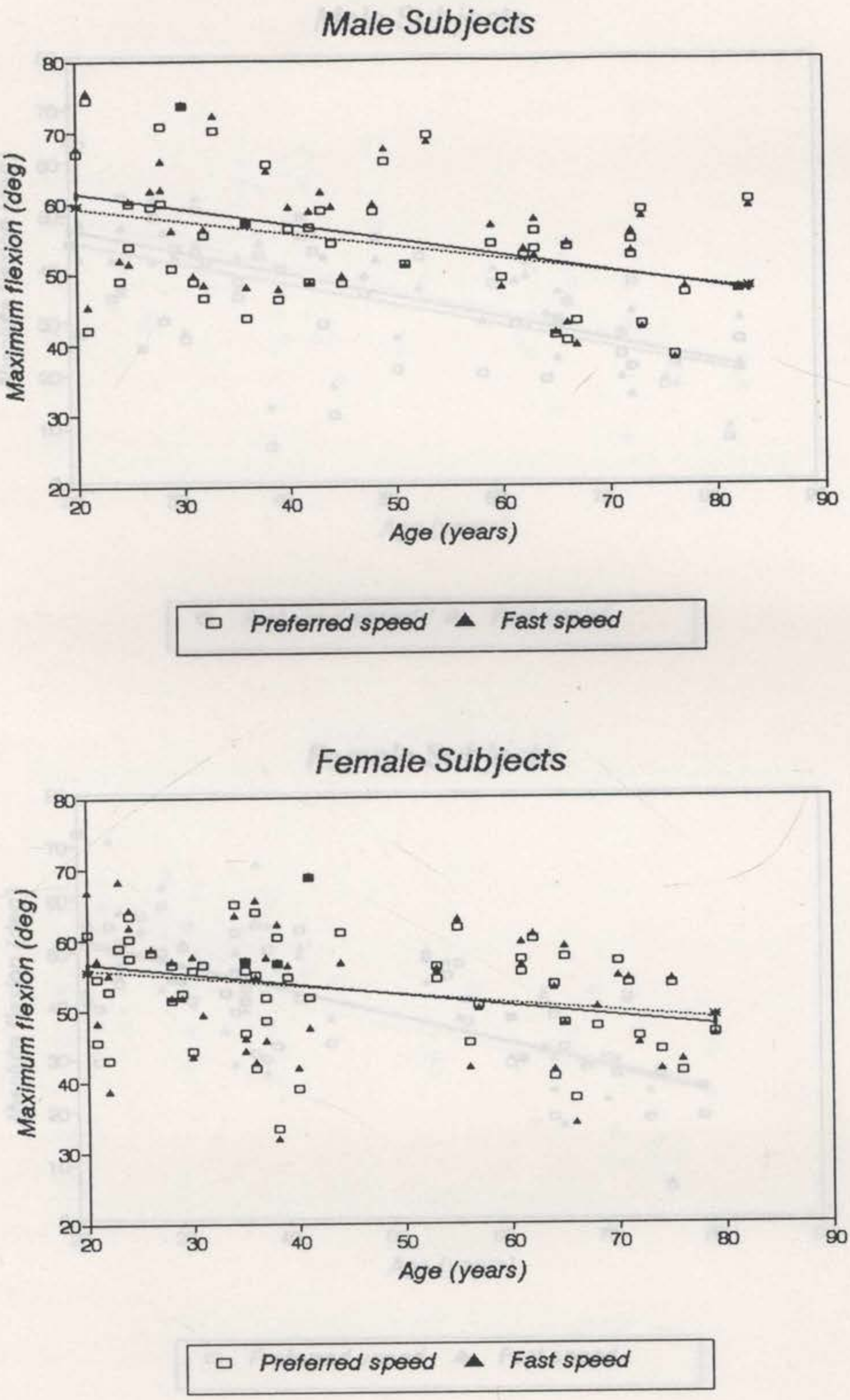
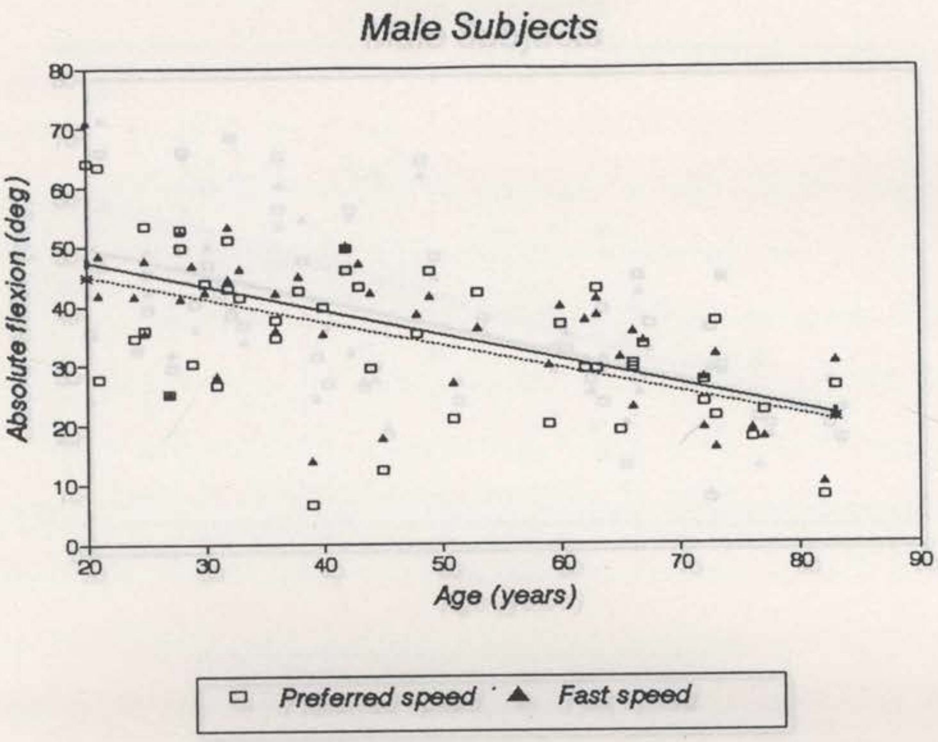


Figure 4.9a Relationships between age and maximum range of forward flexion in the lower thoracic spine in male and female subjects for both speeds of motion (---- preferred speed, —— fast speed).



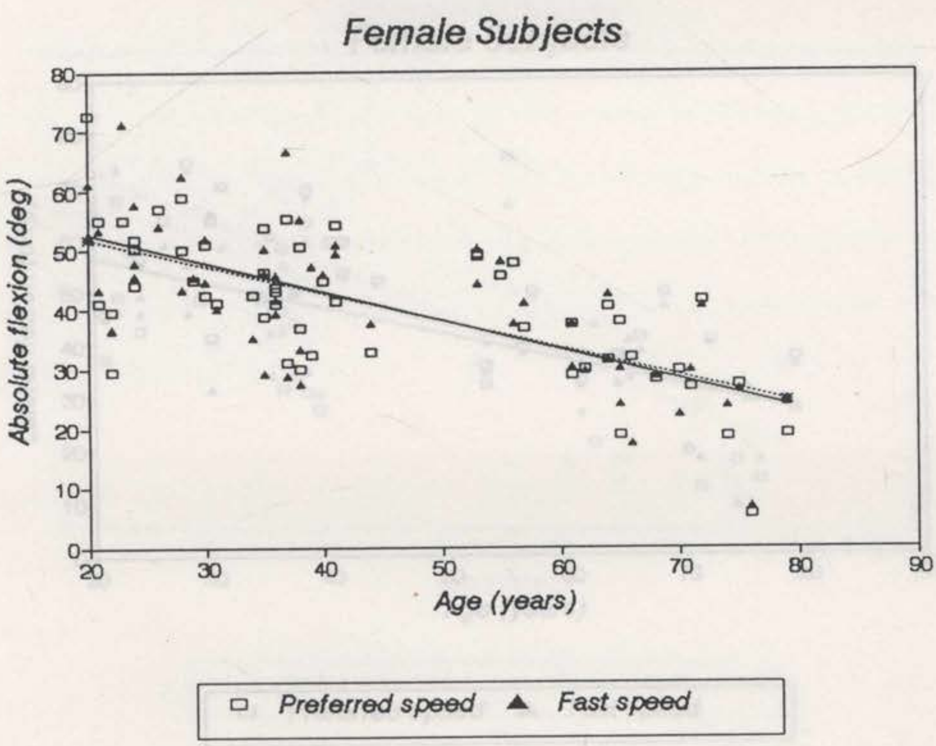
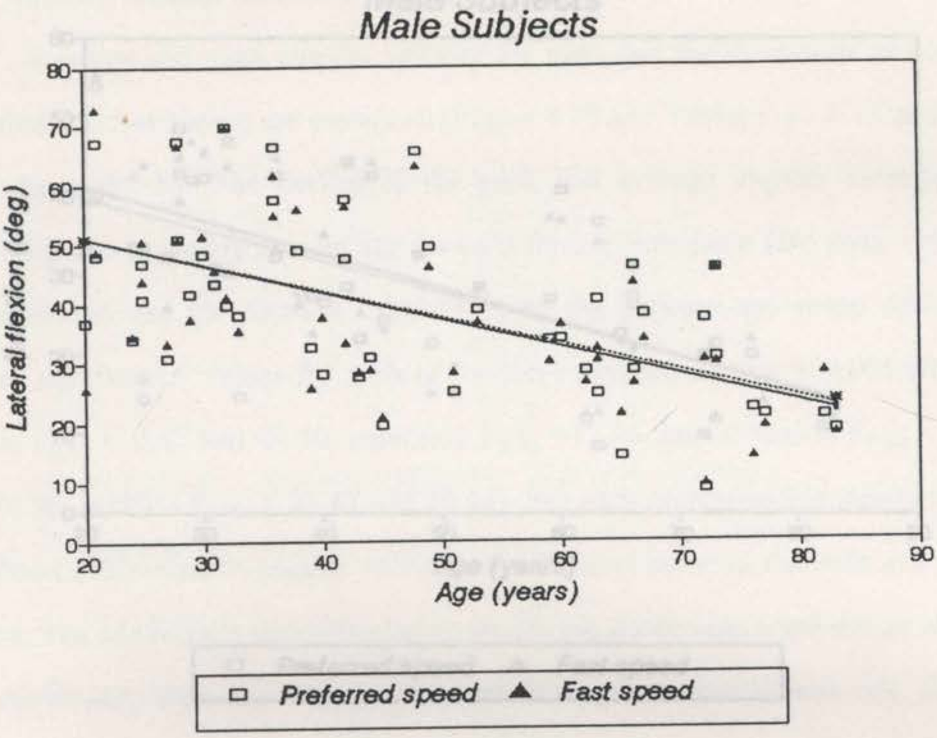


Figure 4.9b Relationships between age and absolute range of forward flexion in the lower thoracic spine in male and female subjects for both speeds of motion (---- preferred speed, —— fast speed).



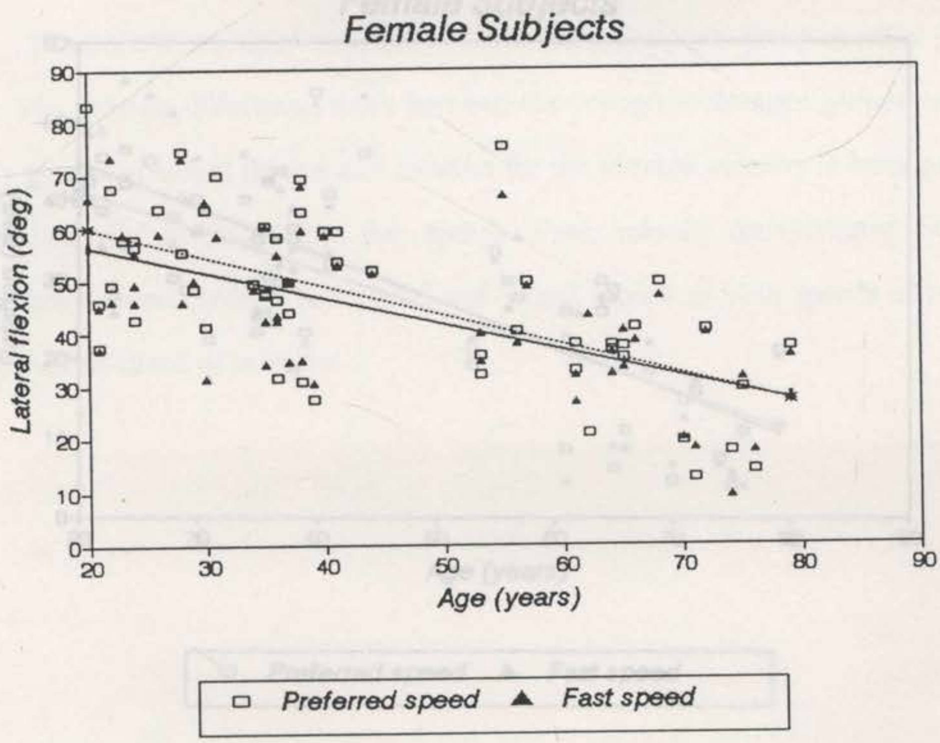


Figure 4.9c Relationships between age and range of lateral flexion in the lower thoracic spine in male and female subjects for both speeds of motion (---- preferred speed, —— fast speed).

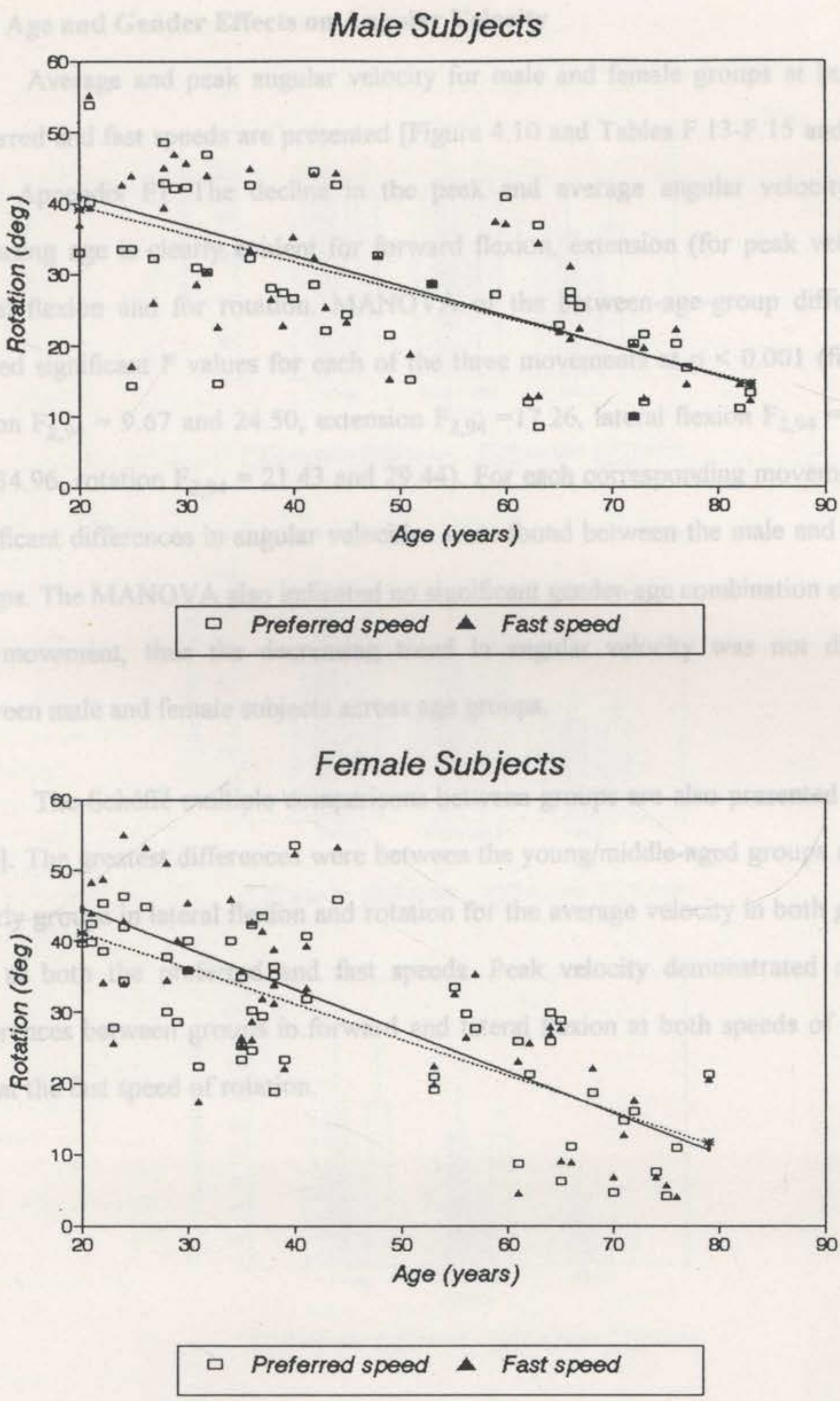


Figure 4.9d Relationships between age and range of rotation in the lower thoracic spine in male and female subjects for both speeds of motion (---- preferred speed, —— fast speed).

4.2.3 Age and Gender Effects on Angular Velocity

Average and peak angular velocity for male and female groups at both the preferred and fast speeds are presented [Figure 4.10 and Tables F.13-F.15 and F.24-F.28; Appendix F]. The decline in the peak and average angular velocity with increasing age is clearly evident for forward flexion, extension (for peak velocity), lateral flexion and for rotation. MANOVA of the between-age-group differences yielded significant F values for each of the three movements at $p < 0.001$ (forward flexion $F_{2,94} = 9.67$ and 24.50, extension $F_{2,94} = 17.26$, lateral flexion $F_{2,94} = 32.70$ and 34.96, rotation $F_{2,94} = 21.43$ and 29.44). For each corresponding movement, no significant differences in angular velocities were found between the male and female groups. The MANOVA also indicated no significant gender-age combination effect in any movement, thus the decreasing trend in angular velocity was not different between male and female subjects across age groups.

The Schéffé multiple comparisons between groups are also presented [Table 4.11]. The greatest differences were between the young/middle-aged groups and the elderly groups in lateral flexion and rotation for the average velocity in both genders and at both the preferred and fast speeds. Peak velocity demonstrated obvious differences between groups in forward and lateral flexion at both speeds of motion and at the fast speed of rotation.

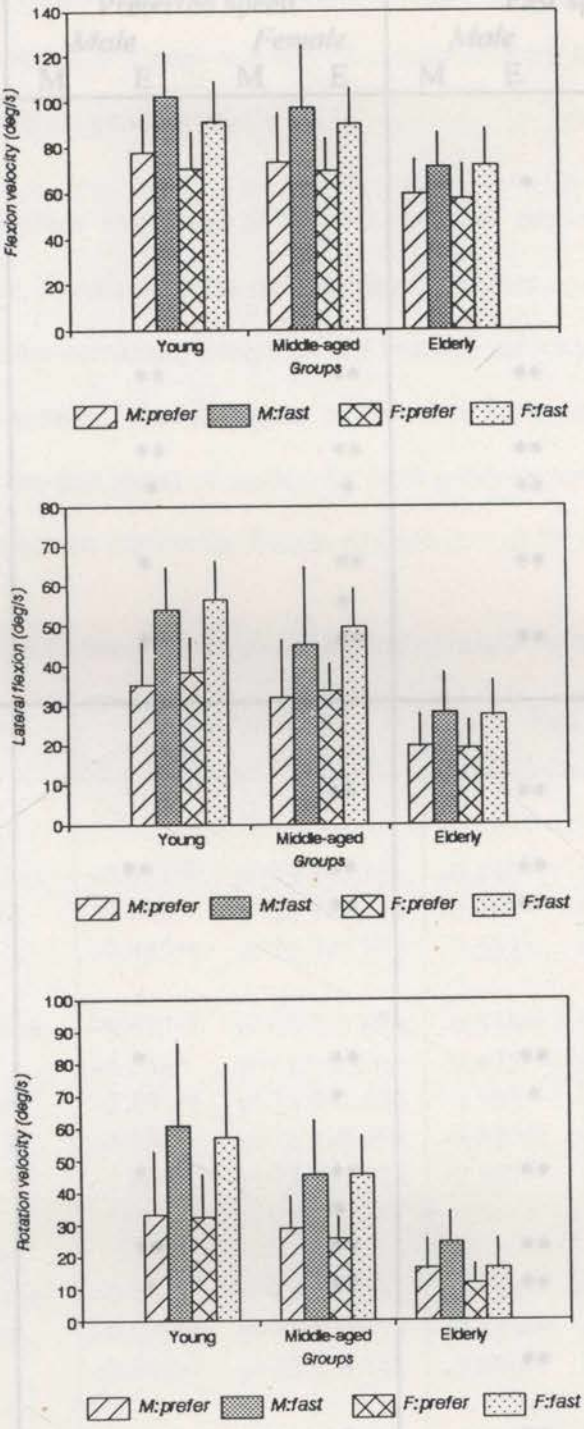


Figure 4.10 Average angular velocity of forward flexion, lateral flexion and rotation in the lower thoracic spine for male and female groups at the preferred and the fast speeds; M=male, F=female, prefer=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].

Table 4.11 Tests for significance of multiple comparison for angular velocity between age groups in the lower thoracic spine.

Movements		Preferred speed				Fast speed			
		Male		*Female*		*Male*		*Female*	
		M	E	M	E	M	E	M	E
Average velocity									
Flexion									
Male	Y						*		*
	M								
Female	Y								
	M								
Lat.flexion									
Male	Y		**		**		**		**
	M						*		*
Female	Y		**		**		**		**
	M		*		*		**		**
Rotation									
Male	Y		*		**		**		**
	M				*				**
Female	Y		*		**		**		**
	M								**
Peak velocity									
Flexion									
Male	Y				**		**		**
	M								
Female	Y		**		**		**		**
	M				**		**		**
Extension									
Male	Y								*
	M								
Female	Y		*		**		**		**
	M				*		*		**
Lat. flexion									
Male	Y		*		**		**		**
	M				*				**
Female	Y		**		**		**		**
	M		*		**		**		**
Rotation L-R									
Male	Y				*		**		**
	M								**
Female	Y				*		**		**
	M								**
Rotation R-L									
Male	Y						**		**
	M								**
Female	Y				**		**		**
	M								**

Note: Y = young group, M = middle-aged group, E = elderly group.
* = $p < 0.05$, ** = $p < 0.01$

No evidence of lack of fit in the relationship between age and angular velocity was found for any movement ($p > 0.1$). Peak and average velocity of forward flexion, lateral flexion and rotation and peak velocity of extension were generally negatively correlated with age in both genders [Table 4.12].

Strong correlations were seen at the fast speed of motion within the same movement. Moreover, female subjects demonstrated a higher correlation than male subjects within the same condition, except for the average velocity of forward flexion at both speeds of motion. The strongest relationship between age and angular velocity was seen at the fast speed of motion for both genders; with rotation for male ($r = -0.632$) and with lateral flexion for female subjects ($r = -0.719$).

Table 4.12 Correlations and regressions for age and angular velocity in the lower thoracic spine.

Angular velocity	Preferred speed r	Preferred speed Equation	Fast speed r	Fast speed Equation
Male(n=46)				
Average velocity				
Forward flexion	-0.311*#	y=79.7-0.36x	-0.440**	y=108-0.64x
Lateral flexion	-0.495**	y=38.9-0.37x	-0.600**	y=58.7-0.61x
Rotation	-0.449**	y=36.9-0.39x	-0.632**	y=66.6-0.85x
Peak velocity				
Forward flexion	-0.423**	y=95.1-0.68x	-0.535**	y=135-1.15x
Extension	-0.338*	y=115-0.83x	-0.475**	y=152-1.19x
Lateral flexion	-0.491**	y=74.9-0.69x	-0.563**	y=109-1.07x
Rotation L - R	-0.337*	y=78.1-0.60x	-0.620**	y=146-1.71x
Rotation R - L	-0.284#	y=73.5-0.52x	-0.587**	y=134-1.45x
Female(n=54)				
Average velocity				
Forward flexion	-0.294*#	y=74.3-0.33x	-0.354**	y=96.2-0.45x
Lateral flexion	-0.639**	y=41.0-0.41x	-0.719**	y=61.5-0.65x
Rotation	-0.648**	y=35.9-0.48x	-0.690**	y=64.2-0.94x
Peak velocity				
Forward flexion	-0.615**	y=109-0.97x	-0.610**	y=140-1.27x
Extension	-0.657**	y=135-1.33x	-0.678**	y=170-1.66x
Lateral flexion	-0.526**	y=74.1-0.64x	-0.663**	y=116-1.27x
Rotation L - R	-0.541**	y=78.9-0.81x	-0.636**	y=134-1.74x
Rotation R - L	-0.578**	y=78.3-0.85x	-0.628**	y=132-1.71x

Note: * = $p < 0.05$, ** = $p < 0.01$, y = angular velocity (deg/s), x = age-20 (years)
r = Pearson product moment correlation coefficient. # = MSE/MSR ratio > 20 %

Average velocity in the preferred speed motions decreased by 1 deg/s every 3 years in both genders, peak velocity by 2 deg/s in male subjects and by between 2 and 4 deg/s every 3 years in female subjects. With increasing age, the rate of decrease in angular velocity at the fast speed was greater than at the preferred speed. For example, a 20 year old female subject might have a peak extension velocity of 135 deg/s and 170 deg/s for the preferred and fast speeds, but at 60 years old she would peak at 80 deg/s for the preferred speed and 100 deg/s for the fast speed. The greatest decrease in angular velocity at the preferred speed was peak extension velocity and at the fast speed was peak rotation velocity in both male and female subjects.

4.3 Lumbar Spine

4.3.1 Age and Gender Effects on Range of Motion

The mean values and standard deviations of the maximum ranges of motion for forward flexion, lateral flexion and rotation are presented [Figure 4.11 and Tables F.7-F.9; Appendix F]. MANOVA revealed significant differences between the groups for the ranges of forward flexion ($F_{2,94} = 12.30$, $p < 0.001$) and lateral flexion ($F_{2,94} = 13.00$, $p < 0.001$). The results of Schéffé's multiple comparisons are presented in Table 4.13. There were significant differences in the young/middle-aged male groups compared to the elderly male and female groups for range of forward flexion whereas no significant differences were found between the female groups. For lateral flexion, significant differences were seen between the young male/female groups and the elderly female group at both speeds of motion. MANOVA also indicated significant gender effects in forward flexion ($F_{1,94} = 12.40$, $p = 0.001$) and rotation ($F_{1,94} = 9.34$, $p = 0.003$). The young and middle-aged females demonstrated a reduced range of forward flexion and rotation compared to males of these age groups as shown in Figure 4.11. No significant differences in gender-age combination effects were found for any movement.

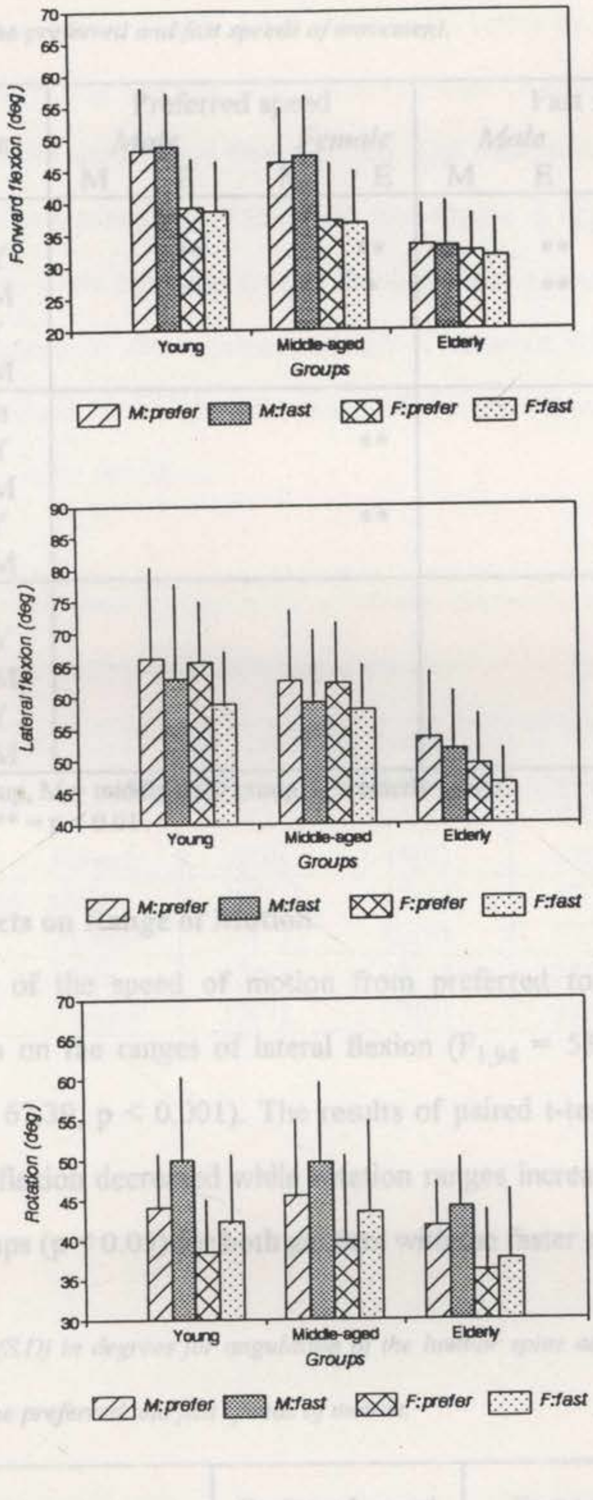


Figure 4.11 Range of forward flexion, lateral flexion and rotation in the lumbar spine for male and female groups at the preferred and the fast speeds; M=male, F=female, prefer=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].

Table 4.13 Tests for significance of multiple comparison for range of motion between age groups in the lumbar spine in the preferred and fast speeds of movement.

Movements		Preferred speed				Fast speed			
		Male		*Female*		*Male*		*Female*	
		M	E	M	E	M	E	M	E
Flexion									
Male	Y		**		**		**	*	**
	M		*		*		**		**
Female	Y								
	M								
Lat. flexion									
Male	Y				**				**
	M								
Female	Y				**				*
	M								
Rotation									
Male	Y								
	M								
Female	Y								
	M								

Note: Y = young group, M = middle-aged group, E = elderly group.
* = $p < 0.05$, ** = $p < 0.01$

4.3.2 Speed Effects on Range of Motion

Changing of the speed of motion from preferred to a faster speed had significant effects on the ranges of lateral flexion ($F_{1,94} = 55.32$, $p < 0.001$) and rotation ($F_{1,94} = 67.39$, $p < 0.001$). The results of paired t-tests demonstrated that ranges of lateral flexion decreased while rotation ranges increased in the young and middle-aged groups ($p < 0.05$) for both genders with the faster speed.

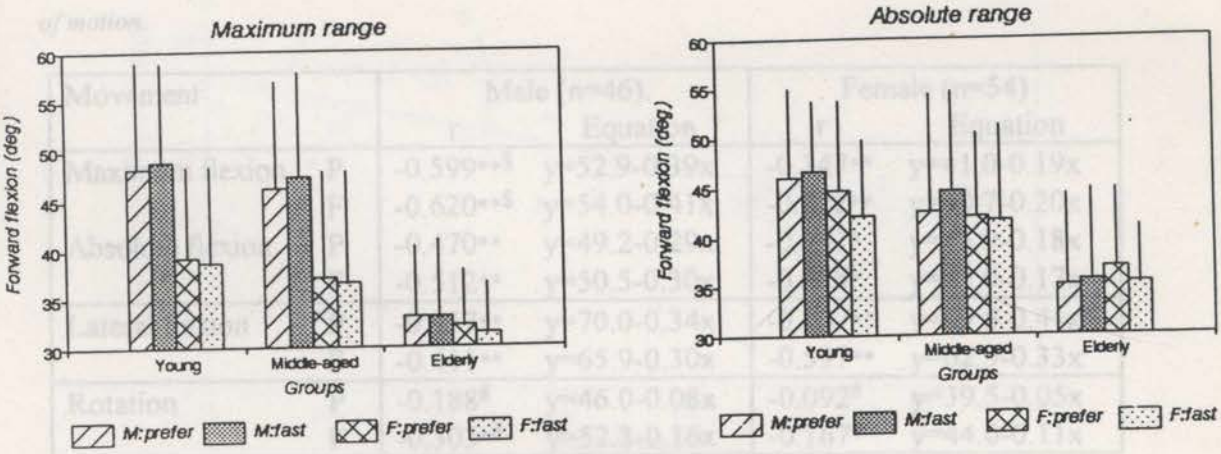
Table 4.14 Means (S.D) in degrees for angulation of the lumbar spine at the starting position for forward flexion at the preferred and fast speeds of motion.

Subject groups		Preferred speed	Fast speed
Young	*Male*	2(7)	2(8)
	Female	-5(9)	-3(9)
Middle-aged	*Male*	4(10)	3(10)
	Female	-5(10)	-5(9)
Elderly	*Male*	-2(11)	-2(11)
	Female	-5(11)	-4(9)

The angulation values of the lumbar spine at the starting position prior to trunk motion are presented [Table 4.14]. This angle refers to the curvature of the lumbar spine in the sitting position. The absolute range of forward flexion refers to the range between the starting and final position. The maximum and absolute ranges of forward flexion are presented [Table 4.15 and Figure 4.12]. The female groups showed an increase while the male groups demonstrated a decrease in the absolute range when compared to the maximum range of forward flexion. No significant differences were found in the absolute range of flexion between male and female subjects within the same condition.

Table 4.15 Maximum and absolute range of forward flexion (degrees) in the lumbar spine of male and female groups at the preferred and fast speeds of motion.

Subject groups		Preferred speed		Fast speed	
		Maximum	Absolute	Maximum	Absolute
Young	*Male*	48(11)	46(9)	49(10)	47(7)
	Female	39(9)	45(9)	39(9)	42(8)
Middle-aged	*Male*	46(11)	42(13)	47(11)	44(12)
	Female	37(11)	42(9)	37(11)	42(10)
Elderly	*Male*	33(9)	35(11)	33(10)	36(11)
	Female	32(7)	37(9)	31(6)	35(7)



<u>Figure 4.12</u> Mean values and standard deviations of maximum and absolute range of forward flexion in the lumbar spine in the young, middle-aged and elderly male and female groups at the preferred and fast speeds; M=male, F=female, prefer=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].

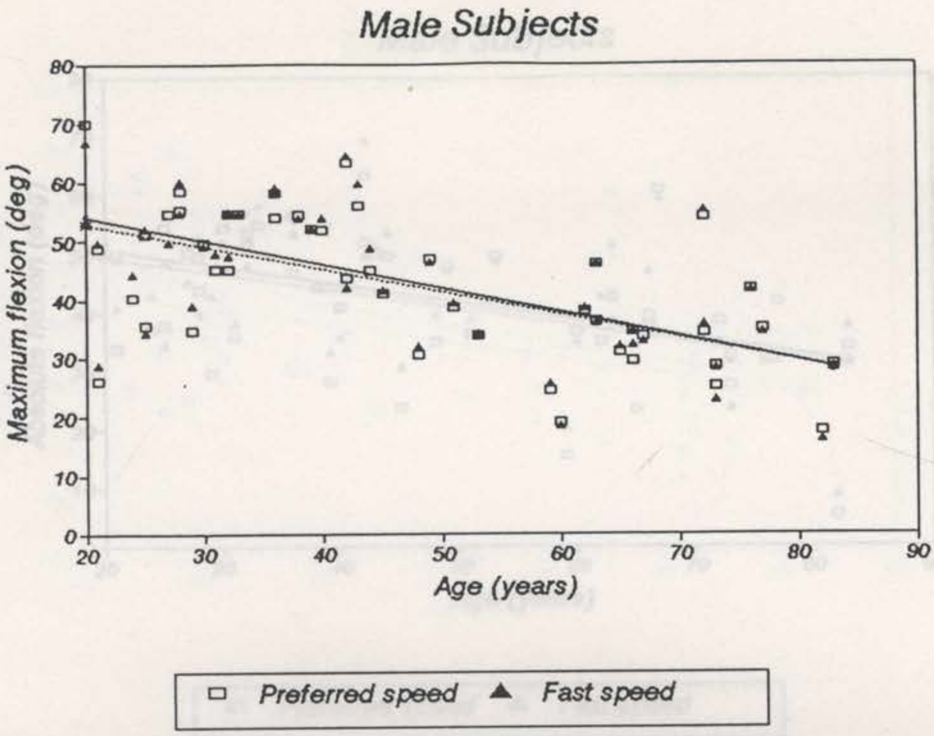
The relationships between range of motion for forward flexion, lateral flexion and rotation and age are illustrated [Figures 4.13a and 4.13b]. No evidence of lack of fit for linearity was detected in any movement ($p > 0.1$), except for the relationship between age and maximum range of forward flexion in male subjects at both speeds of motion (preferred speed $p = 0.035$, fast speed $p = 0.027$). There was no convincing trend for the relationship between age and maximum range of forward flexion with increasing age. The relationship seemed to be fitted with two polynomial curves [Figure 4.13a], however the graph of the residuals of 2nd and 3rd order polynomial equations demonstrated non randomly distributed patterns. No particular relationship between age and range of forward flexion in male subjects could be found. On the other hand, there were significant differences in the mean values between age groups. Thus, the general linear regression was applied to present this relationship.

Table 4.16 Correlation coefficients and regression equations for age and range of motion in forward flexion, lateral flexion and rotation at the lumbar spine in preferred (P) and fast (F) speeds of motion.

Movement		Male (n=46) r	Male (n=46) Equation	Female (n=54) r	Female (n=54) Equation
Maximum flexion	P	-0.599**$	y=52.9-0.39x	-0.347**	y=41.0-0.19x
	F	-0.620**$	y=54.0-0.41x	-0.372**	y=40.7-0.20x
Absolute flexion	P	-0.470**	y=49.2-0.29x	-0.341*	y=45.9-0.18x
	F	-0.512**	y=50.5-0.30x	-0.328*	y=44.0-0.17x
Lateral flexion	P	-0.457**	y=70.0-0.34x	-0.607**	y=69.6-0.41x
	F	-0.411**	y=65.9-0.30x	-0.597**	y=62.9-0.33x
Rotation	P	-0.188#	y=46.0-0.08x	-0.092#	y=39.5-0.05x
	F	-0.303*#	y=52.3-0.16x	-0.167#	y=44.0-0.11x

Note * = p < 0.05, ** = p < 0.01, y = range of motion (deg), x = age-20 (years)
r = Pearson product moment correlation coefficient. # = MSE/MSR ratio > 20%
$ = Significant lack of fit p < 0.05

Negative correlations were found between age and the ranges of motion of lateral flexion in both genders and at both the preferred and the fast speeds of motion [Table 4.16]. The decrease in range of lateral flexion was approximately 1 degree every 3 years. In range of rotation, only one significant correlation was seen in male subjects at the fast speed of motion (r = -0.329, p = 0.026) with the rate of decrease in range of motion 1 degree every 6 years. With maximum and absolute range of forward flexion in female subjects there was a decrease in range of about 1 degree every 5 years and of absolute forward flexion in male subjects with 1 degree every 3-4 years.



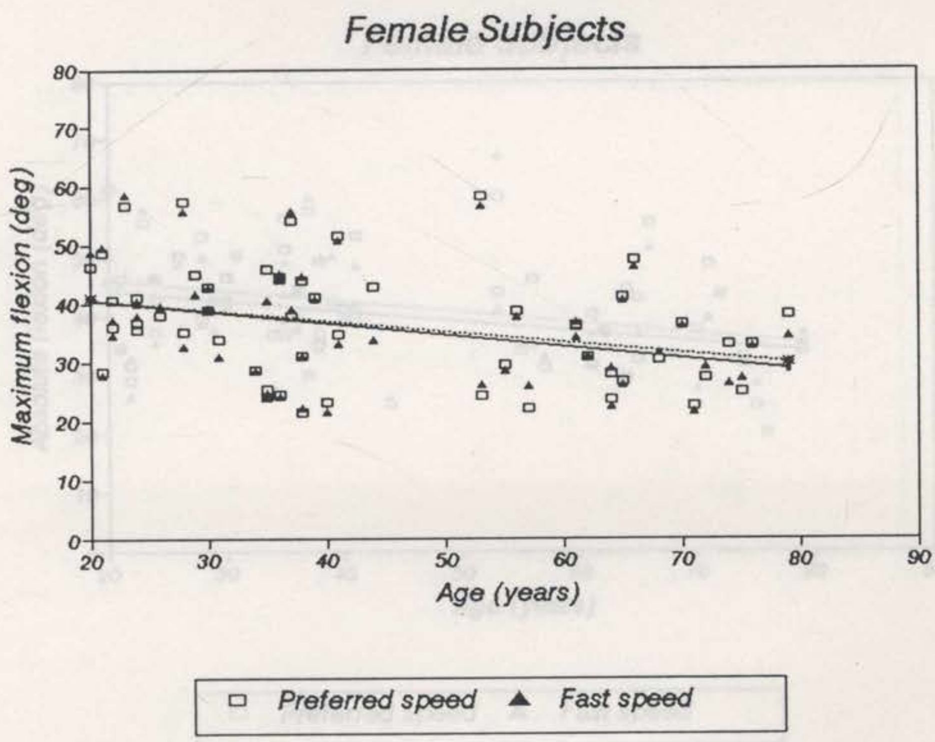
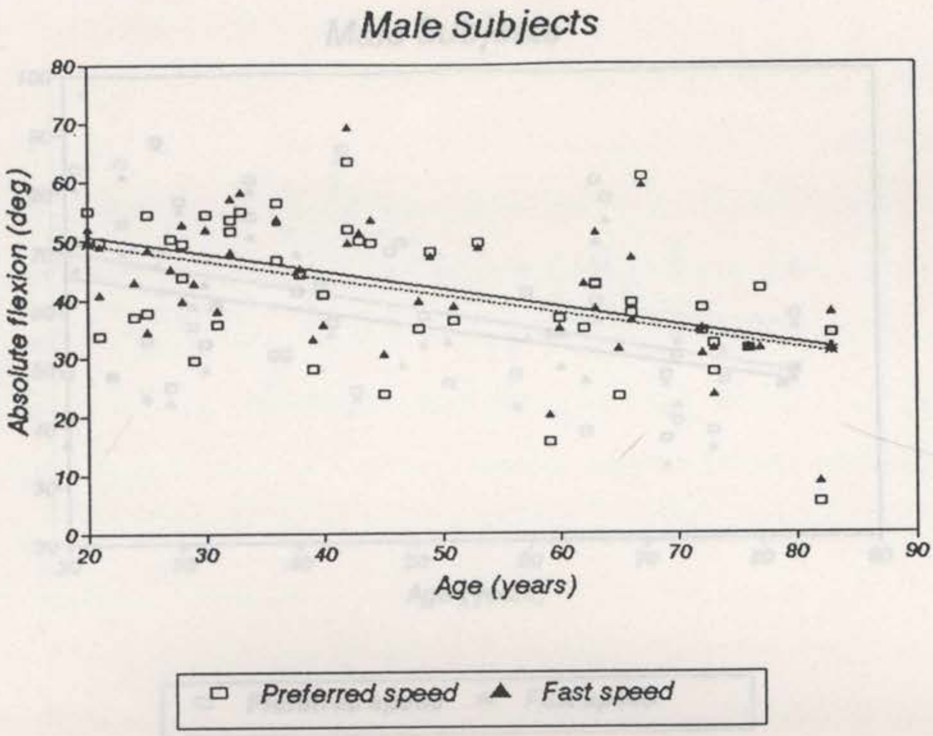
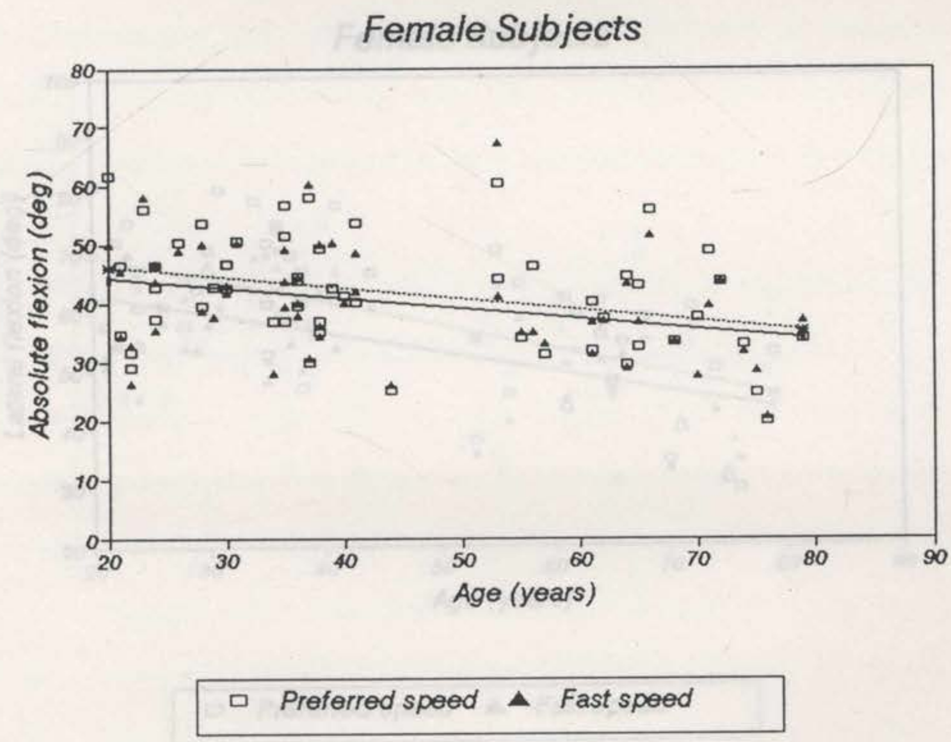
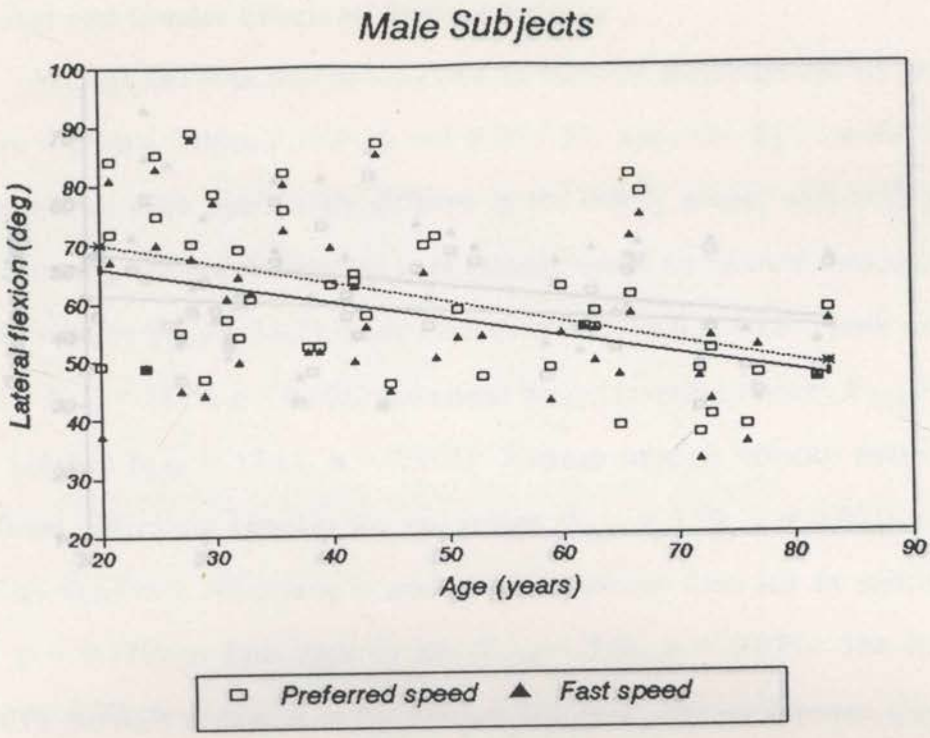


Figure 4.13a Relationships between age and maximum range of forward flexion in the lumbar spine in male and female subjects for both speeds of motion (---- preferred speed, —— fast speed).





<u>Figure 4.13b</u> Relationships between age and absolute range of forward flexion in the lumbar spine in male and female subjects for both speeds of motion (---- preferred speed, —— fast speed).



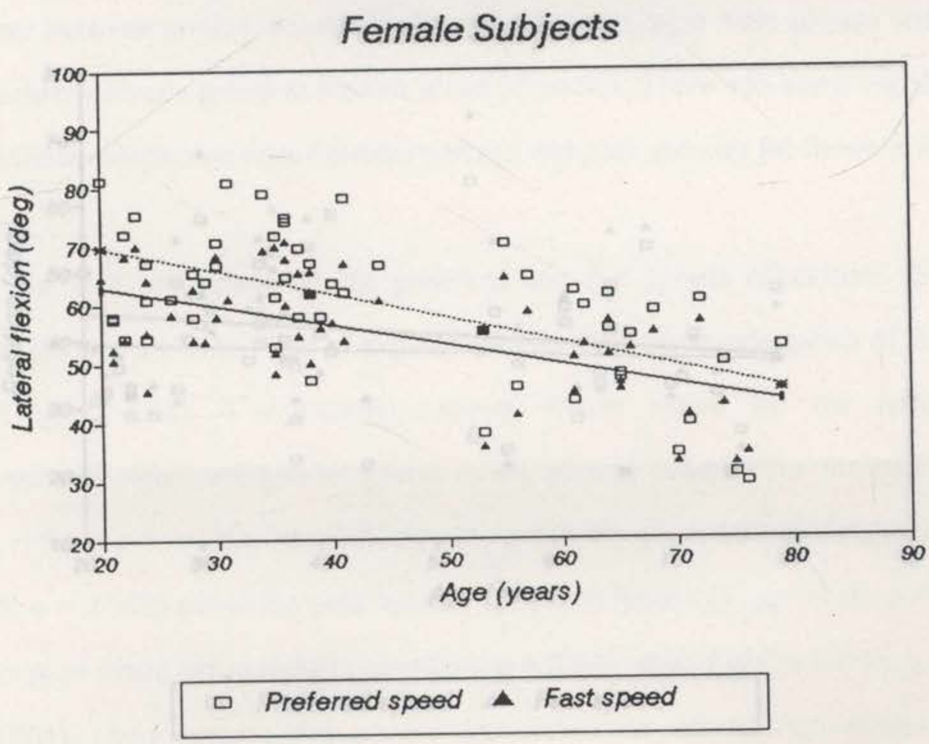
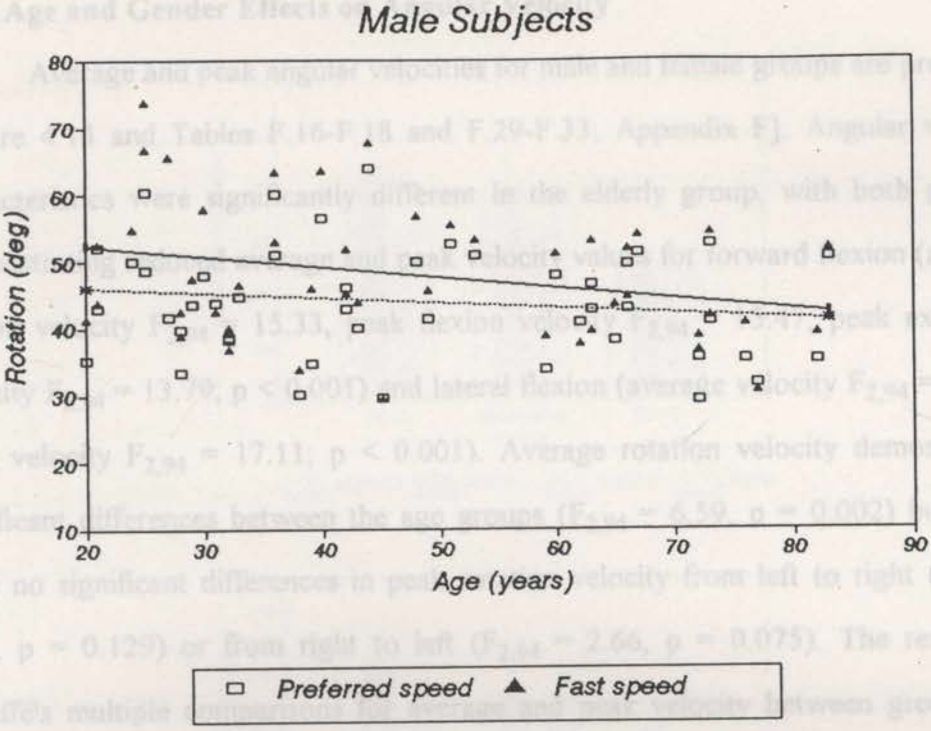


Figure 4.13c Relationships between age and range of lateral flexion in the lumbar spine in male and female subjects for both speeds of motion (---- preferred speed, ___ fast speed).



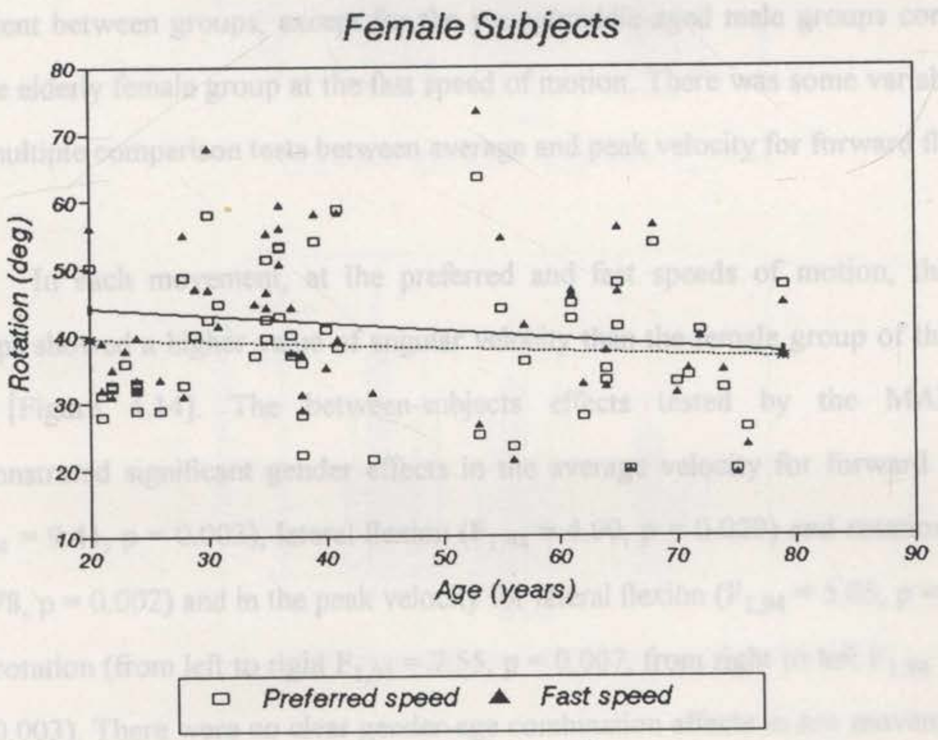


Figure 4.13d Relationships between age and range of rotation in the lumbar spine in male and female subjects for both speeds of motion (---- preferred speed, ___ fast speed).

4.3.3 Age and Gender Effects on Angular Velocity

Average and peak angular velocities for male and female groups are presented [Figure 4.14 and Tables F.16-F.18 and F.29-F.33; Appendix F]. Angular velocity characteristics were significantly different in the elderly group, with both genders demonstrating reduced average and peak velocity values for forward flexion (average flexion velocity $F_{2,94} = 15.33$, peak flexion velocity $F_{2,94} = 15.47$, peak extension velocity $F_{2,94} = 13.79$; $p < 0.001$) and lateral flexion (average velocity $F_{2,94} = 21.75$, peak velocity $F_{2,94} = 17.11$; $p < 0.001$). Average rotation velocity demonstrated significant differences between the age groups ($F_{2,94} = 6.59$, $p = 0.002$) but there were no significant differences in peak rotation velocity from left to right ($F_{2,94} = 2.10$, $p = 0.129$) or from right to left ($F_{2,94} = 2.66$, $p = 0.075$). The results of Schéffé's multiple comparisons for average and peak velocity between groups are shown in Table 4.17. Angular velocity of rotation was variable and not significantly different between groups, except for the young/middle-aged male groups compared to the elderly female group at the fast speed of motion. There was some variability in the multiple comparison tests between average and peak velocity for forward flexion.

In each movement, at the preferred and fast speeds of motion, the male groups showed a higher value of angular velocity than the female group of the same age [Figure 4.14]. The between-subjects effects tested by the MANOVA demonstrated significant gender effects in the average velocity for forward flexion ($F_{1,94} = 9.41$, $p = 0.003$), lateral flexion ($F_{1,94} = 4.90$, $p = 0.029$) and rotation ($F_{1,94} = 9.78$, $p = 0.002$) and in the peak velocity for lateral flexion ($F_{1,94} = 5.05$, $p = 0.027$) and rotation (from left to right $F_{1,94} = 7.55$, $p = 0.007$, from right to left $F_{1,94} = 9.11$; $p = 0.003$). There were no clear gender-age combination effects in any movement for either velocity value. No differences were detected in the decreasing trend of angular velocity between male and female subjects across age groups.

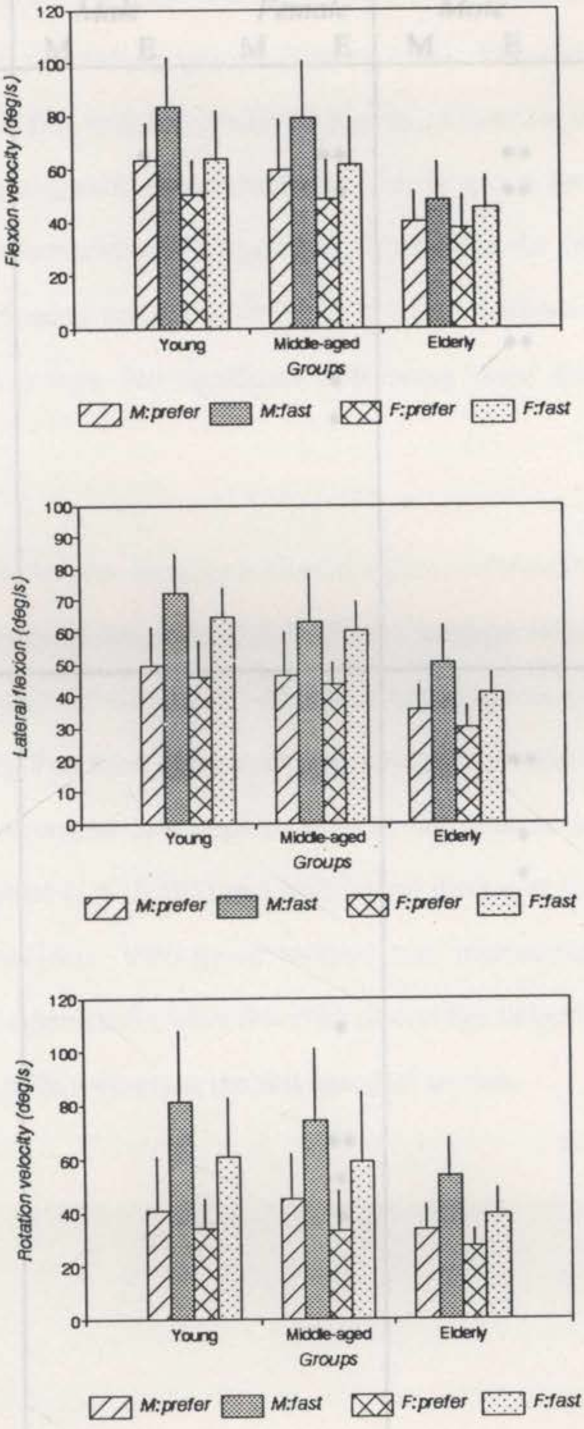


Figure 4.14 *Average angular velocity of forward flexion, lateral flexion and rotation in the lumbar spine for male and female groups at the preferred and the fast speeds; M=male, F=female, prefer=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].*

Table 4.17 Tests for significance of multiple comparison for angular velocity between age groups in the lumbar spine.

Movements		Preferred speed Male M	Preferred speed Male E	Preferred speed Female M	Preferred speed Female E	Fast speed Male M	Fast speed Male E	Fast speed Female M	Fast speed Female E
Average velocity									
Flexion									
Male	Y		*		**		**		**
	M				*		**		**
Female	Y								
	M								
Lat.flexion									
Male	Y				**		**		**
	M				*				**
Female	Y				*				**
	M								**
Rotation									
Male	Y								**
	M								*
Female	Y								
	M								
Peak velocity									
Flexion									
Male	Y						**		**
	M								
Female	Y						*		*
	M						*		*
Extension									
Male	Y								*
	M								
Female	Y				*				*
	M								
Lat. flexion									
Male	Y				**				**
	M				*				**
Female	Y				*				**
	M								**
Rotation L-R									
Male	Y								*
	M								
Female	Y								
	M								
Rotation R-L									
Male	Y								*
	M								*
Female	Y								
	M								

Note: Y = young group, M = middle-aged group, E = elderly group.
$* = p < 0.05$, $** = p < 0.01$

The young and middle-aged male and female subjects demonstrated a greater capability to increase their angular velocity from the preferred to the fast speed of motion compared to the elderly groups [Figure 4.14]. The differences in angular velocity between the fast and the preferred speeds of motion were greater in the young and middle-aged groups compared to the elderly group for both genders. The elderly female group demonstrated a significant decrease in the differential values for forward and lateral flexion and for rotation ($p < 0.02$) compared to the young and middle-aged female groups. No significant differences were detected between the male groups.

The lack of fit test for linearity indicated a linear relationship between age and angular velocity at both speeds of motion. Peak and average velocity values of all the movements were negatively correlated with age in both genders and at both speeds of motion [Table 4.18]. For each movement, the stronger correlation was seen at the faster speed. The strongest relationship in male subjects occurred with forward flexion at the fast speed ($r = -0.595$) and with lateral flexion at the same speed ($r = -0.685$) for female subjects. Velocity of rotation was inconsistently related to age, however significant correlations were detected in average velocity and peak velocity from left to right in male subjects at the fast speed of motion.

Table 4.18 Correlation coefficients and regression equations for age and angular velocity in the lumbar spine.

Angular velocity	Preferred speed r	Preferred speed Equation	Fast speed r	Fast speed Equation
Male(n=46)				
Average velocity				
Forward flexion	-0.526**	y=69.5-0.57x	-0.595**	y=93.4-0.86x
Lateral flexion	-0.444**	y=53.5-0.36x	-0.576**	y=76.8-0.55x
Rotation	-0.200#	y=44.9-0.19x	-0.444**	y=88.7-0.70x
Peak velocity				
Forward flexion	-0.428**	y=106-0.70x	-0.586**	y=148-1.25x
Extension	-0.411**	y=117-0.68x	-0.485**	y=142-0.86x
Lateral flexion	-0.438**	y=105-0.72x	-0.446**	y=143-0.89x
Rotation L - R	-0.073#	y=80.4-0.12x	-0.331*	y=153-0.89x
Rotation R - L	-0.078#	y=80.3-0.14x	-0.269#	y=147-0.69x
Female(n=54)				
Average velocity				
Forward flexion	-0.361**	y=54.4-0.34x	-0.446**	y=68.9-0.46x
Lateral flexion	-0.499**	y=49-0.35x	-0.685**	y=69.4-0.55x
Rotation	-0.154#	y=34.8-0.12x	-0.309*	y=64.5-0.43x
Peak velocity				
Forward flexion	-0.383**	y=99.7-0.53x	-0.460**	y=134-0.87x
Extension	-0.469**	y=118-0.71x	-0.529**	y=138-0.86x
Lateral flexion	-0.468**	y=94.5-0.68x	-0.633**	y=133-1.08x
Rotation L - R	0.031#	y=63.6+0.04x	-0.166#	y=113-0.44x
Rotation R - L	-0.080#	y=66.7-0.11x	-0.230#	y=113-0.54x

Note: * = $p < 0.05$, ** = $p < 0.01$, y = angular velocity (deg/s), x = age-20 (years)
r = Pearson product moment correlation coefficient. # = MSE/MSR ratio > 20%

With forward and lateral flexion, the average velocity at the preferred speed decreased by approximately 1 deg/s every 2-3 years and the peak velocity by 2 deg/s every 3 years. The rate of decrease in velocity with the fast speed was greater than the preferred speed for all movements. The decrease in average velocity in the fast speed was approximately 2 deg/s in male subjects and 1 deg/s in female subjects every 3 years.

The reduction in average velocity of forward flexion in the lumbar spine was greater than in the lower thoracic spine whereas the decreases in average velocity of lateral flexion and rotation were greater in the lower thoracic spine compared to the lumbar spine. For example, from the age of 20 to 70 years old the reduction in average forward flexion velocity was 40% in male subjects and 30% in female subjects in the lumbar spine while the lower thoracic spine demonstrated a 20% reduction in both genders. At the age of 70, the reduction in average velocity of lateral flexion was approximately 50% in the lower thoracic spine and 35% in the lumbar spine. The average velocity of rotation decreased between 50 and 70% in the lower thoracic spine and approximately 20% in the lumbar spine.

Part II: Three Dimensional Kinematic Patterns

4.4 Patterns of Movement

The general patterns of the associated movements for each trunk segment were consistent in all the groups. To demonstrate the pattern of movement, plots of the mean movements for forward flexion, lateral flexion and for rotation, shown with plus one standard deviation, of the young male group are displayed for thoracolumbar, lower thoracic and lumbar spine [Figures 4.15, 4.16 and 4.17 respectively]. The ranges of movement in degrees are plotted over one cycle of movement from the starting position to the opposite extreme position and returning to the starting position. Forward flexion, right lateral flexion and right rotation are displayed as positive values; extension, left lateral flexion and left rotation as negative values.

The amplitudes of primary and associated movements are presented [Tables G.1-G.12; Appendix G]. Directions of the associated movements and the number of subjects performing each movement are also shown.

4.4.1 Thoracolumbar Spine

Forward flexion was associated with effectively no consistent rotation or lateral flexion in any group. Such accompanying rotation and lateral flexion as was seen were between 0 and 5 degrees.

To establish meaningful correlations between the patterns of associated forward flexion and the primary movement of lateral flexion and rotation, the negative values of left lateral flexion and left rotation were converted to positive values, thus making the values non-directional. However, the relationships of lateral flexion and rotation retained their original sense. Correlations between the ranges of primary and associated movements demonstrated that a strong coupling of forward flexion occurred in association with primary lateral flexion and also with rotation [Table 4.19]. Strong couplings between lateral flexion and rotation and vice versa are also demonstrated in Table 4.19. The negative correlations indicated that the primary movement of lateral flexion and the associated rotation acted in opposite directions.

Lateral flexion was always accompanied by forward flexion, except for one subject in the young male group who exhibited extension. Lateral flexion was also accompanied by contralateral rotation, except for one elderly female subject who demonstrated right rotation on right lateral flexion. Rotation was generally accompanied by flexion, however a few subjects in each group showed extension during rotation. Rotation was accompanied by lateral flexion towards the same side in all groups.

Table 4.19 Correlation coefficients for the relationships between the associated and primary movements in the thoracolumbar spine in young, middle-aged and elderly male and female groups at the preferred and fast speeds of motion.

Gender	Primary movement	Associated movement	Preferred speed			Fast speed		
			Young	Middle	Elderly	Young	Middle	Elderly
Male	Lat.flexion	For.flexion	0.946	0.921	0.762	0.935	0.894	0.729
		Rotation	-0.999	-0.996	-0.999	-0.999	-0.994	-0.999
	Rotation	For.flexion	0.930	0.892	0.887	0.876	0.897	0.818
		Lat.flexion	1.000	0.997	0.999	0.999	0.996	1.000
Female	Lat.flexion	For.flexion	0.967	0.933	0.846	0.929	0.912	0.783
		Rotation	-0.998	-0.998	-0.999	-0.999	-0.997	-0.999
	Rotation	For.flexion	0.826	0.682	0.812	0.688	0.725	0.776
		Lat.flexion	0.996	0.997	0.996	0.999	0.997	0.989

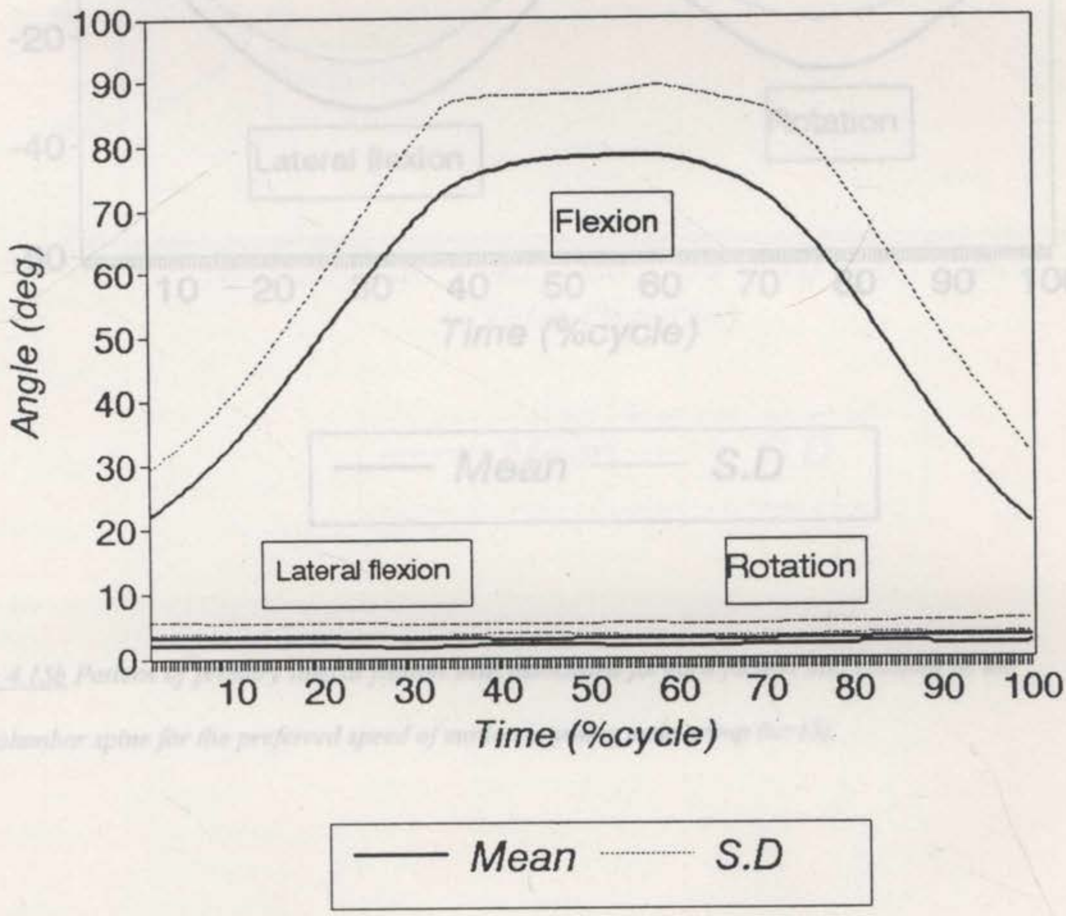


Figure 4.15a Pattern of primary forward flexion with associated lateral flexion and rotation in the thoracolumbar spine for the preferred speed of motion in young male group (n=15).

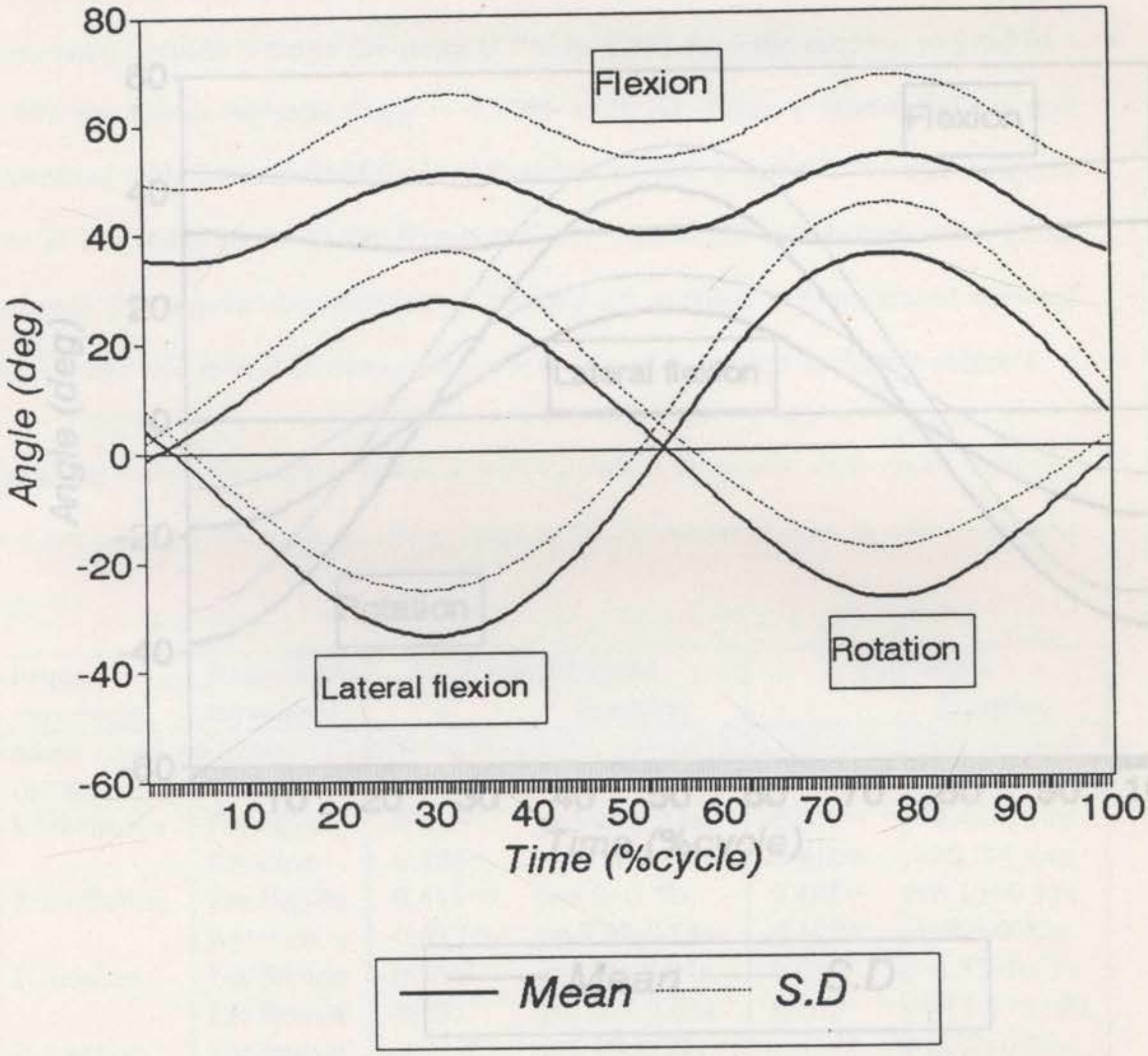


Figure 4.15b Pattern of primary lateral flexion with associated forward flexion and rotation in the thoracolumbar spine for the preferred speed of motion in young male group (n=15).

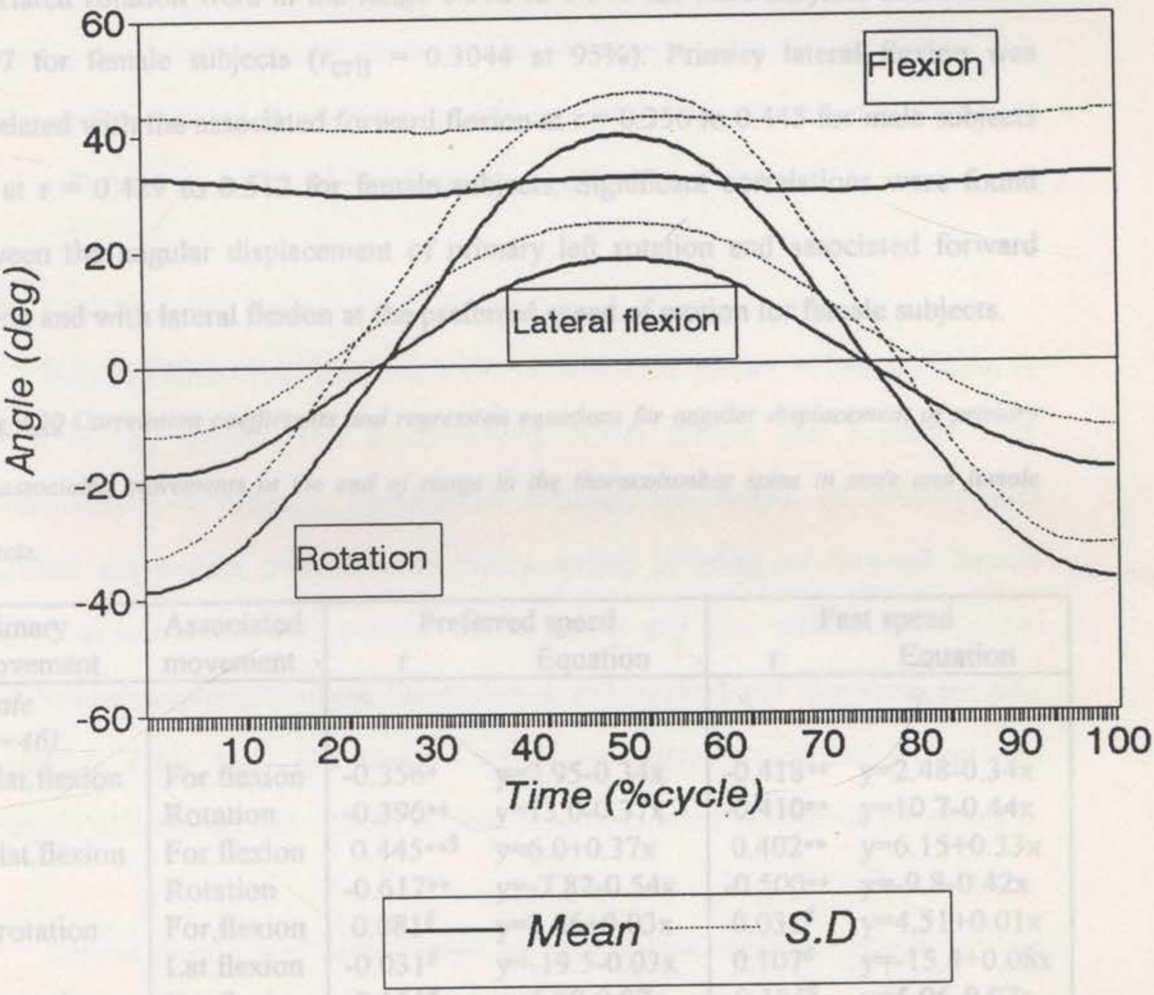


Figure 4.15c Pattern of primary rotation with associated forward flexion and lateral flexion in the thoracolumbar spine for the preferred speed of motion in young male group (n=15).

Regression analysis of the peak values of angular displacement for lateral flexion with accompanying forward flexion and rotation displayed significant correlations [Table 4.20]. The coefficients of the primary lateral flexion and associated rotation were in the range 0.396 to 0.617 for male subjects and 0.370 - 0.497 for female subjects (r_{crit} = 0.3044 at 95%). Primary lateral flexion was correlated with the associated forward flexion at r = 0.356 to 0.445 for male subjects and at r = 0.429 to 0.512 for female subjects. Significant correlations were found between the angular displacement of primary left rotation and associated forward flexion and with lateral flexion at the preferred speed of motion for female subjects.

Table 4.20 Correlation coefficients and regression equations for angular displacement of primary and associated movements at the end of range in the thoracolumbar spine in male and female subjects.

Primary movement	Associated movement	Preferred speed r	Preferred speed Equation	Fast speed r	Fast speed Equation
Male (n=46)					
L.lat.flexion	For.flexion	-0.356*	y=2.95-0.34x	-0.418**	y=2.48-0.34x
	Rotation	-0.396**	y=13.0-0.37x	-0.410**	y=10.7-0.44x
R.lat.flexion	For.flexion	0.445**$	y=6.0+0.37x	0.402**	y=6.15+0.33x
	Rotation	-0.617**	y=-7.82-0.54x	-0.500**	y=-9.8-0.42x
L.rotation	For.flexion	0.081#	y=3.86+0.03x	0.031#	y=4.51+0.01x
	Lat.flexion	-0.031#	y=-19.5-0.03x	0.107#	y=-15.4+0.08x
R.rotation	For.flexion	-0.111#	y=5.09-0.07x	-0.164#	y=5.96-0.07x
	Lat.flexion	-0.196#	y=24.4-0.16x	-0.094#	y=21.9-0.05x
Female (n=54)					
L.lat.flexion	For.flexion	-0.429**	y=0.57-0.50x	-0.445**	y=-0.52-0.52x
	Rotation	-0.412**	y=9.29-0.44x	-0.450**	y=9.02-0.46x
R.lat.flexion	For.flexion	0.512**	y=4.85+0.42x	0.460**	y=4.84+0.41x
	Rotation	-0.497**	y=-9.99-0.35x	-0.370**	y=-9.16-0.33x
L.rotation	For.flexion	-0.321*	y=-2.62-0.19x	-0.060#	y=2.09-0.03x
	Lat.flexion	-0.292*#	y=-23.4-0.22x	-0.171#	y=-21-0.11x
R.rotation	For.flexion	0.135#	y=0.63+0.06x	-0.170#	y=5.98-0.08x
	Lat.flexion	0.003#	y=16.8+0.002x	0.103#	y=15.6+0.06x

Note: * = $p < 0.05$, ** = $p < 0.01$, r = Pearson product moment correlation coefficient.
y = angle of associated motion (deg), x = angle of primary motion (deg)
$ = significant lack of fit at $p < 0.05$, # = MSE/MSR ratio > 20%

In the thoracolumbar spine, the ratio of associated forward flexion to primary lateral flexion was between 42% and 57% in male subjects and between 50% and 58% in female subjects. The ratio of associated rotation to primary lateral flexion was 75% to 80% in males and 64% to 76% in females. Some significant correlations between primary rotation and its associated movements occurred in primary left rotation and associated forward flexion and in primary left rotation and associated lateral flexion during preferred speed movement in female subjects.

4.4.2 Lower Thoracic Spine

Forward flexion was associated with no consistent pattern of lateral flexion or rotation in any group. The accompanying lateral flexion and rotation were approximately 0-4 degrees. Correlations between the ranges of primary and associated movements demonstrated that a strong coupling of forward flexion occurred in association with primary lateral flexion and also with rotation [Table 4.21]. Strong couplings between lateral flexion and rotation and vice versa are also presented in Table 4.21. The negative correlations demonstrated that the primary movement of lateral flexion and the associated rotation acted in opposite directions.

Lateral flexion was accompanied by contralateral rotation, except for one male in both the middle-aged and elderly groups and one female in the elderly group who showed ipsilateral rotation on lateral flexion. Rotation was accompanied by lateral flexion towards the same side in all groups apart from one middle-aged male, one elderly male and three elderly female subjects who exhibited contralateral side flexion during rotation.

Table 4.21 Correlation coefficients for the relationships between the associated and primary movements in the lower thoracic spine in young, middle-aged and elderly male and female groups at the preferred and fast speeds of motion.

Gender	Primary movement	Associated movement	Preferred speed			Fast speed		
			Young	Middle	Elderly	Young	Middle	Elderly
Male	Lat.flexion	For.flexion	0.922	0.884	0.706	0.882	0.822	0.695
		Rotation	-0.999	-0.999	-0.995	-0.999	-0.999	-0.995
	Rotation	For.flexion	0.935	0.920	0.903	0.926	0.952	0.914
		Lat.flexion	0.989	0.995	0.989	0.999	0.994	0.996
Female	Lat.flexion	For.flexion	0.949	0.892	0.823	0.913	0.864	0.776
		Rotation	-0.997	-0.998	-0.996	-0.998	-0.998	-0.998
	Rotation	For.flexion	0.935	0.906	0.901	0.932	0.926	0.875
		Lat.flexion	0.994	0.995	0.992	0.998	0.997	0.993

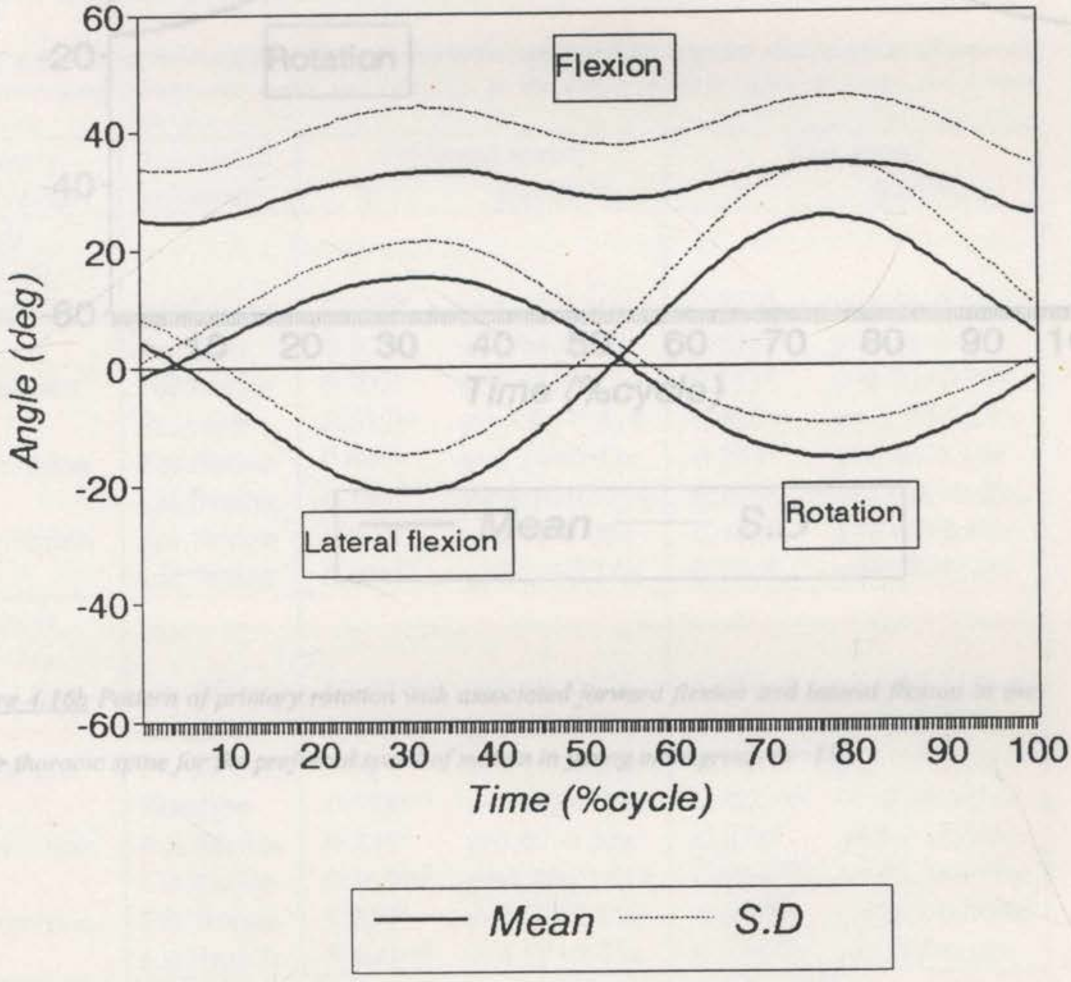


Figure 4.16a Pattern of primary lateral flexion with associated forward flexion and rotation in the lower thoracic spine for the preferred speed of motion in young male group (n=15).

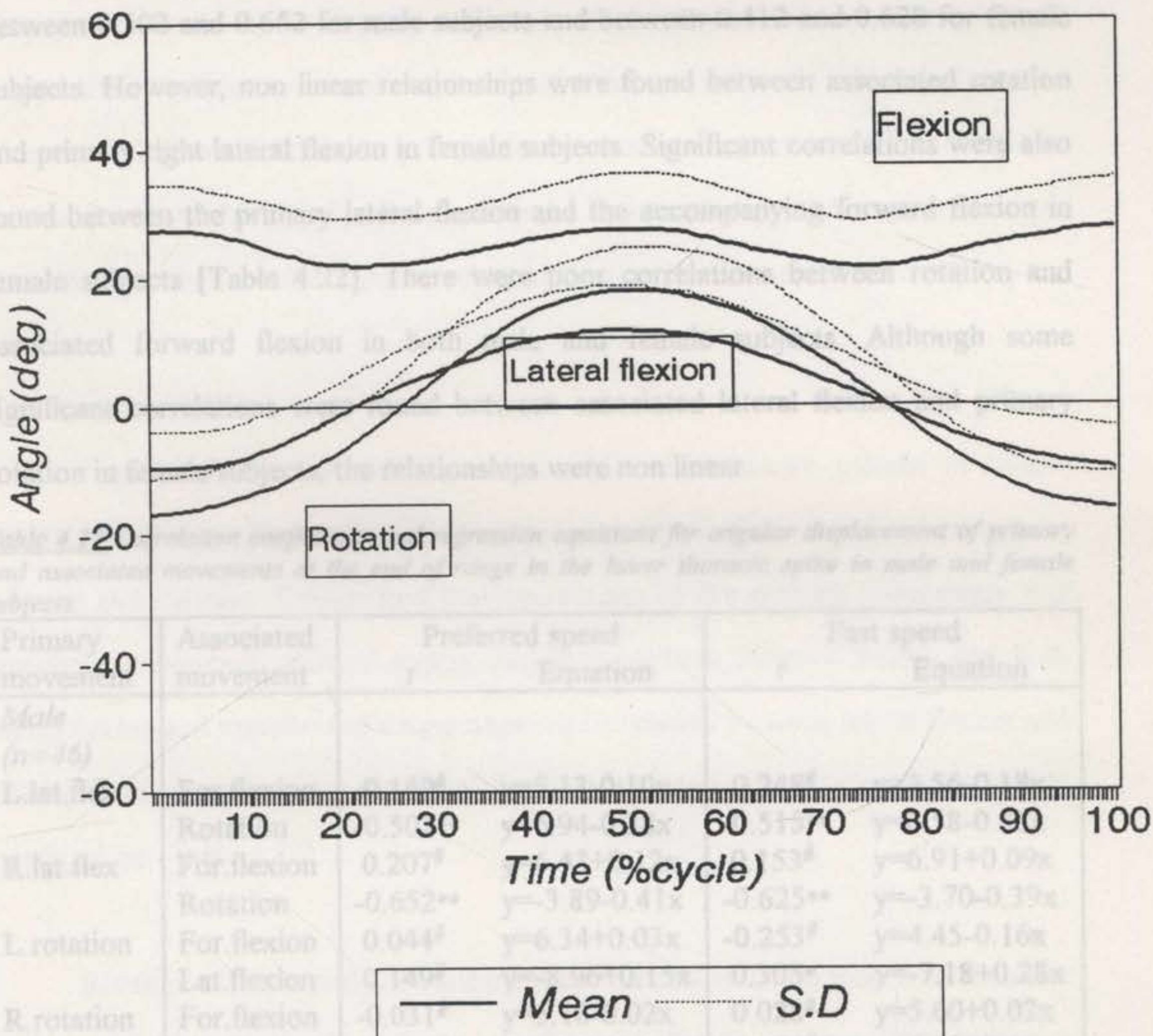


Figure 4.16b Pattern of primary rotation with associated forward flexion and lateral flexion in the lower thoracic spine for the preferred speed of motion in young male group (n=15).

Regression analysis was performed to establish the relationships between primary and associated movements at the extremes of movement [Table 4.22]. The correlation coefficients of primary lateral flexion and accompanying rotation were between 0.502 and 0.652 for male subjects and between 0.412 and 0.628 for female subjects. However, non linear relationships were found between associated rotation and primary right lateral flexion in female subjects. Significant correlations were also found between the primary lateral flexion and the accompanying forward flexion in female subjects [Table 4.22]. There were poor correlations between rotation and associated forward flexion in both male and female subjects. Although some significant correlations were found between associated lateral flexion and primary rotation in female subjects, the relationships were non linear.

<u>Table 4.22</u> Correlation coefficients and regression equations for angular displacement of primary and associated movements at the end of range in the lower thoracic spine in male and female subjects.

Primary movement	Associated movement	Preferred speed		Fast speed	
		r	Equation	r	Equation
Male (n=46)					
L.lat.flex	For.flexion	-0.149#	y=5.13-0.10x	-0.248#	y=3.56-0.18x
	Rotation	-0.502**	y=6.94-0.38x	-0.515**	y=6.58-0.43x
R.lat.flex	For.flexion	0.207#	y=6.43+0.12x	0.153#	y=6.91+0.09x
	Rotation	-0.652**	y=-3.89-0.41x	-0.625**	y=-3.70-0.39x
L.rotation	For.flexion	0.044#	y=6.34+0.03x	-0.253#	y=4.45-0.16x
	Lat.flexion	0.149#	y=-8.96+0.15x	0.305*	y=-7.18+0.28x
R.rotation	For.flexion	-0.031#	y=5.18-0.02x	0.028#	y=5.60+0.02x
	Lat.flexion	0.186#	y=8.26+0.18x	0.174#	y=9.08+0.16x
Female (n=54)					
L.lat.flex	For.flexion	-0.442**	y=0.58-0.37x	-0.376**	y=1.97-0.30x
	Rotation	-0.513**	y=5.49-0.38x	-0.574**	y=4.84-0.45x
R.lat.flex	For.flexion	0.365**	y=3.79+0.25x	0.415**	y=3.37+0.28x
	Rotation	-0.628**$	y=-4.02-0.31x	-0.412**$	y=-5.03-0.25x
L.rotation	For.flexion	-0.245#	y=3.67-0.20x	-0.076#	y=6.23-0.06x
	Lat.flexion	0.365**$	y=-4.26+0.51x	0.274*$#	y=-7.56+0.30x
R.rotation	For.flexion	0.230#	y=4.70+0.13x	-0.007#	y=6.97-0.004x
	Lat.flexion	0.400**$	y=4.57+0.45x	0.326*$	y=7.19+0.40x

Note: * = $p < 0.05$, ** = $p < 0.01$, r = Pearson product moment correlation coefficient.
y = angle of associated motion (deg), x = angle of primary motion (deg)
$ = significant lack of fit at $p < 0.05$, # = MSE/MSR ratio > 20%

On average every 10 degrees of primary lateral flexion was accompanied by approximately 4 degrees of rotation in all cases. The ratio of associated rotation to primary lateral flexion was between 38 and 43% in male subjects and 25-45% for female subjects. Every 10 degrees of primary lateral flexion was associated with 1 degree of forward flexion in male subjects and 3 degrees in female subjects. The ratio of associated forward flexion to primary lateral flexion was between 10 and 18% in male subjects and 25-37% for female subjects. For example, at 30 degrees of right lateral flexion, female subjects had associated forward flexion of about 11 degrees.

4.4.3 Lumbar Spine

Forward flexion generally occurred with no consistent pattern of lateral flexion or rotation. The ranges of accompanying lateral flexion and rotation were between 0-4 degrees. Correlations between ranges of the primary movements and associated movements showed strong couplings between forward flexion and both lateral flexion and rotation and strong negative correlation between lateral flexion and rotation in all groups, except for lateral flexion associated with rotation in the elderly female group [Table 4.23].

Rotation was generally accompanied by contralateral side flexion in the male groups and in the young and the middle-aged female groups. No particular association of lateral flexion with primary rotation was found in the elderly female group at either speed. For example, left rotation was accompanied by right lateral flexion in 8 subjects and by left lateral flexion in 8 subjects at both the preferred and the fast speeds of motion.

Table 4.23 Correlation coefficients for the relationships between the associated and primary movements in the lumbar spine in young, middle-aged and elderly male and female groups at the preferred and fast speeds of motion.

Gender	Primary movement	Associated movement	Preferred speed			Fast speed		
			Young	Middle	Elderly	Young	Middle	Elderly
Male	Lat.flexion	For.flexion	0.901	0.845	0.689	0.888	0.803	0.667
		Rotation	-0.975	-0.931	-0.954	-0.972	-0.860	-0.951
	Rotation	For.flexion	0.952	0.962	0.890	0.972	0.971	0.879
		Lat.flexion	-0.981	-0.970	-0.877	-0.965	-0.954	-0.977
Female	Lat.flexion	For.flexion	0.949	0.902	0.846	0.872	0.849	0.769
		Rotation	-0.994	-0.948	-0.984	-0.988	-0.924	-0.977
	Rotation	For.flexion	0.931	0.897	0.860	0.924	0.916	0.893
		Lat.flexion	-0.991	-0.992	0.520	-0.988	-0.972	0.161

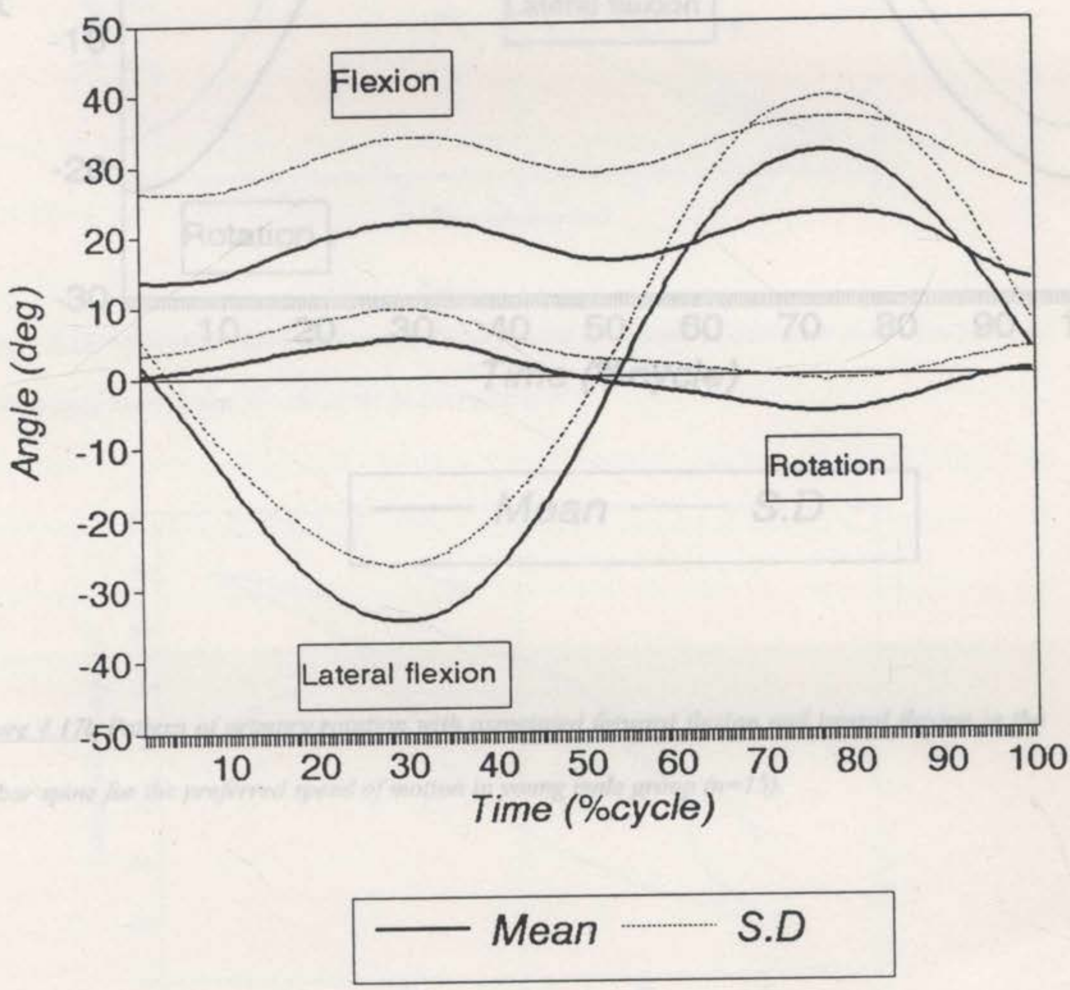


Figure 4.17a Pattern of primary lateral flexion with associated forward flexion and rotation in the lumbar spine for the preferred speed of motion in young male group (n=15).

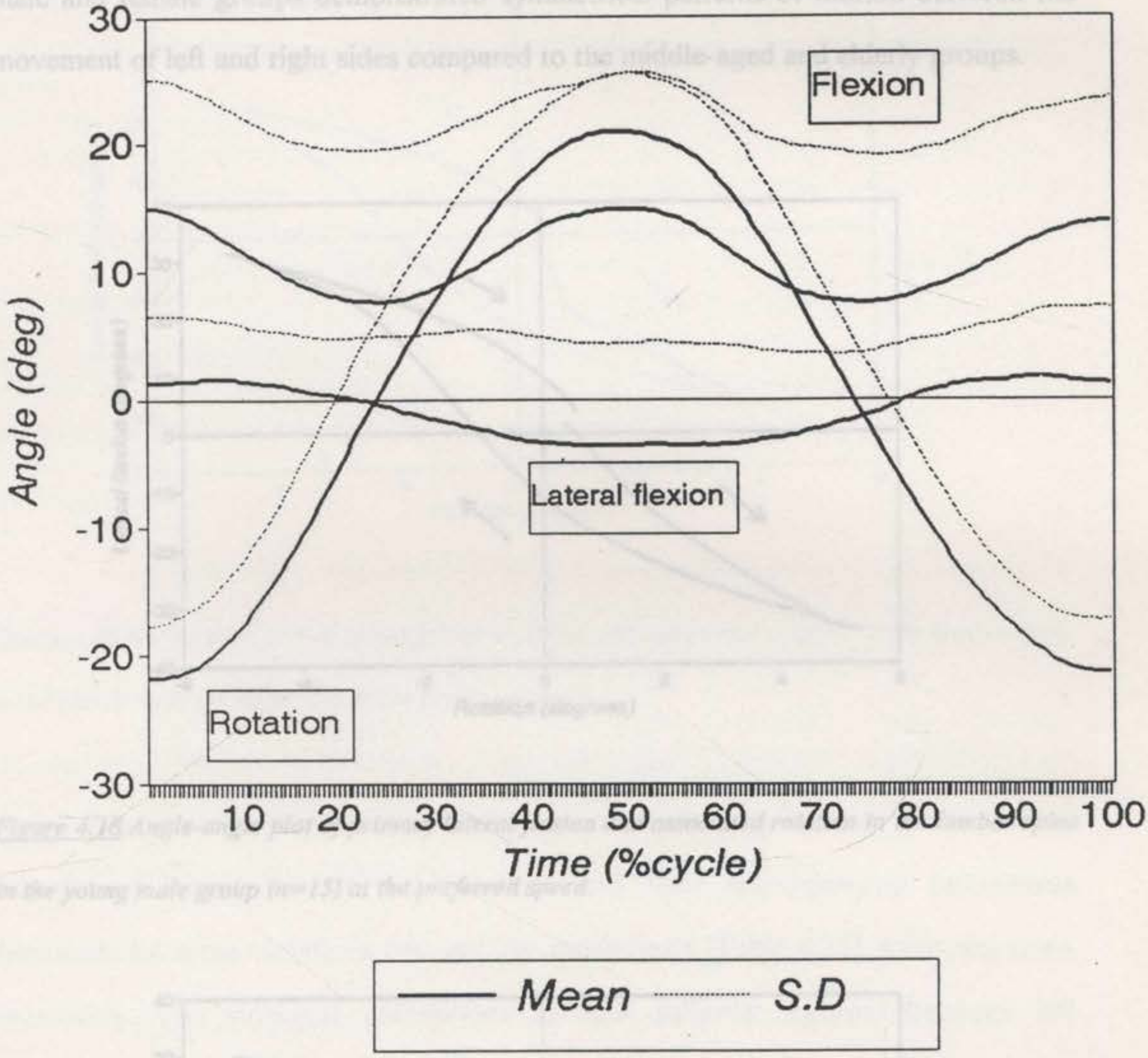


Figure 4.17b Pattern of primary rotation with associated forward flexion and lateral flexion in the lumbar spine for the preferred speed of motion in young male group (n=15).

Angle-angle plots of primary lateral flexion and associated rotation in the lumbar spine in the male groups are presented [Figures 4.18 to 4.20]. The young male and female groups demonstrated symmetrical patterns of motion between the movement of left and right sides compared to the middle-aged and elderly groups.

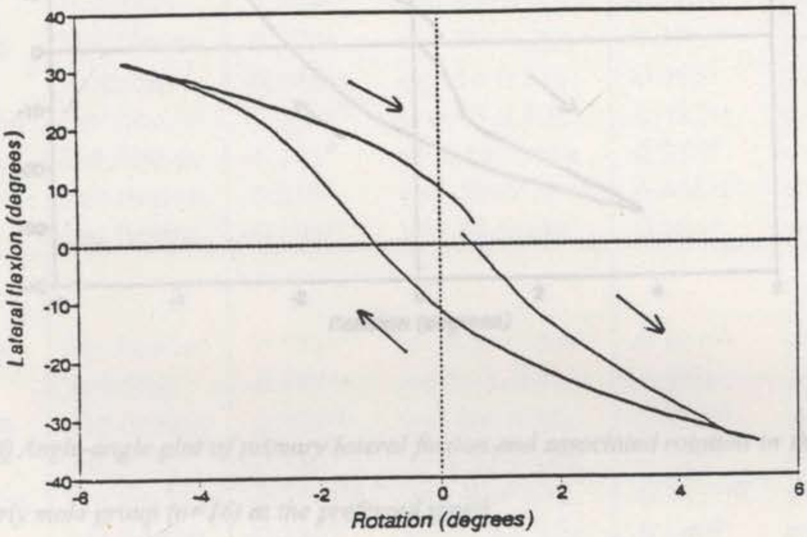


Figure 4.18 Angle-angle plot of primary lateral flexion and associated rotation in the lumbar spine in the young male group (n=15) at the preferred speed.

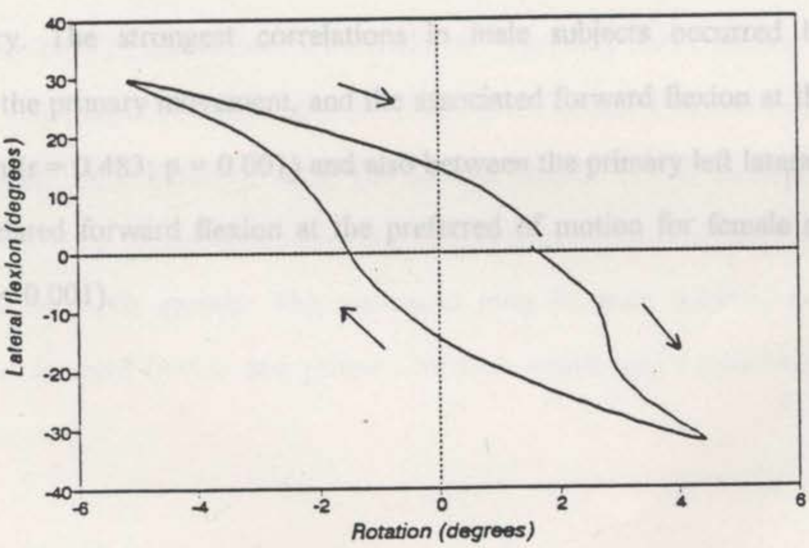


Figure 4.19 Angle-angle plot of primary lateral flexion and associated rotation in the lumbar spine in the middle-aged male group (n=15) at the preferred speed.

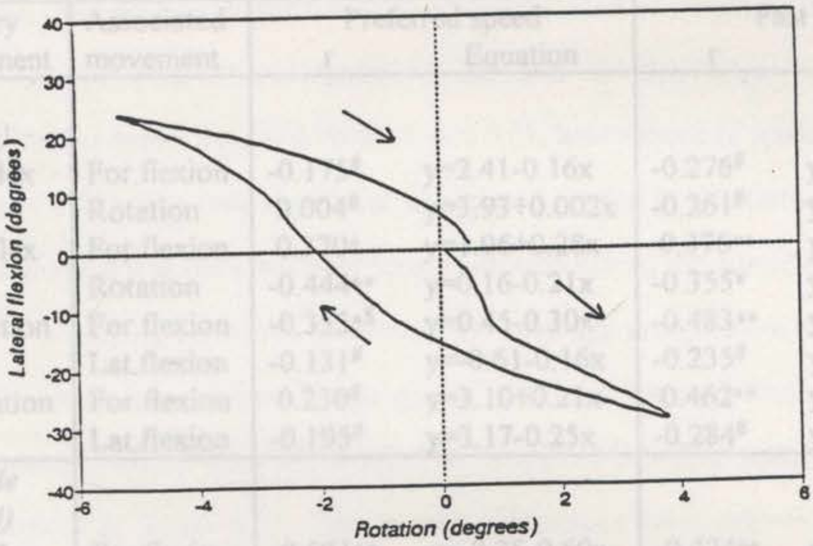


Figure 4.20 Angle-angle plot of primary lateral flexion and associated rotation in the lumbar spine in the elderly male group (n=16) at the preferred speed.

Regression analysis relating the maximum angular displacement of the primary movements, lateral flexion and rotation, and their accompanying movements demonstrated some variations between the movements [Table 4.24], including some asymmetry. The strongest correlations in male subjects occurred between left rotation, the primary movement, and the associated forward flexion at the fast speed of motion ($r = 0.483$; $p = 0.001$) and also between the primary left lateral flexion and the associated forward flexion at the preferred of motion for female subjects ($r = 0.521$; $p < 0.001$).

Table 4.24 Correlation coefficients and regression equations for angular displacement of primary and associated movements at the end of range in the lumbar spine in male and female subjects .

Primary movement	Associated movement	Preferred speed r	Preferred speed Equation	Fast speed r	Fast speed Equation
Male (n=46)					
L.lat.flex	For.flexion	-0.175#	y=2.41-0.16x	-0.276#	y=0.62-0.21x
	Rotation	0.004#	y=3.93+0.002x	-0.261#	y=-1.16-0.15x
R.lat.flex	For.flexion	0.370*	y=1.96+0.28x	0.376**	y=1.35+0.28x
	Rotation	-0.444**	y=0.16-0.21x	-0.355*	y=-0.32-0.19x
L.rotation	For.flexion	-0.355*$	y=0.45-0.30x	-0.483**	y=0.17-0.38x
	Lat.flexion	-0.131#	y=-0.61-0.16x	-0.235#	y=-1.98-0.24x
R.rotation	For.flexion	0.230#	y=3.10+0.21x	0.462**	y=1.74+0.35x
	Lat.flexion	-0.195#	y=3.17-0.25x	-0.284#	y=3.75-0.28x
Female (n=54)					
L.lat.flex	For.flexion	-0.521**	y=-8.25-0.60x	-0.424**	y=-6.05-0.51x
	Rotation	-0.447**	y=-5.71-0.32x	-0.300*	y=-3.13-0.24x
R.lat.flex	For.flexion	0.289*#	y=3.03+0.24x	0.292*#	y=2.78+0.25x
	Rotation	-0.135#	y=-2.85-0.06x	-0.080#	y=-3.89-0.04x
L.rotation	For.flexion	-0.274*$#	y=1.39-0.22x	-0.347**$	y=1.59-0.26x
	Lat.flexion	-0.180#	y=-1.15-0.22x	-0.140#	y=0.12-0.14x
R.rotation	For.flexion	0.319*	y=1.38+0.23x	0.265*#	y=3.35+0.17x
	Lat.flexion	-0.126#	y=0.24-0.12x	-0.116$#	y=-0.62-0.11x

Note: * = p < 0.05, ** = p< 0.01, r = Pearson product moment correlation coefficient.
y = angle of associated motion (deg), x = angle of primary motion (deg)
$ = significant lack of fit at p < 0.05, # = MSE/MSR ratio > 20%

The ratio of associated forward flexion to primary lateral flexion was between 30-35%. The range of associated rotation and primary lateral flexion demonstrated an asymmetrical ratio between male (20%) and female (13%) subjects. In female subjects the ratio of associated forward flexion to primary rotation was between 25 and 30% for both speeds. The maximum ratio in male subjects occurred with associated forward flexion and primary rotation which was approximately 40% for the fast motion.

4.5 Age Effects on the Associated Movements

The statistically significant age-related decline in the range of motion of associated forward flexion and rotation with primary left and right lateral flexion was evident in the total thoracolumbar spine and in the lower thoracic spine (thoracolumbar spine: $F_{2,94} = 6.76\text{-}8.15$, $p < 0.01$; lower thoracic spine: $F_{2,94} = 4.77\text{-}14.49$, $p < 0.01$). The only significant age-related change in associated movement in the lumbar spine was the associated forward flexion during left lateral flexion ($F_{2,94} = 3.73$, $p = 0.028$), however the differences between age groups were not detected by Schéffé multiple comparison. The ranges of associated forward flexion and rotation are presented [Tables 4.25 and 4.26]. The results of Schéffé's multiple comparison are presented in Table 4.27. The greatest differences were detected between the young and the elderly groups for both genders. In the case of primary rotation, no consistent decrease in the ranges of the associated movements were found with increasing age at any of the trunk segments.

Ranges of associated movements during the primary movements of lateral flexion and rotation were generally negatively correlated with age in all cases. Significant negative correlations were found between age and range of associated forward flexion and between age and range of associated rotation during the primary movement of lateral flexion at the total thoracolumbar spine and the lower thoracic spine [Table 4.28].

Table 4.25 Means (S.D) of range of motion (degrees) of associated forward flexion and rotation with primary lateral flexion in the thoracolumbar spine in the young, middle-aged and elderly male and female groups at the preferred and fast speeds of motion.

Subject groups	Left lateral flexion		Right lateral flexion	
	Ass.flexion	Ass.rotation	Ass.flexion	Ass.rotation
Preferred speed				
Male: Young	15(9)	29(9)	18(9)	-26(8)
Middle-aged	16(9)	25(7)	20(8)	-26(10)
Elderly	10(6)	22(5)	13(6)	-19(7)
Female: Young	21(8)	27(7)	21(7)	-23(7)
Middle-aged	18(10)	23(8)	20(10)	-22(7)
Elderly	11(6)	20(8)	13(6)	-18(5)
Fast speed				
Male: Young	14(8)	28(12)	16(7)	-25(8)
Middle-aged	14(7)	22(7)	18(11)	-23(10)
Elderly	10(4)	22(7)	13(7)	-19(7)
Female: Young	18(7)	26(7)	19(9)	-20(8)
Middle-aged	17(9)	23(7)	19(8)	-22(5)
Elderly	10(6)	19(6)	12(6)	-14(10)

Note: Negative values of associated rotation refer to movement towards the left side.

Table 4.26 Means (S.D) of range of motion (degrees) of associated forward flexion and rotation with primary lateral flexion in the lower thoracic spine in the young, middle-aged and elderly male and female groups at the preferred and fast speeds of motion.

Subject groups	Left lateral flexion		Right lateral flexion	
	Ass.flexion	Ass.rotation	Ass.flexion	Ass.rotation
Preferred speed				
Male: Young	8(7)	17(6)	9(5)	-14(6)
Middle-aged	8(5)	15(6)	10(6)	-13(6)
Elderly	5(4)	11(4)	7(4)	-9(4)
Female: Young	12(6)	18(5)	10(6)	-13(5)
Middle-aged	10(7)	14(5)	12(8)	-12(5)
Elderly	6(5)	11(5)	6(4)	-8(3)
Fast speed				
Male: Young	7(6)	18(8)	9(5)	-13(5)
Middle-aged	8(5)	14(4)	10(7)	-12(7)
Elderly	5(4)	12(5)	8(5)	-9(5)
Female: Young	11(5)	18(5)	11(7)	-13(6)
Middle-aged	9(6)	15(6)	11(6)	-12(4)
Elderly	6(5)	11(4)	6(4)	-6(5)

Note: Negative values of associated rotation refer to movement towards the left side.

Table 4.27 Schéffé's multiple comparisons between age groups for associated forward flexion and rotation with primary lateral flexion at the thoracolumbar spine and lower thoracic spine at the preferred and fast speeds of motion.

Movements		Preferred speed				Fast speed			
		Male		*Female*		*Male*		*Female*	
		M	E	M	E	M	E	M	E
Thoracolumbar segment									
Flexion on left lat flexion									
Male	Y								
	M								
Female	Y		*		*		*		
	M								
Flexion on right lat flexion									
Male	Y								
	M								
Female	Y		*						
	M								*
Rotation on left lat. flexion									
Male	Y								*
	M								
Female	Y								
	M								
Rotation on right lat. flexion									
Male	Y								*
	M								
Female	Y								
	M								
Lower thoracic spine									
Flexion on left lat flexion									
Male	Y								
	M								
Female	Y		*						
	M								
Flexion on right lat flexion									
Male	Y								
	M								
Female	Y								
	M				*				
Rotation on left lat. flexion									
Male	Y								*
	M								
Female	Y		*		*				**
	M								
Rotation on right lat. flexion									
Male	Y				*				*
	M								
Female	Y								*
	M								

Note: Y = young group, M = middle-aged group, E = elderly group, * = $p < 0.05$, ** = $p < 0.01$

Table 4.28 Correlations between age and range of associated movement during lateral flexion in the thoracolumbar and lower thoracic spine.

Primary movement	Associated movement	Preferred speed r	Preferred speed Equation	Fast speed r	Fast speed Equation
Thoracolumbar					
Male subjects					
Left lat. flexion	For. flexion	-0.253#	y=16.8-0.11x	-0.257#	y=15.3-0.10x
	Rotation	-0.420**	y=29.7-0.18x	-0.320*	y=28.2-0.16x
Right lat. flexion	For. flexion	-0.319*	y=21.0-0.14x	-0.221#	y=18.6-0.10x
	Rotation	-0.386**	y=28.9-0.18x	-0.298*#	y=26.0-0.14x
Female subjects					
Left lat. flexion	For. flexion	-0.459**	y=22.8-0.23x	-0.464**	y=20.7-0.21x
	Rotation	-0.333*	y=27.7-0.15x	-0.411**	y=27.3-0.17x
Right lat. flexion	For. flexion	-0.349**	y=22.2-0.16x	-0.303*	y=20.5-0.14x
	Rotation	-0.274*#	y=23.8-0.11x	-0.267#	y=22.0-0.13x
Lower thoracic					
Male subjects					
Left lat. flexion	For. flexion	-0.215#	y=8.8-0.06x	-0.154#	y=8.0-0.04x
	Rotation	-0.512**	y=18.5-0.16x	-0.469**	y=18.8-0.15x
Right lat. flexion	For. flexion	-0.156#	y=9.9-0.04x	-0.093#	y=9.4-0.03x
	Rotation	-0.362*	y=15.1-0.11x	-0.303*#	y=13.9-0.10x
Female subjects					
Left lat. flexion	For. flexion	-0.420**	y=12.8-0.15x	-0.413**	y=11.8-0.13x
	Rotation	-0.463**	y=17.9-0.15x	-0.516**	y=18.8-0.16x
Right lat. flexion	For. flexion	-0.274*#	y=12.0-0.10x	-0.326*	y=12.3-0.11x
	Rotation	-0.386**	y=13.8-0.10x	-0.407**	y=13.8-0.13x

Note: * = $p < 0.05$, ** = $p < 0.01$, y = range of associated movement, x = age-20 (years)
= MSE/MSR ratio > 20%

The strongest age related correlation was found in the range of rotation associated with left lateral flexion at the preferred speed of motion for the lower thoracic spine in male subjects ($r = -0.512$, $p < 0.001$) and with the same movement at the fast speed of motion in female subjects ($r = -0.516$, $p < 0.001$). For the thoracolumbar segment, the strongest correlation was seen between age and the rotation associated with left lateral flexion at the preferred speed of motion in male subjects ($r = -0.420$, $p = 0.004$) and with associated forward flexion on left lateral flexion at the fast speed of motion in female subjects ($r = -0.464$, $p < 0.001$). Ranges of associated movements at the lumbar spine were not significantly related to age, with the exception of the forward flexion accompanying left lateral flexion in female subjects (preferred speed r = -0.401, p = 0.003, y=13.3-0.15x; fast speed r = -0.363, p = 0.007, y=11.0-0.12x).

Some significant correlations were found between age and range of associated forward flexion and between age and range of associated lateral flexion during primary rotation in female subjects [Table 4.29]. The ranges of associated movements decreased by approximately 1 degree every 10 years. The only significant correlation in male subjects occurred in associated forward flexion during primary left rotation at the fast motion (r = -0.404, p = 0.005, y = 11.7-0.09x; y = range of associated movement, x = age-20).

<u>Table 4.29</u> Correlations between age and range of associated movement during rotation in female subjects (n=54).

Primary movement	Associated movement	Preferred speed r	Preferred speed Equation	Fast speed r	Fast speed Equation
Thoracolumbar					
Left rotation	For. flexion	-0.395**	y=6.4-0.11x	$-0.225^{\#}$	y=4.8-0.06x
	Lat. flexion	$-0.274^{*\#}$	y=13.6-0.09x	$-0.261^{\#}$	y=14.6-0.09x
Lower thoracic					
Left rotation	Lat. flexion	-0.322*	y=15.3-0.15x	$-0.318^{*\$}$	y=15.4-0.13x
Lumbar spine					
Left rotation	For. flexion	-0.394**	y=8.1-0.10x	-0.338*	y=9.0-0.09x
	Lat. flexion	-0.345*	y=6.2-0.13x	-0.431**	y=6.5-0.14x
Right rotation	Lat. flexion	-0.395**	y=5.0-0.12x	-0.376**	y=5.9-0.13x

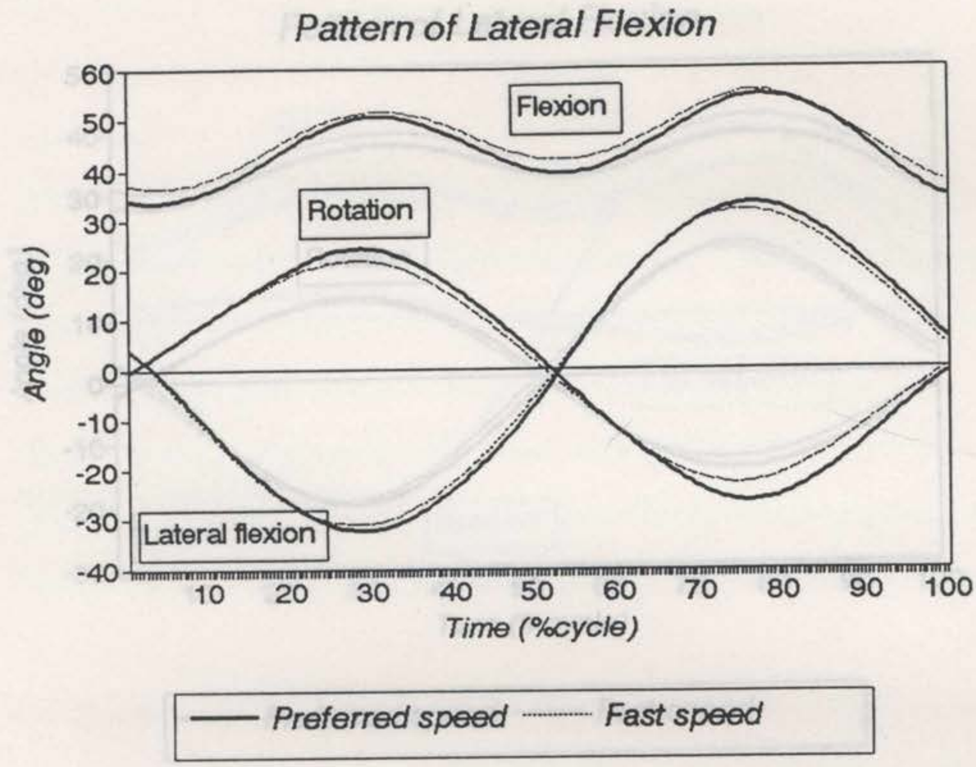
Note: * = $p < 0.05$, ** = $p < 0.01$, y = range of associated movement (deg), x = age-20 (years)
$ = Significant lack of fit at $p < 0.05$, # = MSE/MSR ratio > 20%

4.6 Gender Effects on the Associated Movements

For each primary movement there were no differences in the overall pattern of the associated movements between male and female groups, with the exception of lumbar spine lateral flexion associated with right rotation in elderly females. Rotation was generally accompanied by 6-8 degrees of contralateral side flexion, however most elderly female subjects (9 out of 16) demonstrated approximately 6 degrees of ipsilateral lateral flexion during rotation. MANOVA demonstrated that no significant differences between male and female subjects were found in the ranges of any of the associated movement in all age groups.

4.7 Speed Effects on the Nature of Movements

Changing the speed of motion from preferred to a faster speed had no significant effects on the ranges or the overall pattern of the associated movements in any case. There were high correlations (r = 0.667-1.000) between the patterns of motion of primary lateral flexion and rotation and their accompanying movements at both speeds [Tables 4.19, 4.21 and 4.23], except for the pattern of associated lateral flexion with primary rotation in the lumbar spine in the elderly female group. The correlation coefficients demonstrated remarkably consistent pattern of motion. The patterns of motion of lateral flexion and rotation of the middle-aged male group are illustrated [Figures 4.21, 4.22 and 4.23]. Generally, only one or two subjects in each age group exhibited different patterns of the associated movement with the faster speed from the rest. There were some variations regarding the patterns of associated lateral flexion during rotation in young females and elderly males in the lumbar spine, however the majority of subjects demonstrated the same patterns of movement at both speeds.



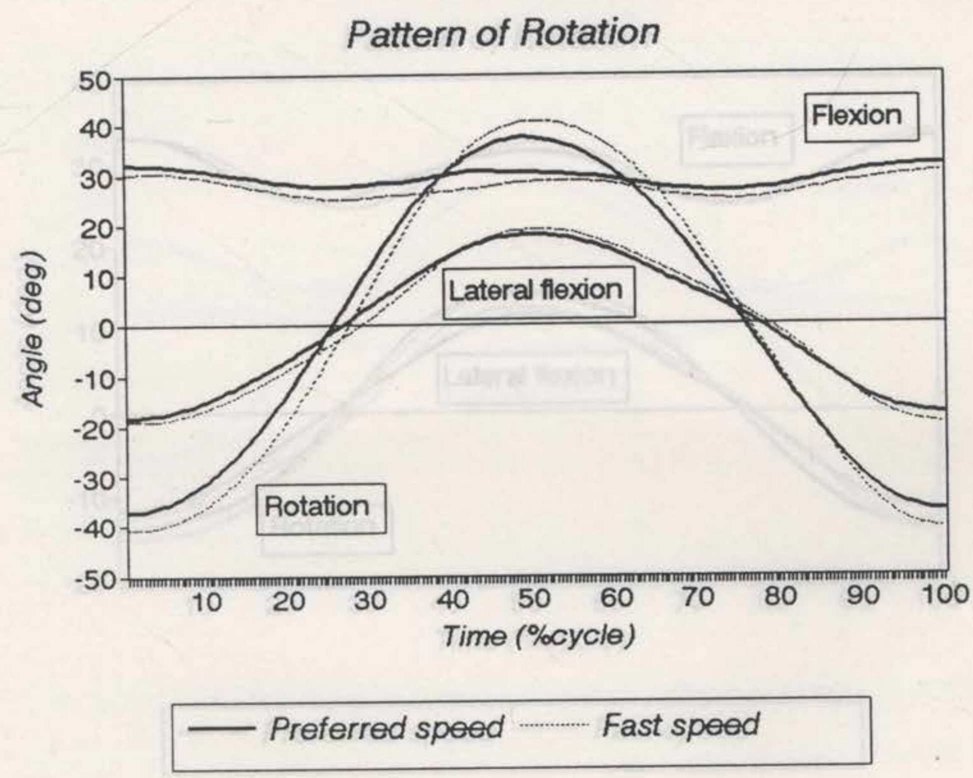
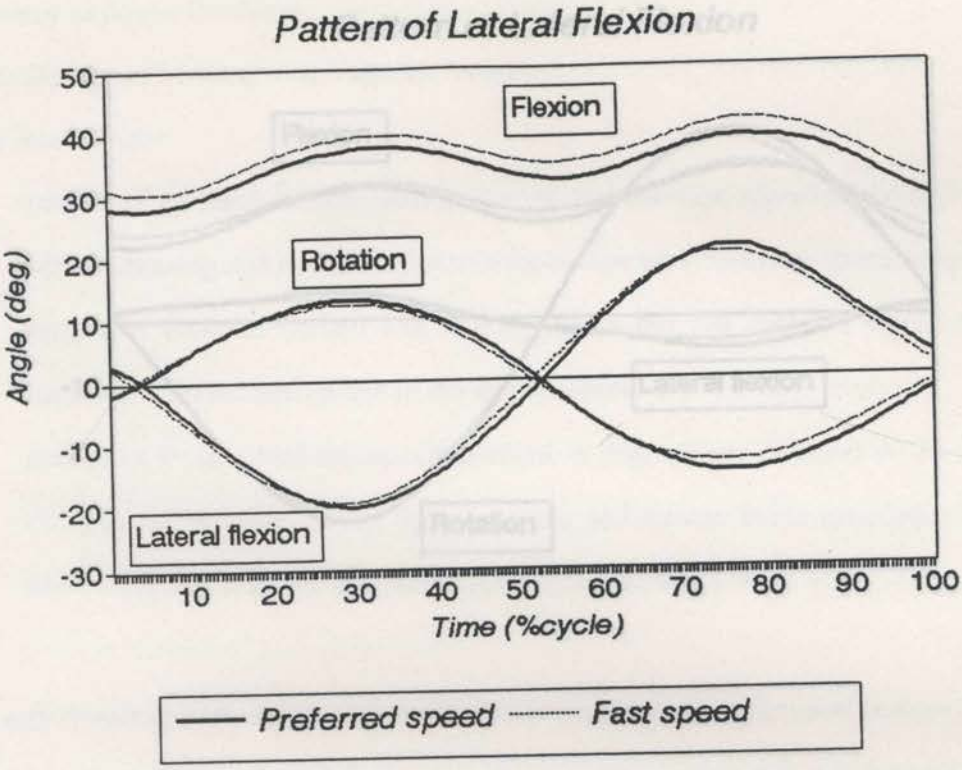


Figure 4.21 Patterns of motion of lateral flexion and rotation in the thoracolumbar spine in the middle-aged male group (n=15) at the preferred and fast speeds of motion.



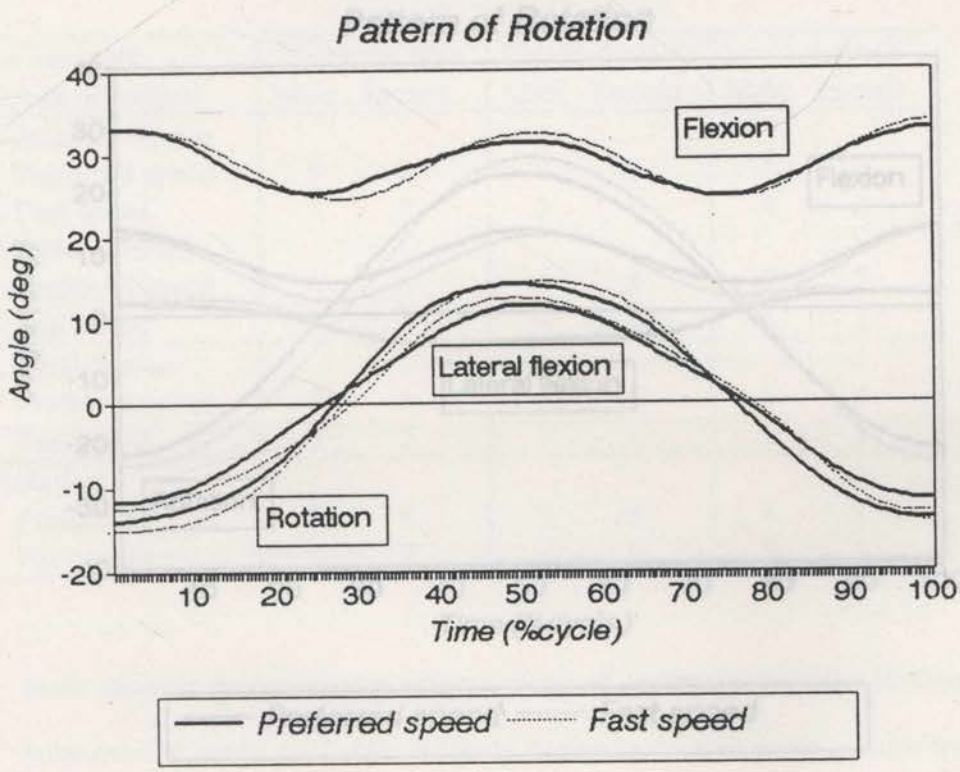
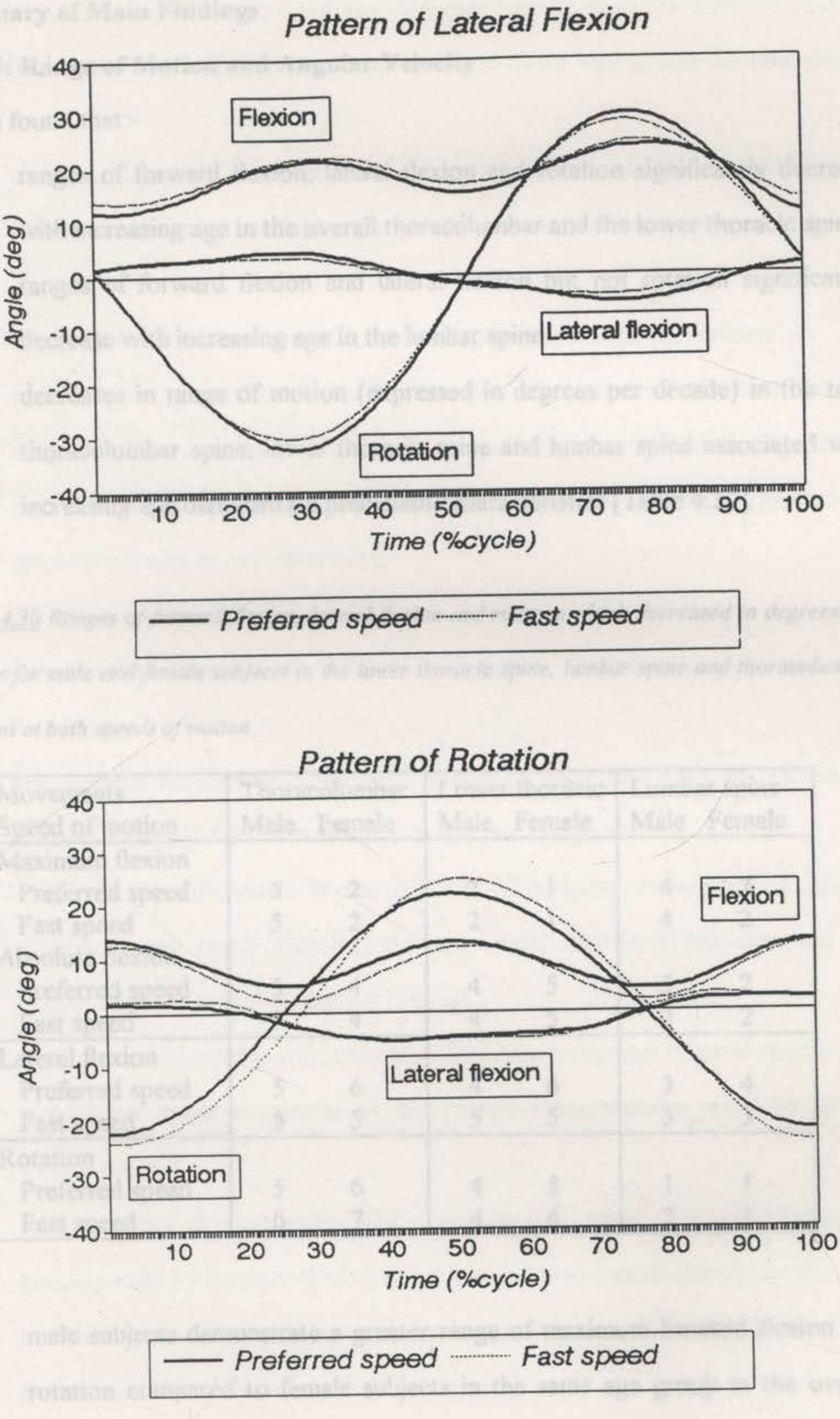


Figure 4.22 Patterns of motion of lateral flexion and rotation in the lower thoracic spine in the middle-aged male group (n=15) at the preferred and fast speeds of motion.



<u>Figure 4.23</u> Patterns of motion of lateral flexion and rotation in the lumbar spine in the middle-aged male group (n=15) at the preferred and fast speeds of motion.

Summary of Main Findings

Part I: Range of Motion and Angular Velocity

It was found that:-

- ranges of forward flexion, lateral flexion and rotation significantly decrease with increasing age in the overall thoracolumbar and the lower thoracic spine.
- ranges of forward flexion and lateral flexion but not rotation significantly decrease with increasing age in the lumbar spine.
- decreases in range of motion (expressed in degrees per decade) in the total thoracolumbar spine, lower thoracic spine and lumbar spine associated with increasing age demonstrate predictable characteristics [Table 4.30].

Table 4.30 Ranges of forward flexion, lateral flexion and rotation which decreased in degrees per decade for male and female subjects in the lower thoracic spine, lumbar spine and thoracolumbar segment at both speeds of motion.

Movements	Thoracolumbar		Lower thoracic		Lumbar spine	
Speed of motion	Male	Female	Male	Female	Male	Female
Maximum flexion						
Preferred speed	5	2	2	1	4	2
Fast speed	5	2	2	1	4	2
Absolute flexion						
Preferred speed	5	4	4	5	3	2
Fast speed	5	4	4	5	3	2
Lateral flexion						
Preferred speed	5	6	4	6	3	4
Fast speed	5	5	5	5	3	3
Rotation						
Preferred speed	5	6	4	5	1	1
Fast speed	6	7	4	6	2	1

- male subjects demonstrate a greater range of maximum forward flexion and rotation compared to female subjects in the same age group in the overall thoracolumbar and the lumbar spine while male subjects show a reduction in range of lateral flexion in the lower thoracic spine.

- no significant differences are found in the range of absolute forward flexion between male and female subjects in the same age group in any trunk segment.
- there is a general trend towards a decreasing range of lateral flexion and increasing range of rotation with the faster speed of movement in all trunk segments.
- angular velocities decrease with advancing age in all three movements.
- male subjects generally show a higher value of angular velocity than female subjects of the same age in the overall thoracolumbar and the lumbar spine.
- there are no significant gender-age combination effects in range of motion or angular velocity in any movement.

Part II: Patterns of Movement

It was found that:-

- the primary movement of forward flexion is associated with no consistent pattern of lateral flexion or rotation in any trunk segment.
- there are no differences in the patterns of coupling movement of lateral flexion in any trunk segment; primary lateral flexion is accompanied by forward flexion and contralateral rotation.
- there are differences in the patterns of coupling movement of axial rotation in the lumbar spine compared to the overall thoracolumbar and the lower thoracic spine.
- in the overall thoracolumbar and lower thoracic spine, primary rotation is accompanied by forward flexion and lateral flexion towards the same side.
- in the lumbar spine primary rotation is generally accompanied by forward flexion and lateral flexion to the opposite side.
- there are no clear age-related changes in the range of associated forward flexion and lateral flexion with primary rotation in any trunk segment.

- age-related declines in the range of associated forward flexion and rotation with primary lateral fle xion can be detected in the overall thoracolumbar and the lower thoracic spine.
- no significant gender or speed effects are detectable with respect to the range or the nature of the associated movements.

CHAPTER 5

DISCUSSION

CONTENTS

DISCUSSION

5.1 Spinal Segments

This study was concerned with the kinematics of the mobile part of the thoracolumbar spine. The kinematic characteristics of T6-T12 and T12-L5 were measured for the lower thoracic and the lumbar spine respectively. The reasons for excluding L5-S1 interspace are discussed in the following paragraphs.

The morphology of the L5-S1 vertebrae differs from the rest of the lumbar spine (Posner et al., 1982; Van Schaik et al., 1985; Taylor and McCormick, 1987; Noren et al., 1991) and the ranges of motion at L5-S1 are small compared to the other lumbar motion segments (Pearcy et al., 1984; Yamamoto et al., 1989; White and Panjabi, 1990). White and Panjabi (1990) and Yamamoto et al. (1989) found that the range of motion in the sagittal plane showed an increase in range from L1 to L5, with L5-S1 having the greatest range of motion, whereas Pearcy et al. (1984) reported that the greatest range in this plane occurred at L4-L5. However, White and Panjabi (1990) and Pearcy et al. (1984) also noted that a greater range of extension took place at L5-S1. It is said that the total range of sagittal plane movement in cadavers is between 2 and 10 degrees greater than in living subjects (Taylor and Twomey, 1980; Bogduk and Twomey, 1991). The reported range of lateral flexion at L5-S1 by White and Panjabi (1990), Pearcy and Tibrewal (1984) and Yamamoto et al. (1989) were 3, 1.5 and 5.5 degrees respectively and 1, 1 and 1.4 degrees for axial rotation. In addition, the patterns of the movement associated with the primary lateral flexion and axial rotation of L5-S1 differ from the patterns of L1-L5 vertebrae.

The anatomy, kinematics and kinetics of L5-S1 are significantly different from the rest of the lumbar spine (Posner et al., 1982; White and Panjabi, 1990). In the present study, ranges of the lumbar spine were measured in a sitting position. The pelvis was tilted posteriorly and the posterior ligaments of the lumbar region were subsequently stretched. This can be expected to reduce the range of motion at the L5-S1 interspace. Therefore, it is not unreasonable to believe that measurement of lumbar spinal motion from T12 to L5 in the sitting position will give a clearer understanding of the functional kinematics of the lumbar spine and how they change with advancing age.

5.2 Subject Groups

This study used a wide range of ages across the spectrum from 20 to 80 years. Subjects were divided into 3 groups; young, middle-aged and elderly groups. The young groups start at age 20 years and the elderly groups refer to ages 60 years and over (Perlmutter and Hall, 1985; Victor, 1987; Timiras, 1988; Twomey and Taylor, 1985, 1991). Theoretically, defining age range of the middle-aged is difficult (Farrell and Rosenberg, 1981; Giele, 1982). The age-related changes in physiology and function of body systems begin to decline around ages 30 to 40. (Payton and Poland, 1983; Timiras, 1988; Minichiello et al., 1992). With respect to the age-related changes in the structures and functions of the lumbar spine, the age range of the young group was between 20 and 35 years, middle-aged group between 36 and 59 years and elderly group 60 years and over (Twomey and Taylor, 1985, 1991).

A few studies have examined the changes in lumbar spine mobility in men and women by dividing subjects into age groups (Fitzgerald et al., 1983; Batti'e et al., 1987; Einkauf et al., 1987; Hindle et al., 1990). Fitzgerald et al. (1983) found that none of the spinal motion characteristics of flexion, extension and left and right lateral flexion of the adjacent decade age groups were significantly different from each other, except for the 30- to 39-year-old versus the 40- to 49-year-old and the 50- to 59-year-old versus the 60- to 69-year-old age groups. The pattern of age-related changes in spinal mobility shows a systematic decrease in the measurements over 20-year intervals. Einkauf et al. (1987) found that the greatest differences in flexion, extension and left and right lateral flexion occurred only between the two youngest (20-29 and

30-39 years) and the elderly groups (60 years and over), with the middle groups (30-39, 40-49 and 50-59) showing no significant differences. These findings supported the method of division of the subjects in this study into young, middle-aged and elderly groups.

Each age group contained at least 15 subjects of each gender (Table 3.1 gives the number of subjects in each group). All variables analysed demonstrated clear evidence of either significant or non significant differences. It is believed that the number of subjects in each group is appropriate to justify the findings reported in this study. To test the hypothesis that sample size was appropriate, a power analysis was carried out on results which showed proximity to the preset alpha level for significance of 0.05. For example, a power analysis (power = 0.8) of the non significant ($p = 0.145$) result of range of lumbar spine rotation showed that even with a large sample size in each age group ($n > 95$ for male subjects and $n > 150$ for female subjects) a significant result ($p < 0.05$) for this variable would not have been obtained (Cohen, 1988).

5.3 Patterns of Movement

The results of this study have shown that the spinal column exhibits coupled motions in a consistent manner for each trunk segment in all groups. Changing the speed of motion from preferred to a faster speed had no effect on the nature of the patterns of motion in any trunk segment. It seems that coupling is an inherent property of the spine, as advocated by Lovett (1905 cited by Panjabi et al., 1989). It can also be said that coupling is an essential component of spinal motion. The patterns of coupling are attributable to the geometry of the individual vertebrae, the connecting ligaments and intervertebral disc, the orientation of the articular facet joints, as well as the local spinal posture (White and Panjabi, 1990; Bogduk and Twomey, 1991).

The details of the mechanisms for each movement have not been determined. From first principles, they probably involve a combination of the way apophyseal joints move and are impacted during axial rotation or lateral flexion, the way in which discs are subjected to torsional strain and lateral shear, and the segmental weight force and line of action of the muscles that produce either axial rotation or lateral flexion (Bogduk and Twomey, 1991). It is probable that there is an interplay between the spinal movements and the muscle activity. However, there is not enough evidence to explain the mechanisms of the coupled motion and it is beyond the scope of this study to resolve these questions.

Mathematical models and computer simulations may be helpful in understanding the motion coupling in the spinal column. Mathematical models must account for the differences in spinal curvature and the complex geometry of the intervertebral joints (Panjabi et al., 1989). The results of this study showed that spinal curvature does affect the range of forward flexion. A kyphotic or lordotic curvature of the spine will affect the apparent range and the pattern of the associated forward flexion during primary lateral flexion or axial rotation.

Panjabi et al. (1989) found that the magnitude and direction of the coupled motions were related to the posture of the intervertebral joints. In an experiment, they investigated the patterns of motion for lateral flexion and rotation in five postures; full flexion, full extension, half flexion, half extension and a neutral position. At all levels, the coupled motion to lateral flexion and rotation was forward flexion, except in the fully flexed posture, when the coupled movement was extension. They also reported that the coupled motion reached its highest value in the neutral posture and decreased when the spine was in a flexed or extended posture.

The tests reported in this study were conducted in a seated position. Therefore, the pelvis was fixed and the lumbar spine movements were not influenced by hip or pelvis motion. The pattern of primary forward flexion in the present study supports the results of previous studies which have assessed the movements of the lumbar spine in the sagittal plane using three-dimensional X-ray analysis (Pearcy et al., 1984; Pearcy, 1985) and three-dimensional surface measurement (Pearcy et al., 1987; Pearcy and Hindle, 1989; Hindle et al., 1990).

A strongly associated forward flexion occurring with lateral flexion and rotation was shown in this study. This supports Farfan's (1973) observations and the study of Panjabi et al. (1989). However, this finding is in contrast to Pearcy and associates study (1987), where lateral flexion was generally accompanied by extension. Hindle et al. (1990) reported no significant associated forward flexion or extension with axial rotation. One possible reason for the difference may be that the subjects studied by Pearcy and Hindle et al. were standing in a slightly flexed posture, which would introduce extension coupling when the spine is subjected to axial torque as shown in the study of Panjabi et al. (1989).

Most studies of the patterns of spinal motion have been carried out in the lumbar spine. In the present study, patterns of the associated lateral flexion occurring with the primary rotation and vice versa did not differ from previously reported studies in which the subjects were standing (Pearcy et al., 1987; Pearcy and Hindle, 1989; Hindle et al., 1990). In addition, the patterns of motion in this study agree broadly with the coupling Pearcy (1985) and Panjabi et al. (1989) noted at the intervertebral levels using radiographic techniques. Such confirmatory findings support the use of the video based system as a means of measuring dynamic three-dimensional trunk movements and indicate that the kinematic results are closely related to the movements of the underlying spine as detected by X-ray analysis.

There is little information available regarding the normal kinematic patterns of movement in the thoracic spine. Most data related to the kinematics of the thoracic spine have been collected through *in vitro* studies (White, 1969; White and Hirch, 1971; Panjabi et al., 1976). It is believed that the present study is the first of its kind to quantify the coupling patterns of the thoracic spine (from T6-T12) during anatomical movements in living subjects using non-invasive measurement techniques. The results show consistent patterns of motion in all conditions and support the *in vitro* findings.

Panjabi (1978) reported a coupling of primary lateral flexion with contralateral axial rotation. Primary rotation was associated with lateral flexion. He did not report the direction of the associated lateral flexion during the primary movement of rotation. In living subjects, clear patterns of coupled motions in the lower thoracic spine can be noted as shown in this study. The primary lateral flexion was accompanied by forward flexion and contralateral rotation and the primary rotation was accompanied by forward flexion and lateral flexion towards the same side.

Although there were strong correlations between the patterns of primary and associated movements in all conditions (see Tables 4.28, 4.30 and 4.32), the relationship between these patterns was non linear. This is probably due to the complexity of the patterns of movement. The spine is a complex structure moving in three dimensional space with multiaxial displacements. Motion segments have up to six possible degrees of freedom, these being the movements of rotation around and translation along the three orthogonal axes. In fact, the movement of rotation about one axis is not only accompanied by rotation about the other two axes but could be accompanied by translation along any of the 3 axes. For example, rotation around the vertical axis is accompanied by horizontal translation. Lateral flexion of the lumbar spine involves a complex, and variable, combination of lateral bending and rotatory movements of the inter-body joints and diverse movements of the facet joints (Bogduk and Twomey, 1991). Flexion and extension involve the coupling of anterior and posterior translations (White and Panjabi, 1978; Pearcy et al., 1984; Bogduk and

Twomey, 1991). Therefore, the ratio of coupling, which defines the proportionality between the amplitude of one motion and the amplitude of its associated motion, may not be easily determined. The relationship of the primary and the accompanying movements may also vary with various factors including the elasticity of the ligaments and soft tissues and the orientation of the facet joint.

In the present study, angle-angle plots of the associated rotation against primary lateral flexion in the lumbar spine are presented [see Figures 4.18-4.20]. The elderly group demonstrated a differently shaped curve compared to the young and the middle-aged groups. The young groups also demonstrated symmetrical patterns between the movements of left and right directions when compared to the patterns of the middle-aged and elderly groups. This may support the fact that the relationship between the range of the primary and associated movements may change with increasing age.

Hindle et al. (1990) suggested that, overall, the coupled movements of the lumbar spine tend to be affected in the same manner as the primary movements, being reduced with age, however, the ranges of the associated movements were not reported. The results of the present study do not agree with those of Hindle's study. No clear age-related changes were found in the associated movements of the lumbar spine. Significant age-related changes in the associated movements were seen in the associated forward flexion and rotation during primary lateral flexion in the lower thoracic spinal segment. The reduction in range of the associated movements with age may be brought about by structural changes in the vertebral bodies or the facet joints and could be related to the mechanism of the coupling motion which has not been determined. There is not enough evidence from results gathered through this and other studies to explain the age-related changes in the range of associated movements in the lower thoracic segment.

5.4 Age Effects on Range of Motion

There is a general acceptance of the idea that mobility of the spine will decrease with ageing. It is not clear whether this reduction in range is an independent variable, having to do with spontaneous changes in the mechanical properties of the tissues, or whether it is related to lifestyle changes occurring as a result of functional inactivity (White and Panjabi, 1990).

Previous studies have agreed that lumbar spine mobility decreases with increasing age, particularly in the sagittal and coronal planes of movement (Macrae and Wright, 1969; Moll et al., 1972; Fitzgerald et al., 1983; Batti'e et al., 1987; Einkauf et al., 1987). Most of the studies into spinal mobility have limited measurements to the movements in these planes. There is little information concerning motion in the horizontal plane, largely because of methodological problems. It has previously been proved difficult to measure lumbar rotation in the living, either directly or radiographically, with any degree of accuracy (Taylor and Twomey, 1980; Andersson, 1981; Einkauf et al., 1987; Mellin, 1987).

Progressive decreases in range of motion associated with advancing age have been demonstrated in cadaveric studies (Tanz, 1953; Hilton et al., 1979; Taylor and Twomey, 1980). However, Evans and Lissner (1959) studied a group of 11 specimens of the lumbar spine and pelvis and found no apparent relationship between the age of the individuals and the biomechanical properties that would affect kinematics.

Although the present study found differences in the mean values for range of motion in the young and the middle-aged groups, the calculated values of minimum and maximum ranges, from 95% confidence intervals for all movements, indicated wide variation in each group and overlapped between age groups as shown in the Tables of MANOVA (Appendix F). Therefore, most of the results in this study demonstrated no statistically significant differences in the young and the middle-aged groups.

A search of the literature reveals considerable variation in the values reported for the ranges of lumbar spine motion. These variations are largely attributable to the different age, race and numbers of subjects studied and from the different measurement methods used (Taylor and Twomey, 1980). In previous studies, Taylor and Twomey (1980) and Dillard (1991) have measured lumbar mobility using surface measurements which were found to be accurate and easy to apply to the subject's back. Pearcy et al. (1989, 1990) measured lumbar spinal mobility by using a three-dimensional technique. Although the various methods were applied in different studies, it is interesting to compare the results. The results are summarized in Table 5.1.

Table 5.1 Mean values of lumbar spine motion (degrees) measured by different methods.

Studies	Sex	No.	Flex.	Lat.	Rot.	Measurement techniques
Taylor&Twomey(1980)*$ (subjects 18-87 yrs)	M F	246 191	38.2 36.6	- -	28.1 27.2	Spondylometer and rotameter
Pearcy&Hindle(1989)# (subjects 22-49 yrs)	M	10	75.6	55.8	30.7	3space Isotrak
Pearcy et al.(1990)# (subjects 20-50+ yrs)	M F	40 40	73.8 66.7	48.4 54.1	27.1 30.8	3space Isotrak
Dillard et al.(1991)# (subjects 20-40 yrs)	M&F	20	63.0	77.0	54.0	Goniometers
Present study(1993)* (subjects 20-87 yrs)	M F	46 54	42.3 36.4	60.5 59.6	43.7 38.2	Motion Analysis "ExpertVision"

Note: * Measured in sitting position, # Measured in standing position
$ Calculated from data presented
Lat = range of left and right lateral flexion
Rot = range of left and right rotation

There was some variation in the ranges of lumbar spine motion reported in the different studies. Generally, the results of this study represent the average values of lumbar motion compared to the other studies. The results of Pearcy and Hindle (1989), Pearcy et al. (1990) and Dillard et al. (1991) demonstrated a greater amount of forward flexion than the study of Taylor and Twomey (1980) and the present study. The reason for this may be the difference in starting position. The results of the studies which measured lumbar spine mobility in the standing position had a greater range of forward flexion. In the sitting position, movement was limited by contact of the abdomen and the thighs, which would not be so in standing. Also, in the standing position, forward flexion included movement of L5-S1 interspace.

Ranges of rotation in the studies of Dillard et al. (1991) and the present study, which measured the range of the lumbar spine including T12-L1, were greater than the other studies which measured from L1. This finding is not surprising due to the fact that a few degrees of rotation occurs at T12-L1 interspace. In the horizontal plane there are 8 to 9 degrees of unilateral axial rotation in the upper half of the thoracic spine and 2 degrees for each interspace of the three lower segments (White and Panjabi, 1990). Gregerson and Lucas (1967) studied axial rotation in the thoracic spines of seven live subjects by inserting Steinmann pins into the spinous processes. They noted an average of 6 degrees of rotation at each level.

In the present study, female subjects showed a small decrease in range of lumbar spine forward flexion per decade. So, over a 60 year period they might have lost between 5 and 10 degrees of forward flexion. In functional terms the subjects could probably lose 10 degrees of forward flexion, possibly due to extraneous factors such as hamstring tightness, and not be particularly aware of it. Decreased forward flexion can be compensated for by hip, knee and shoulder movements. Functional activity in the sagittal plane is not exclusive to the thoracolumbar spine but is achieved through many combinations of movement involving complex segmental chains. The subjects may not really be concious of any substantial functional impairment resulting from a loss of 10-20 degrees of spinal flexion over the lifespan.

The lower thoracic spine loses about 5 degrees of lateral flexion per decade. So, between the ages of 20 and 60 years, 20 degrees are lost. Side flexion is not a movement that is easily compensated for by other movements. Coronal plane motion is present in the hip joint but not in the knee joint, so if subjects reach to the side with limited spinal movement, their only compensation for decreased spinal motion might be to displace their whole body mass laterally. The results of this study showed that lateral flexion had the greatest decrease in range of motion with increasing age in both the lower thoracic and lumbar spine. One possible explanation for this is that lateral flexion is not regularly performed in daily activities and this may lead to adaptive shortening of muscles and soft tissues in the direction of side bending.

Interestingly, in the elderly groups, the measured range of lateral flexion in the total thoracolumbar spine was equal to or less than that in the lumbar spine alone. During bending to one side, the upper thoracic segment of the elderly subject tends to move towards the opposite side (see Figure E.1; Appendix E). To demonstrate the way the subjects move their trunk in side bending, Figure 5.1 shows the tracing of the spine in lateral flexion. The young and middle-aged groups bend their trunk to the side in a C curve while the elderly subjects have a S curve. The pattern of lateral flexion in the elderly subject is more like swaying to one side instead of fully side bending. This may be due to the fear of falling. This pattern of lateral flexion occurs in both male and female elderly subjects.

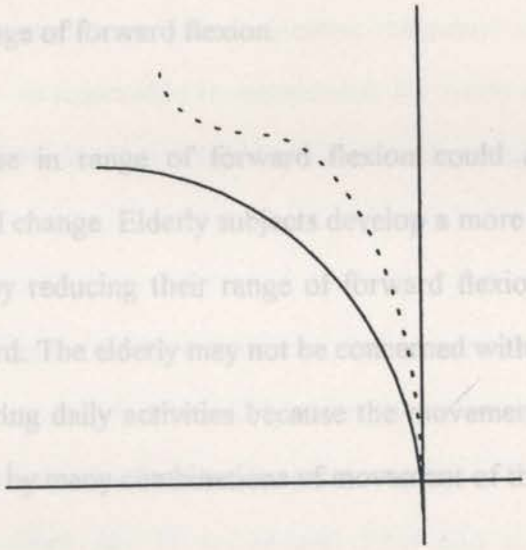


Figure 5.1 Tracing of young and elderly spines during lateral flexion. [___ represents young spine, ----- represents elderly spine].

The maintenance of range of rotation in the lumbar spine is interesting and somewhat unexpected, although this finding has previously been reported in the studies of Wolf et al. (1979) and Hindle et al. (1990). This result may reflect the fact that the structural changes in the lumbar spine associated with ageing predominantly affect the movements in which the vertebral bodies "tilt" on one another rather than moving in parallel planes. The decrease in range of forward flexion, but not rotation, may be explained by the functions of, and the age-related changes in, the apophyseal joints of the lumbar spine. The lumbar apophyseal joints not only restrict rotation but also prevent excessive forward flexion. The anteromedial third of the facet joint, which is orientated in the coronal plane, limits the forward translational component of forward flexion. The posterior two-thirds, lying in the sagittal plane, restricts rotation (Twomey and Taylor, 1983). The differences in the function of the two parts of the lumbar apophyseal joints are reflected by differences in the age-related changes in these two parts. Taylor and Twomey (1986) reported that sclerotic changes and thickening of the articular cartilage occur particularly in the coronal component of the superior articular process more than in the sagittal component. This sclerosis may lead to a limitation in range of forward flexion.

The decrease in range of forward flexion could also be associated with progressive postural change. Elderly subjects develop a more kyphotic posture (Robin et al., 1982) thereby reducing their range of forward flexion although they are still able to reach forward. The elderly may not be concerned with their decreased range of forward flexion during daily activities because the movement of forward flexion can be compensated for by many combinations of movement of the hip and knee joints.

Taylor and Twomey (1980) found that a decline in range of rotation in the lumbar spine with increasing age is clearly evident in living subjects. The conflicting results may be attributed to differences between the two population samples. The subjects in the Taylor and Twomey study were recruited as a part of a large population survey which included a great many subjects with a diverse functional ability range. The subjects in this study were healthy, physically active and lived independently, often being members of sport clubs such as bowling or golf clubs. Most of the elderly subjects exercised regularly. This may be the reason that most elderly subjects in this study maintained their range of rotation. It is not unreasonable to suggest that loss of spinal range of motion is not an inevitable consequence of age but the maintenance of the range could be in response to the requirements of daily activities. Therefore, the movement of rotation may well be preserved through daily activities more so than forward or lateral flexion.

It is interesting to note that there is an increase in range of forward flexion up to the age of 40 followed by a progressive decrease until the age of about 60 in the elderly male subjects. The range of forward flexion appeared to increase again between 65 and 75 years old. However, this study is not a longitudinal study and the subjects in each group are not the same. The subjects in the elderly male group may be more physically active compared to the middle-aged group. In other words, the elderly subjects may have more time to exercise compared to subjects in the middle-aged group. It may be reasonable to expect that the more active the subject is, the greater the range of motion that would be maintained, particularly in the sagittal and horizontal planes.

Moll and Wright (1971) carried out measurements of thoracolumbar spine motion in 119 male and 118 female subjects aged between 15 and 75 years. Their results showed a comparative increase in spinal mobility in forward flexion, extension and lateral flexion from age 15 to 24 and from age 25 to 34, followed by a progressive decrease with advancing age.

A greater representation of inactive elderly subjects in the present study might demonstrate a progressive decrease in range of motion with increasing age or more significant differences between the age groups. The results of the young and middle-aged groups may be more representative of the population for these age because a wider range of athletic and non-athletic subjects were used.

As mentioned before the elderly subjects in this study have maintained a relatively active life-style, however, ranges of motion in the lower thoracic spine do decrease with increasing age. The relatively greater thoracic reduction may be explained by the influence of age-related change in the costovertebral joints. Increasing age is often accompanied by ossification of costal cartilages and ankylosis of the costovertebral joints. This ankylosis reduces the chondrocostal elasticity. With increased age, the thorax becomes almost rigid and segmental movement is correspondingly reduced (Kapandji, 1978). Taken in conjunction with soft tissue stiffness in the elderly people the decrease in the range of motion may be explained by these factors.

Goldspink et al. (1987) reported that if a muscle is maintained in a shortened position for a prolonged period of time, there will be an increase in collagen and an increase in covalent cross-linking. Williams and Goldspink (1984) demonstrated that, during immobilisation in the shortened position, there is an increase in the proportion of collagen to muscle fibre. It should be noted that this is only a proportional increase; there is in fact a total loss of collagen but an even greater loss of muscle fibre. The distances between the cross-links in the collagen meshwork have a tendency to shorten to the length to which the connective tissue is habitually extended. If a part of the body is immobilised or used through a restricted range, the connective tissue gradually contracts and reorganises, becoming more dense. Joint and muscle range of motion are therefore reduced by immobilisation and disuse. The decline in movement occurs as a result of increasing stiffness of the soft tissue elements associated with changes in the shape and structure of bone (Hall, 1976; Twomey and Taylor, 1984).

On the other hand, if muscles and connective tissues are regularly stretched through a full range of joint motion, the mobility of soft tissues and joints will be maintained (Goldspink et al., 1987). It is therefore reasonable to believe that the more active the life style, particularly in retired people, the more flexibility will be retained. More research about spinal range of motion in subjects with active and inactive life style is needed to determine the effects of level of physical activity on spinal mobility.

5.5 Gender Effects on Range of Motion

Many authors have reported gender differences with respect to range of lumbar mobility, with greater values for men than for women, particularly in the sagittal plane (Troup et al., 1968; Moll and Wright, 1971; Biering-Sorensen, 1984). Burton and Tillotson (1988) reported that males have higher values for flexion, whilst females show higher values for extension. Wolf et al. (1979) and Hindle et al. (1990) reported that women tended to show greater range of motion for trunk rotation and lateral flexion while forward flexion was greater in men.

All previous studies have measured the maximum angular displacement of forward flexion, that is, how far the subjects can move in the sagittal plane. The effects of the spinal curvature attributable to acquired posture on the range of forward flexion has been largely ignored. In terms of maximum range of forward flexion, this study has found that male subjects have a greater range than female subjects in the same age group for all trunk segments. This suggests that male subjects can move their trunk forward further than female subjects in the same age group. In fact, if the subjects' starting posture is taken into account, the amplitude of the movement changes substantially. The "maximum range" of forward flexion is, therefore, misleading due to the curvature of the spine. Range of forward flexion from the starting to the final position is more accurately represented by the *absolute range* of forward flexion. The different findings between the maximum and absolute ranges are now discussed.

All subjects demonstrated a decrease in the absolute range compared to the maximum range of forward flexion in the lower thoracic spine. This would be attributable to the thoracic kyphosis at the starting position. Interestingly, the young and middle-aged male groups showed a greater difference between absolute range and maximum range than female subjects in the same age group [see Figure 4.8]. This may suggest that the young and the middle-aged males have a more kyphotic thoracic posture than female subjects in the same age group.

Loebl (1967) found that, below the age of 40, the thoracic spine in women seemed to be 4 or 5 degrees less kyphotic than in men. This difference was not found after the age of 40, when the female thoracic spine becomes as kyphotic as the male. The results of the present study demonstrated similar findings. The young and middle-aged male groups demonstrated approximately 10 degrees greater kyphosis than female subjects [see Table 4.12].

In the lumbar spine, male subjects demonstrated a greater maximum range of forward flexion than female subjects. On the other hand, the female groups showed an *increase* in the absolute range and the male groups demonstrated a *decrease* when compared to the maximum range of forward flexion [see Figure 4.12]. This suggests that female subjects had a more accentuated lumbar lordosis than male subjects in the same age group [see Table 4.14]. Fermand and Fox (1985) measured lordotic angle on roentgenograms of 973 adults and reported that female subjects demonstrated a greater lumbar lordosis than male subjects. Fermand and Fox also reported that this difference was maintained in all age groups. The main reason for this may be due to the differences in structure of the pelvis. It is possible that the male pelvis is oriented in a more posterior direction than the female, and the sacral end-plate in men is therefore in a more horizontal position, leading to a flattening of the lumbar lordosis. Alternatively, it is assumed that the difference in lumbar lordosis is due to the greater curve of women's buttocks (Stagnara et al., 1982).

5.6 Joint Orientation Effects on Range of Motion

While mobility generally decreased with increasing age at all three segments, there were some differences in the patterns of maximum range of motion at each segment. This is probably due to differences in the vertebral body architecture and the shape and position of the articulating processes of the facet joints, as pointed out by Humphry (1858 cited by White, 1971). In the present study, a greater range of forward flexion in the lumbar spine compared to lateral flexion or rotation to each side was demonstrated. This finding supports the results of other studies which have been conducted in living subjects (Pearcy and Hindle, 1989; Pearcy et al., 1990; Dillard et al., 1991) and in cadaveric spines (White and Panjabi, 1978; Pearcy et al., 1984; Yamamoto et al., 1989). However, this finding is not surprising. The orientation of the lumbar facet joints in the sagittal plane will permit a greater freedom of movement in this plane compared to the other two planes.

In this study, the lower thoracic spine also showed a greater range of forward flexion compared to lateral flexion or rotation. The orientation of the facet joints in the thoracic spine is generally considered to allow lateral flexion and rotation to occur more freely than forward flexion (Kapandji, 1978; White and Panjabi, 1990). In the upper thoracic spine, the range of forward flexion is generally less than the ranges of lateral flexion and rotation, particularly at the segments T3-T6 (Grieve, 1988; White and Panjabi, 1990). The range of forward flexion is between 2 and 5 degrees at each segment, lateral flexion 6 degrees and rotation approximately 8-9 degrees. The transition of the facet joint orientation from thoracic to lumbar may occur from the 9th thoracic vertebra. The patterns of motion in the lower thoracic spine would be expected to differ from the upper thoracic spine. Ranges of forward flexion and lateral flexion increase from T10 caudally. The median range of the two lower segments for forward flexion is 11-12 degrees and for lateral flexion 8-9 degrees, whereas range of rotation decreases, reducing to 2 degrees for the lowest three segments. Changes in the orientation of the thoracic facet joints lead to a greater range of forward flexion and relatively small range of lateral flexion and rotation in the lower thoracic spine as shown in results of the present study (see Tables F.4-F.6; Appendix F).

5.7 Speed Effects on Range of Motion

In the present study, the speeds of movement were not standardised. However, the within-subject effect of the average and peak velocity values over the preferred and fast speeds of movement clearly demonstrated significant differences ($p < 0.001$) for all movements in all trunk segments as shown by MANOVA (see Tables F.10-F.33). This means that velocities of trunk motion at the fast speed were greater than at the preferred speed.

During forward flexion, the subjects seemed to move through a maximum range that was limited by compression of the abdominal soft tissues, therefore, no speed effects on range of forward flexion were detected. A general trend for increasing range of axial rotation with the fast speed was found in all groups. A simple explanation for this would be the effect of the body's inertia (Hay and Reid, 1988). When the trunk rotates with a high angular velocity it has a large angular momentum. This momentum would tend to cause the trunk to continue to rotate to a greater range of motion at end of range. By observation, when the subjects were asked to rotate at a faster speed, they could not arrest their trunk motion at the neutral position and tended to overshoot.

By the same principles, lateral flexion would be expected to increase in range at the faster speed. However, as the subjects moved their trunk away from the stable midline position and away from their base of support during lateral flexion, they may have felt a tendency to fall over and to become less stable. In order to minimise the instability, they limited the range of motion and did not reach the end of range. A general trend towards decreasing range of lateral flexion with increasing speed was thus noted.

Although a consistency of speed effects was found in the ranges of lateral flexion and rotation, the statistically significant differences in the range must be greater than the measurement errors of the system before "functional" significance can be reported. The Motion Analysis 'ExpertVision' system used in this study has been shown to have a systematic error about ± 2 degrees for lateral flexion and < 0.2 degrees for rotation (see Experiment II; Appendix D). The small changes in range of lateral flexion at the fast motion, therefore, should not be considered to be a real change and could be attributable to simple systematic error. The greatest differences in range of rotation with the faster speed occurred in the thoracolumbar spine. However, even here the magnitudes of the differences may be too small to be of functional significance.

5.8 Angular Velocity

With increasing age there was a decrease in values of average and peak angular velocities for both genders. Angular velocities were significantly different in the elderly group compared to the young/middle-aged groups for all movements, although the elderly retained their range and velocity at the preferred speed of rotation in the lumbar spine. The relationships between age and angular velocities demonstrated linear declines for all movements. This may suggest that, with advancing age, the reduction in speed of motion is inevitable and may not be related to the level of function activity demonstrated by the subject.

During the movement of rotation some elderly subjects reported slight dizziness, particularly in the fast speed. It is possible, therefore, that they reduced their speed of movement in order to prevent these symptoms. Many people over 60 year olds are reported to have asymptomatic degenerative change in the cervical spine (Anderson and Williams, 1983). Dizziness or vertigo can be brought on by rapid movement of the head which causes compression of the vertebral arteries and compromises the cerebral blood supply.

The peak extension velocity generally demonstrated a greater decrease with increasing age compared to the peak forward flexion velocity. The movements of forward flexion and extension are affected by gravity and controlled by muscular effort. The erector spinae muscle group controls forward flexion by contracting eccentrically during the gravity-assisted phase, while controlling extension by contracting concentrically during the gravity-resisted phase. Elderly people may have difficulty in extending their spine rapidly due to weakness of the back extensor muscles.

5.7 Clinical Implications

Because the ageing process can cause decreased spinal mobility, the physiotherapist must be able to distinguish between age-related decreases in spinal mobility and pathological limitations to spinal mobility (Sturrock et al., 1973; Einkauf et al., 1987). When measuring spinal motion of a patient, the physiotherapist should be aware of normal values for each motion based on the patient's age and gender.

Clinically, distinguishing between age-related and pathological limitations on spinal mobility is difficult because the values of spinal mobility may vary widely within the same group (Moll et al., 1972; Taylor and Twomey, 1980; Fitzgerald et al., 1983; Batti'e et al., 1987). Knowledge of spinal range of motion may aid in determining levels of spinal pathology, guidelines for treatment and patient response to that treatment. Spinal range of motion has long been considered an acceptable means of evaluating the impairment of patients with low back pain. However, considering spinal mobility alone will not provide enough information to determine the nature of a spinal disorder. Reports on the relationship between spinal mobility and history of back pain have been varied. Some studies have reported a general decrease in spinal mobility associated with back problems (Mayer et al., 1984; Pearcy et al., 1985; Marras and Wongsam, 1986) while others have reported that chronic back pain patients may show increased spinal motion. Biering-Sorensen (1984) examined spinal flexibility in a large population, following them up for one year for subsequent back injuries. He reported that men who experienced an episode of back pain had significantly flexibility than those who did not have back pain. Marras and Wongsam (1986) suggested that the changes in trunk velocity associated with back pain or back injury are substantial and may be subjected to less variability compared to changes in range of motion. The angular velocity of the spinal motion should therefore be considered in the assessment of the spine.

During clinical assessment of patients with back pain, the complexity of the patterns of movement may confuse the physical finding. For example, if the patient has pain during the movement of lateral flexion or rotation, the pain might arise from either the primary movement or its associated movements. Although ranges of the associated movements are small compared to the primary movement, their patterns are very consistent. In such cases, the physiotherapist needs to be concerned with which movement or what direction causes the pain. During forward flexion there is no substantial associated lateral flexion or rotation. So if the patient has pain during forward flexion, it suggests that pain emanates from the movement of forward flexion rather than the associated movements.

In common with other studies, the results of this study have demonstrated a significant decrease in spinal range of motion with increasing age. However, the reduction occurred in different motions for different trunk segments. Lateral flexion and rotation were the movements that showed the greatest decrease with age in the lower thoracic spine while forward flexion and lateral flexion showed the greatest decreases in the lumbar spine. Range of motion declined most markedly between the young/middle-aged and the elderly groups in both genders. No significant differences were found between the young and the middle-aged groups in any of the movements in either the male or female groups. These findings are important to clinicians who are in a primary role of instructing patients of all ages in flexibility exercises for the spine. Perhaps specific maintenance exercises during the middle years could prevent a significant decrease in spinal range of motion in later life.

Movements of the spine, even those apparently confined to one plane, occur in three dimensional space as shown by the results of this study. Paravertebral muscles are complex aggregations of various oblique and longitudinally running fibres that connect the transverse processes, spinous processes, intervertebral discs and adjacent vertebral margins. Some muscles also attach to ribs or the bones of the pelvis. Due to the multi-axial motion of the spine and the complexity of back muscles, therefore, it may be more effective to increase or maintain range of motion by stretching in the direction of *patterns* of movement rather than a single plane movement, for example, a combination of forward flexion, lateral flexion to the left and rotation to the right. Thus, the capsule, ligament and soft tissues around the joint can also be stretched.

This study has shown the existence of age-related changes in the kinematics of the spine and also quantified the patterns of motion through the range of movement in normal subjects. The results reported in this study are believed to be relevant and useful to the clinicians. The vertebral levels studied included most of the clinically significant levels in patients with low back pain (Markolf, 1972). In addition, the patterns of motion reported in the present study are consistent with the *in vitro* roentgenographic studies. Further research into the kinematics of specific spinal disorders are needed to determine the abnormalities of the spine.

CHAPTER 6

SPINAL KINEMATICS DURING A MULTIAXIAL MOVEMENT

CONTENTS

SPINAL KINEMATICS DURING A MULTIAXIAL MOVEMENT

6.1 Introduction

Many activities in daily living are associated with the sitting position. Lifting and placing an object while seated is often seen in daily activity and in certain work practices. With increasing age there is a reduction in spinal range of motion that may lead to back pain problems and difficulty in performing functional tasks such as lifting objects from the floor (McKenzie, 1981; Bergstrom et al., 1985a; 1985b). The results of the investigation of spinal kinematics during anatomical movements have demonstrated that ranges of motion and angular velocity values generally decrease with increasing age. Age and speed of motion has no effect on the patterns of the movement (see sections 4.1-4.3). It is interesting to investigate age-related changes in a functional activity which involves a combination of the anatomical movements previously described. Such an investigation may assist understanding of the demands and limitations on the spine associated with lifting as well as the effects of age, gender and speeds of motion on the kinematics of the spine during the task.

The purpose of this part of the study was therefore to describe the kinematics of the spine during a simulated functional activity (i.e. seated lifting) in the different age groups. The relationships between age, gender, speed of motion and range of motion and angular velocity were studied for the overall thoracolumbar spine and the lumbar spine. The task was chosen to provide a condition in which three rotations about the spinal axis system were likely to occur in order that the activity was performed in a natural fashion, the movement was one of lifting, however, since no constraint to movement arising from load imposition was desired, the weight of the object to be lifted was minimised.

In order to simulate the lifting situation in a seated position and allow combinations of the spinal motions to occur, the object to be lifted was positioned between the sagittal and coronal planes of the body. In such a position, the composite movements associated with the task would be expected to involve forward flexion, lateral flexion and rotation.

6.2 Methods

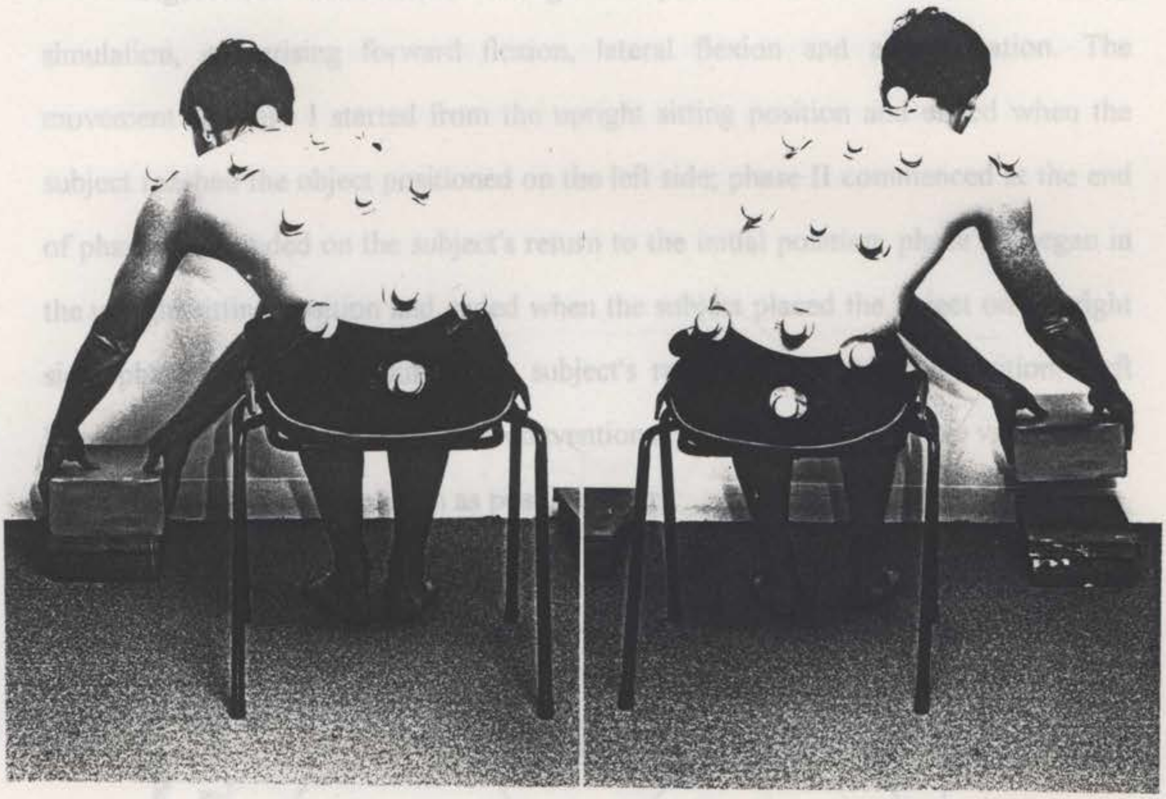
The same procedure as measured the kinematics of the spine in the anatomical movements was used (see section 3.6). It has been reported that total height will relate significantly to movements of the spine i.e., side-bending, sit-and-reach, and lumbar forward flexion (Batti'e et al., 1987). The sit-and-reach measurement, recorded as the distance between the fingertips and the toes in a long sitting position, decreased while ranges of side-bending and forward flexion increased with increasing height. In order to compensate for differences between subjects' height, which could affect the range of motion of the spine during lifting, the position of the object for this task was standardised. The object was placed at 45 degrees to the left of the median sagittal plane of the subject. The distance between the object and the front legs of the stool was set at 17 percent of the height of each subject (see Experiment IV; Appendix D). The height of the object was at the level of the subject's fingertip as measured when the subject was sitting on the stool with both arms hanging relaxed by the sides. The subjects, therefore, could reach the object without difficulty by moving their trunk and reaching with their upper limbs.

The task consisted of 4 phases of movement:-

- Phase I reaching forward and sideway to the left,
- Phase II picking up the object and returning to the mid position,
- Phase III moving towards the opposite side to place the object, and,
- Phase IV recovering to the starting position.

The subject sat upright on the stool with both arms hanging relaxed by the sides. He/she was asked to pick up a 300 gramme box (20 cm. X 30 cm. X 10 cm.) positioned on the left, bring it level with his/her thigh and place it down on the right side [Figure 6.1]. Four repetitions of the activity were carried out at the subject's preferred speed and then at a self-determined faster speed.

In this part of the study, the kinematics of the thoracolumbar and lumbar spinal segments were measured. The relative motion between the upper thoracic segment and the lumbar segment has been referred to in the previous study of anatomical movements as the movement of the lower thoracic spine. During the lifting simulation, the movements of the upper thora3cic spine would be affected by movements of arms and shoulders thus the measurements obtained may not accurately represent the kinematics of the lower thoracic spine. The motion of the lower thoracic spine was therefore not taken into consideration in analysis of the seated lift.



(A) (B)

<u>Figure 6.1</u> *Seated Lift. (A) Phase I. (B) Phase III.*

6.3 Results

The results of this section are presented in terms of range of motion, angular velocity and patterns of the composite movements during lifting and are related to age-related changes in the kinematics of the overall thoracolumbar spine and the lumbar spine. The effects of gender and two different speeds of motion on the kinematic characteristics of the spine are also reported.

6.3.1 Patterns of movement

Figure 6.2 demonstrates the general patterns of motion for the lifting simulation, comprising forward flexion, lateral flexion and axial rotation. The movement in phase I started from the upright sitting position and ended when the subject reached the object positioned on the left side; phase II commenced at the end of phase I and ended on the subject's return to the initial position; phase III began in the upright sitting position and ended when the subject placed the object on the right side; phase IV occurred during the subject's return to the starting position. Left lateral flexion and left rotation were conventionally described as negative values; right lateral flexion and right rotation as positive values.

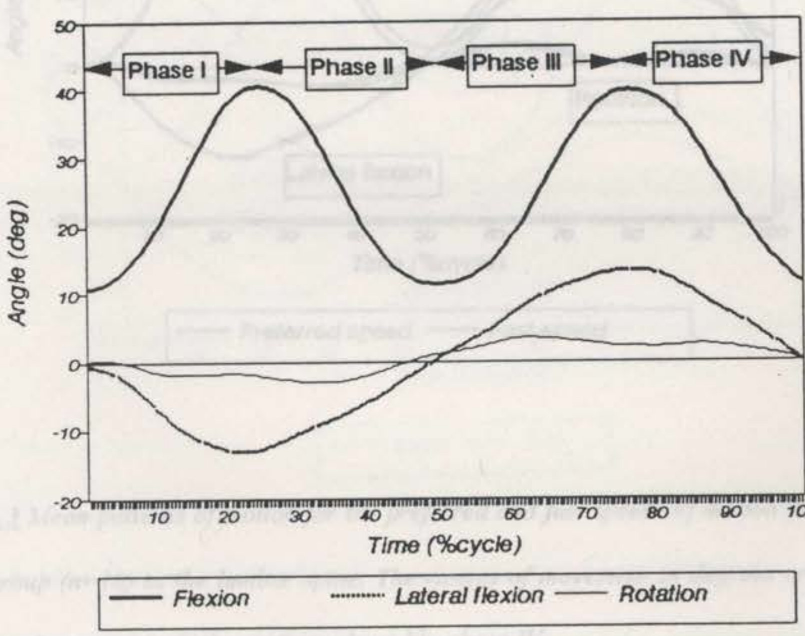


Figure 6.2 Patterns of the composite movements in the lumbar spine in the lifting simulation.

There were consistent patterns of forward flexion and lateral flexion in the lifting simulation at both the preferred and fast speeds [Figure 6.3]. Male and female subjects for each age group displayed comparable movement characteristics. The patterns of motion of forward flexion, lateral flexion and rotation in the lumbar spine are presented [Figures 6.4 to 6.6]. Forward flexion and lateral flexion were found to be the major components of this lifting simulation. The direction of lateral flexion was consistent to the left and then to the right following the direction of the movements. No associated patterns of rotation were found in any segment or gender, however most subjects demonstrated rotation to the left and then to the right in the lumbar spine. In the thoracolumbar spine, rotation seemed to occur in the early period of phase III when the subject was turning from left side to right side [Figure 6.7].

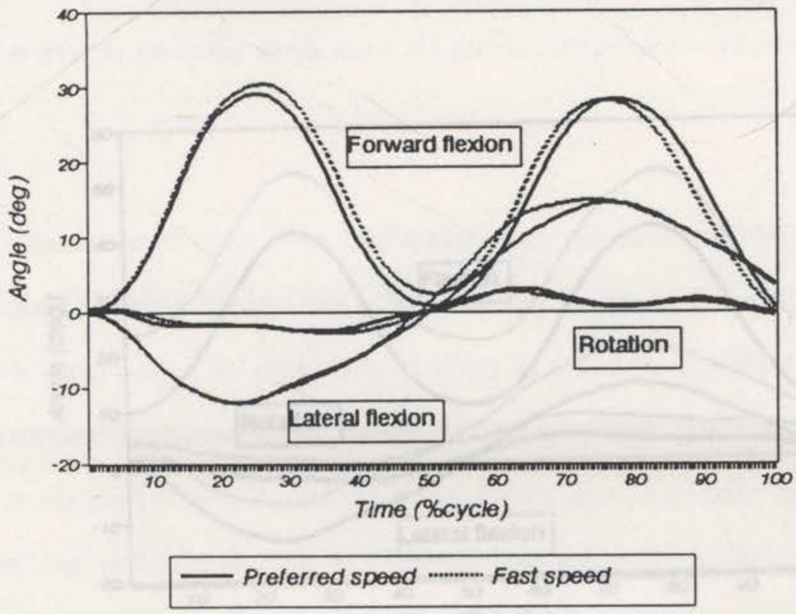


Figure 6.3 Mean patterns of motion for the preferred and fast speeds of motion in the middle-aged female group (n=18) in the lumbar spine. The ranges of movement in degrees are plotted against one cycle of movement which was from phase I to phase IV.

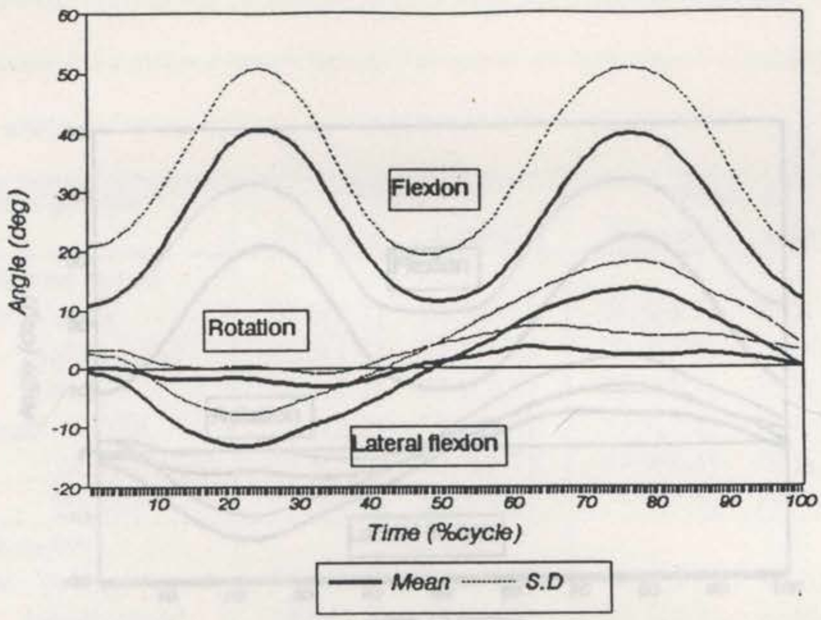


Figure 6.4 *Mean patterns of motion (with + 1sd) of forward flexion, lateral flexion and rotation in the lumbar spine for the lifting simulation in the young male group (n=15) at the preferred speed of motion.*

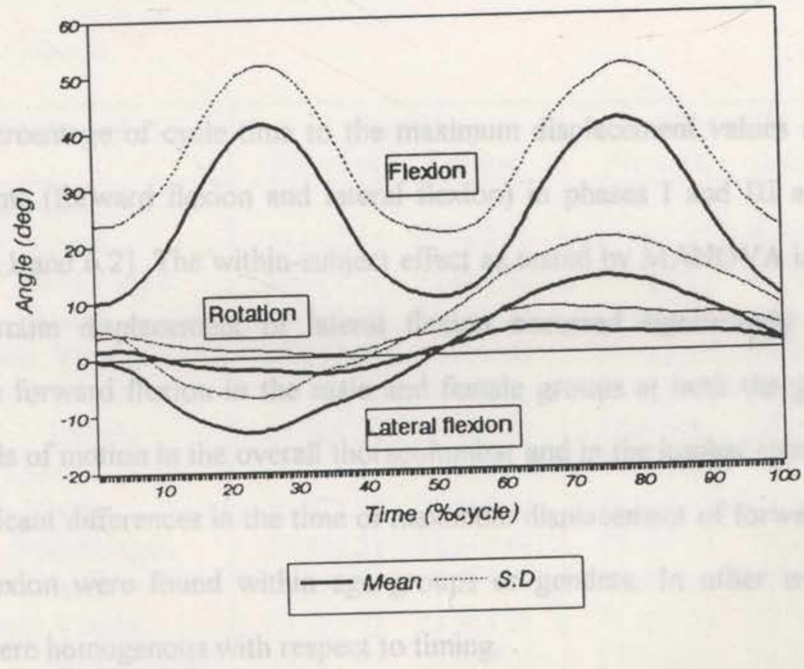


Figure 6.5 *Mean patterns of motion (with + 1sd) of forward flexion, lateral flexion and rotation in the lumbar spine for the lifting simulation in the middle-aged male group (n=15) at the preferred speed of motion.*

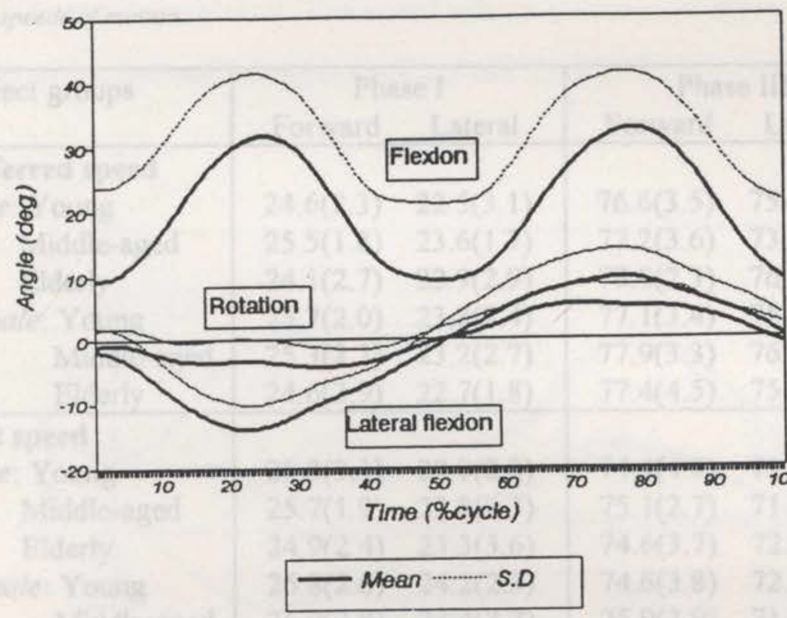


Figure 6.6 Mean patterns of motion (with +1 sd) of forward flexion, lateral flexion and rotation in the lumbar spine for the lifting simulation in the elderly male group (n=16) at the preferred speed of motion.

Percentage of cycle time to the maximum displacement values of the major components (forward flexion and lateral flexion) in phases I and III are presented [Tables 6.1 and 6.2]. The within-subject effect as tested by MANOVA indicated that the maximum displacement of lateral flexion occurred significantly earlier than maximum forward flexion in the male and female groups at both the preferred and fast speeds of motion in the overall thoracolumbar and in the lumbar spine ($p<0.001$). No significant differences in the time of maximum displacement of forward flexion or lateral flexion were found within age groups or genders. In other words, all the groups were homogenous with respect to timing.

Table 6.1 Means (S.D) of the percentage of cycle time to the maximum displacement values of forward flexion (Forward) and lateral flexion (Lateral) in the thoracolumbar spine in phase I and III in both speeds of motion.

Subject groups	Phase I		Phase III	
	Forward	Lateral	Forward	Lateral
Preferred speed				
Male: Young	24.6(2.3)	22.5(3.1)	76.6(3.5)	75.2(4.3)
Middle-aged	25.5(1.8)	23.6(1.7)	77.2(3.6)	73.2(4.5)
Elderly	24.1(2.7)	22.9(2.9)	78.0(2.3)	76.2(3.3)
Female: Young	25.7(2.0)	23.8(2.4)	77.1(3.4)	75.4(3.7)
Middle-aged	25.3(2.3)	23.2(2.7)	77.9(3.3)	76.2(3.1)
Elderly	24.6(3.9)	22.7(1.8)	77.4(4.5)	75.7(6.5)
Fast speed				
Male: Young	25.8(3.1)	22.9(2.8)	74.4(4.9)	71.3(5.1)
Middle-aged	25.7(1.9)	22.8(2.3)	75.1(2.7)	71.0(3.8)
Elderly	24.9(2.4)	23.3(3.6)	74.6(3.7)	72.8(4.5)
Female: Young	26.8(2.6)	24.2(2.3)	74.6(3.8)	72.5(4.9)
Middle-aged	26.0(2.8)	23.4(2.7)	75.9(3.9)	71.9(4.7)
Elderly	26.1(3.4)	24.1(4.1)	76.1(5.1)	74.7(5.5)

Table 6.2 Means (S.D) of the percentage of cycle time to the maximum displacement values of forward flexion (Forward) and lateral flexion (Lateral) in the lumbar spine in phase I and III in both speeds of motion.

Subject groups	Phase I		Phase III	
	Forward	Lateral	Forward	Lateral
Preferred speed				
Male: Young	24.3(2.4)	21.6(2.7)	77.3(3.5)	76.0(3.4)
Middle-aged	25.4(1.5)	23.4(1.9)	77.9(3.2)	73.5(4.9)
Elderly	25.3(2.7)	22.2(3.2)	78.6(2.9)	75.8(3.9)
Female: Young	25.2(1.9)	22.2(3.2)	77.4(3.3)	75.3(3.7)
Middle-aged	25.7(2.4)	21.4(3.1)	78.6(4.0)	76.9(6.0)
Elderly	23.6(4.9)	20.1(5.0)	77.8(5.2)	75.6(4.0)
Fast speed				
Male: Young	26.4(2.7)	21.8(3.1)	74.6(4.7)	71.1(4.9)
Middle-aged	25.4(1.3)	21.6(4.6)	75.7(2.9)	72.8(7.1)
Elderly	26.2(2.7)	21.6(3.2)	75.5(3.1)	72.0(6.9)
Female: Young	27.3(3.7)	23.9(3.2)	75.8(3.7)	72.9(4.5)
Middle-aged	25.8(2.8)	21.6(3.2)	75.9(3.9)	72.3(4.8)
Elderly	25.3(5.3)	21.1(4.6)	76.3(5.9)	73.4(6.6)

Changing the speed of motion from preferred to a faster speed had no significant effect on the nature of the composite movements in either gender or segment [Figures 6.3 and 6.7]. The speed effects on range of forward flexion and lateral flexion are reported in sections 6.3.2.2 and 6.3.3.2.

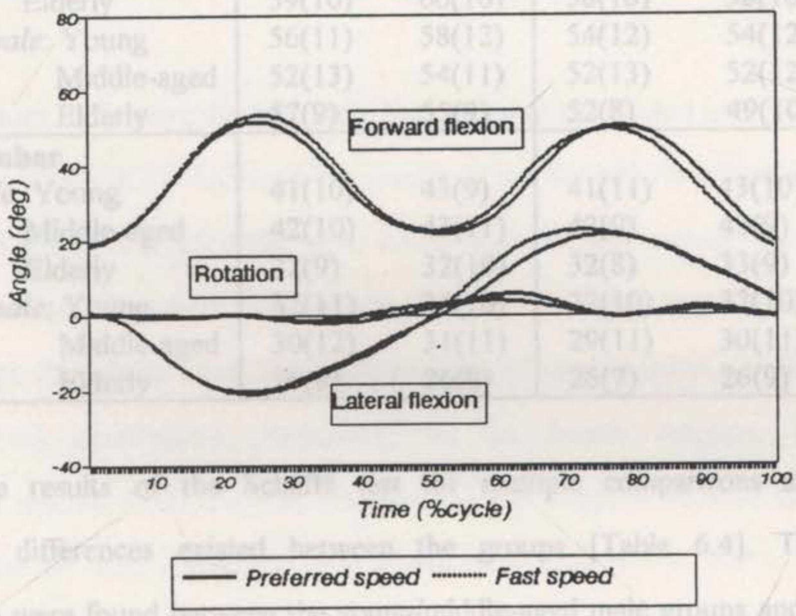


Figure 6.7 Patterns of motion for the preferred and fast speeds of motion in the thoracolumbar spine in the middle-aged female group.

6.3.2 Range of Forward Flexion Component

6.3.2.1 Age and Gender Effects on Range of Forward Flexion

Ranges of forward flexion in phase I and III during the lifting simulation are presented [Table 6.3]. No age effects were found in the thoracolumbar spine (forward flexion in phase I: $F_{2,94} = 1.30$; $p = 0.276$, in phase III: $F_{2,94} = 2.67$; $p = 0.075$) whereas the decline in the means of ranges with increasing age was evident in the lumbar spine (forward flexion in phase I: $F_{2,94} = 7.51$; $p = 0.001$, in phase III: $F_{2,94} = 5.99$; $p = 0.004$).

Table 6.3 Means (S.D) of range of forward flexion (degrees) in the thoracolumbar and lumbar spine in phase I and III at the preferred and the fast speeds of motion.

Subject groups	For. flexion: phase I Preferred	For. flexion: phase I Fast	For. flexion: phase III Preferred	For. flexion: phase III Fast
Thoracolumbar				
Male: Young	66(13)	68(13)	65(14)	66(14)
Middle-aged	67(10)	68(10)	68(10)	68(11)
Elderly	59(10)	60(10)	58(10)	58(10)
Female: Young	56(11)	58(12)	54(12)	54(12)
Middle-aged	52(13)	54(11)	52(13)	52(12)
Elderly	57(9)	55(9)	52(8)	49(10)
Lumbar				
Male: Young	41(10)	43(9)	41(11)	43(10)
Middle-aged	42(10)	43(11)	42(9)	43(9)
Elderly	32(9)	32(10)	32(8)	33(9)
Female: Young	32(11)	34(10)	32(10)	32(10)
Middle-aged	30(12)	31(11)	29(11)	30(11)
Elderly	26(8)	26(8)	26(7)	26(9)

The results of the Schéffé test for multiple comparisons showed that significant differences existed between the groups [Table 6.4]. The greatest differences were found between the young/middle-aged male groups and the elderly female group ($p < 0.01$). There were no significant differences between groups for the female subjects in the lumbar spine.

Table 6.4 Schéffé multiple comparisons between age groups for range of forward flexion in the lumbar spine.

Movements	Preferred speed				Fast speed			
	Male		*Female*		*Male*		*Female*	
	M	E	M	E	M	E	M	E
Flexion:phase I								
Male Y				**			*	**
M				**			*	**
Female Y								
M								
Flexion:phase III								
Male Y				**			*	**
M			*	**			*	**
Female Y								
M								

Note: Y= young group, M = middle-aged group, E = elderly group. * = $p < 0.05$, ** = $p < 0.01$

In each corresponding movement, male subjects displayed a significantly greater range of forward flexion than female subjects in both the thoracolumbar and lumbar spine at $p < 0.001$ (thoracolumbar: forward flexion phase I: $F_{1,94} = 17.40$, phase III: $F_{1,94} = 27.63$; lumbar spine: forward flexion phase I: $F_{1,94} = 20.20$, phase III: $F_{1,94} = 25.52$). The differences were between 3 and 16 degrees for the thoracolumbar spine and 6-13 degrees for the lumbar spine.

Ranges of forward flexion in the lumbar spine in phases I and III are plotted against age [Figure 6.8]. Although the results of the MANOVA indicated that there were significant differences in the mean values of the ranges between age groups for the lumbar spine, there were large variations between subjects in the same age group [Figure 6.8]. Therefore, most regression analyses of range against age demonstrated no significant correlations, particularly for the female subjects. There were statistically significant correlations between age and range of forward flexion in the lumbar spine for male subjects at both speeds of motion ($r = -0.409$ to -0.493, $p < 0.01$), however the lack of fit test for linearity demonstrated evidence of lack of fit at $p < 0.05$. It is reasonable to say that there was no clear age effect in the range of forward flexion at either the thoracolumbar or lumbar spine during the lifting simulation.

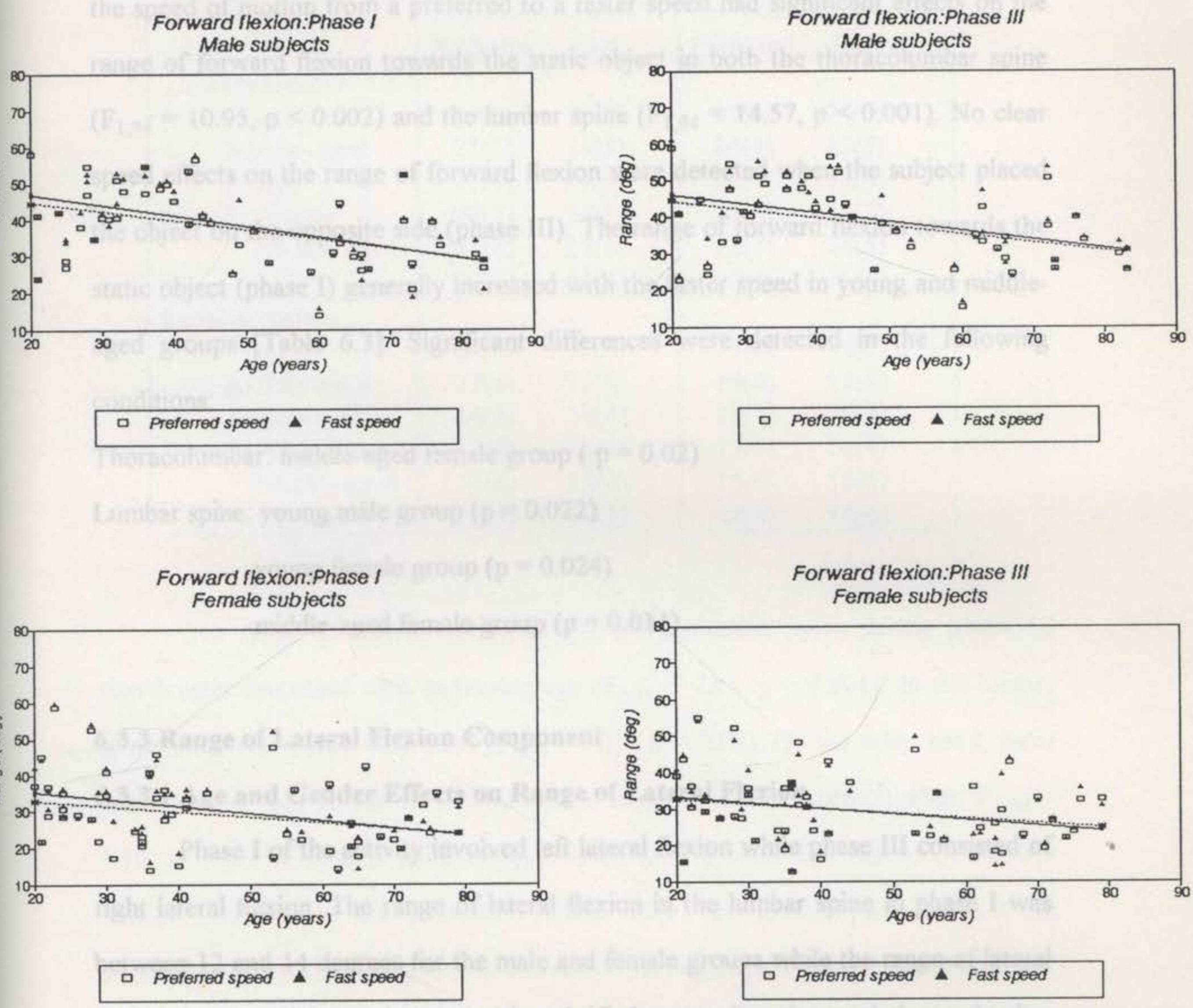


Figure 6.8 Relationships of age and range of forward flexion in the lumbar spine for male (n=46) and female subjects (n=54) at the preferred and fast speeds of motion (---- preferred speed, —— fast speed).

6.3.2.2 Speed Effects on Range of Forward Flexion

The within-subject effect as tested by the MANOVA showed that changing the speed of motion from a preferred to a faster speed had significant effects on the range of forward flexion towards the static object in both the thoracolumbar spine ($F_{1,94} = 10.95$, $p < 0.002$) and the lumbar spine ($F_{1,94} = 14.57$, $p < 0.001$). No clear speed effects on the range of forward flexion were detected when the subject placed the object on the opposite side (phase III). The range of forward flexion towards the static object (phase I) generally increased with the faster speed in young and middle-aged groups [Table 6.3]. Significant differences were detected in the following conditions:

Thoracolumbar: middle-aged female group ($p = 0.02$)

Lumbar spine: young male group ($p = 0.022$)

young female group ($p = 0.024$)

middle-aged female group ($p = 0.011$)

6.3.3 Range of Lateral Flexion Component

6.3.3.1 Age and Gender Effects on Range of Lateral Flexion

Phase I of the activity involved left lateral flexion while phase III consisted of right lateral flexion. The range of lateral flexion in the lumbar spine in phase I was between 12 and 14 degrees for the male and female groups while the range of lateral flexion in phase III was between 10 and 17 degrees. For the total thoracolumbar spine, the range of lateral flexion was between 19 and 24 degrees in both directions [Table 6.5].

Table 6.5 Means (S.D) of range of lateral flexion (degrees) in the thoracolumbar and lumbar spine at the preferred and fast speeds of motion.

Subject groups	Lat. flexion: phase I Preferred	Fast	Lat. flexion: phase III Preferred	Fast
Thoracolumbar				
Male: Young	19(6)	20(7)	23(5)	24(4)
Middle-aged	21(5)	21(5)	24(5)	23(5)
Elderly	23(4)	23(5)	20(4)	19(4)
Female: Young	20(5)	21(5)	24(6)	24(7)
Middle-aged	21(6)	22(5)	22(7)	24(5)
Elderly	22(6)	21(6)	20(4)	19(5)
Lumbar spine				
Male: Young	14(5)	13(5)	14(5)	14(5)
Middle-aged	13(6)	13(6)	14(6)	13(6)
Elderly	14(4)	14(4)	10(4)	10(4)
Female: Young	13(4)	13(4)	17(4)	16(4)
Middle-aged	12(4)	12(4)	15(6)	16(5)
Elderly	12(4)	12(3)	14(4)	14(4)

The range of lateral flexion in the thoracolumbar spine during phase III significantly decreased with increasing age ($F_{2,94} = 7.63$, $p = 0.001$). In the lumbar spine it showed similar decreases ($F_{2,94} = 4.10$, $p = 0.02$). On the other hand, there were no clear age effects for lateral flexion during phase I (thoracolumbar: $F_{2,94} = 1.10$, $p = 0.338$; lumbar spine: $F_{2,94} = 0.20$, $p = 0.819$). The results of Schéffé multiple comparison are presented [Table 6.6]. The greatest differences were detected between the young female and elderly male groups at the preferred speed of motion in the lumbar spine ($p < 0.01$). Some differences between groups for the female subjects were detected at the faster speed of motion. No significant differences between groups for the male subjects were found in any of the movements.

Table 6.6 *Tests for significance of multiple comparison for range of lateral flexion between age groups in the thoracolumbar and lumbar spine in phase III at the preferred and fast speeds.*

Trunk segments/ Subject groups	Preferred speed *Male* M	Preferred speed *Male* E	Preferred speed *Female* M	Preferred speed *Female* E	Fast speed *Male* M	Fast speed *Male* E	Fast speed *Female* M	Fast speed *Female* E
Thoracolumbar								
Male Y								
M								
Female Y								*
M								
Lumbar spine								
Male Y								
M								
Female Y		**				*		
M						*		

Note: Y = young group, M = middle-aged group, E = elderly group. * = $p < 0.05$, ** = $p < 0.01$

The between-subjects effects as tested by the MANOVA also indicated that there were significant differences in the ranges of lateral flexion in phase III between the male and female subjects in the lumbar spine ($F_{1,94} = 8.76$, $p < 0.005$). Male subjects demonstrated a reduced range when compared to female subjects in the same age group.

No significant correlations were found between age and range of lateral flexion in phase I at either speed or in either trunk segment. In phase III, significant negative correlations were detected at both the preferred and fast speeds in the thoracolumbar and lumbar spine in male subjects ($r = -0.341$ to -0.468, $p < 0.05$). There was no significant trend for decreasing range of lateral flexion with age in female subjects at either trunk segment, except for lateral flexion in phase III with the fast speed of motion in the thoracolumbar spine ($r = -0.384$, $p < 0.005$). Although the statistical analysis demonstrated significant differences in the range of lateral flexion during phase III, the difference in the mean values between the age groups was only 5 degrees for thoracolumbar spine and 7 degrees for lumbar spine [Table 6.5]. Variations in the ranges between subjects in the same age group were also noted.

6.3.3.2 Speed Effects on Range of Lateral Flexion

Changing the speed of motion had no clear effect on the range of lateral flexion to either side in any condition. The within-subject effect as tested by the MANOVA indicated no significant difference in any movement (thoracolumbar: phase I: $F_{1,94} = 0.11$, $p = 0.738$, phase III: $F_{1,94} = 0.04$, $p = 0.846$; lumbar spine: phase I: $F_{1,94} = 2.09$, $p = 0.152$, phase III: $F_{1,94} = 2.03$, $p = 0.158$).

6.3.4 Range of Rotational Component

The ranges of rotation were between 0 and 17 degrees for the total thoracolumbar spine and between 0 and 10 degrees for the lumbar spine. However, most subjects demonstrated only a small amount of rotation [Table 6.7]. No consistent patterns of rotation were found during the lifting simulation, therefore, range of rotation was recorded at the time of maximum displacement of forward flexion in phase I and III. Median, minimum and maximum values for the ranges of rotation during phase I and III are presented [Table 6.7].

Table 6.7 Median (minimum, maximum) values of range of rotation in degrees in the thoracolumbar and lumbar spine in phase I and III at both speeds.

Subject groups	Phase I		Phase III	
	Preferred	Fast	Preferred	Fast
Thoracolumbar				
Male: Young	1(-10,6)	-1(-7,9)	1(-5,12)	3(-7,10)
Middle-aged	-1(-10,9)	0(-13,11)	0(-14,13)	3(-9,12)
Elderly	-1(-8,9)	-1(-8,9)	5(-4,14)	5(0,15)
Female: Young	-1(-6,8)	1(-9,8)	-2(-13,10)	-2(-13,7)
Middle-aged	1(-12,8)	0(-10,5)	1(-17,10)	2(-15,7)
Elderly	0(-5,10)	0(-5,7)	1(-11,9)	3(-10,12)
Lumbar spine				
Male: Young	-2(-7,2)	-2(-8,1)	1(-2,10)	2(-2,10)
Middle-aged	-3(-7,5)	-2(-10,5)	4(-4,11)	5(-3,11)
Elderly	-4(-10,5)	-4(-10,5)	5(0,11)	6(0,10)
Female: Young	-1(-4,7)	-1(-5,6)	-1(-5,6)	0(-6,6)
Middle-aged	-1(-8,3)	-1(-8,3)	1(-5,6)	0(-5,3)
Elderly	-2(-10,2)	-3(-9,2)	3(-3,10)	3(-4,10)

6.3.5 Angular Velocity

6.3.5.1 Patterns of Angular Velocity

The patterns of angular velocity for forward flexion and lateral flexion demonstrated consistent characteristics across the age groups with respect to the timing of peak values. The mean values of angular displacement and angular velocity for forward flexion, lateral flexion and for rotation in the lumbar spine in the young male group at the preferred speed of motion are displayed [Figures 6.9 to 6.11].

The peak flexion angular velocity occurred about the midpoint between the starting position and the end of range in each phase of movement [Figure 6.9]. Maximum lateral flexion velocity was seen during phase I and reached a plateau between the motion of phase II and III. During phase IV, lateral flexion velocity reversed in direction and peaked again when the subjects returned to the starting position.

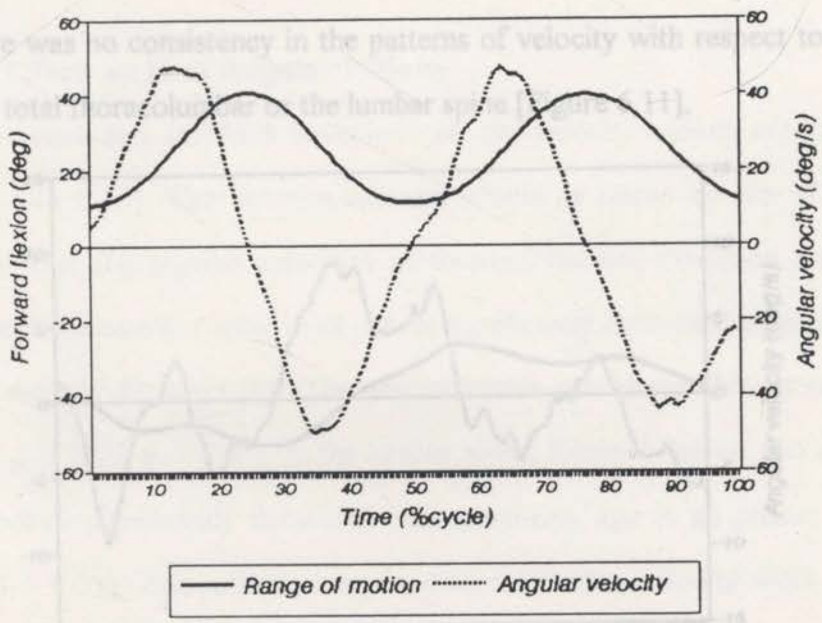


Figure 6.9 Mean values of angular displacement and velocity for forward flexion in the lumbar spine in the young male group (n=15) at the preferred speed of motion. The angular velocity of forward flexion in phases I and III are displayed as positive values and in phases II and IV as negative values (extension phases).

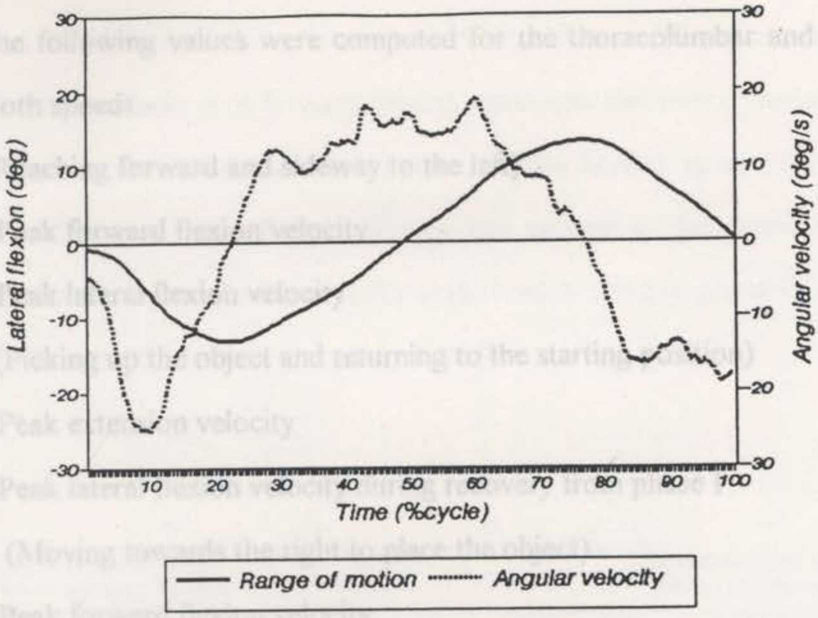


Figure 6.10 Mean values of angular displacement and velocity for lateral flexion in the lumbar spine in the young male group (n=15) at the preferred speed of motion. The angular velocity of lateral flexion in phases I and IV is displayed as negative values and in phases II and III as positive values.

There was no consistency in the patterns of velocity with respect to rotation in either the total thoracolumbar or the lumbar spine [Figure 6.11].

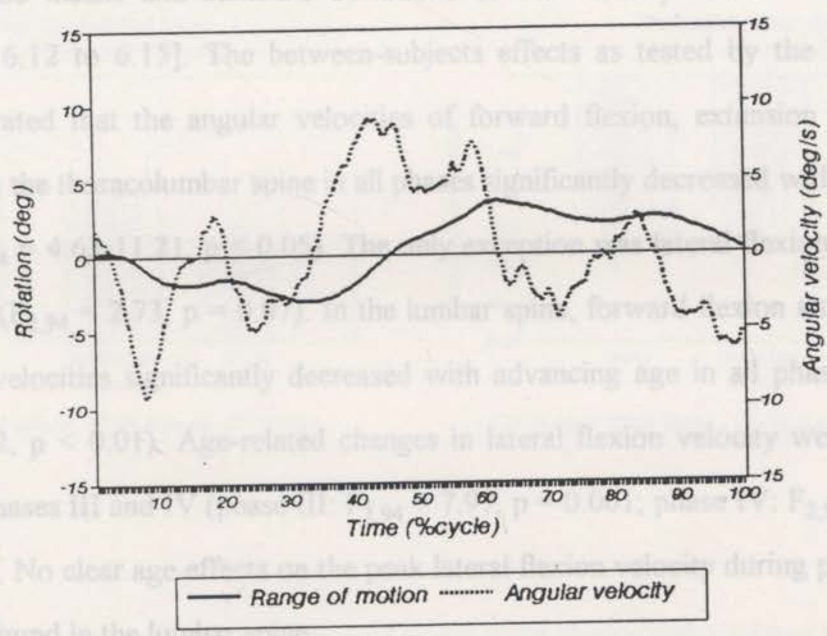


Figure 6.11 Mean values of angular displacement and velocity for rotation in the lumbar spine in the young male group (n=15) at the preferred speed of motion.

The following values were computed for the thoracolumbar and the lumbar spine at both speeds:-

Phase I (Reaching forward and sideway to the left)

- Peak forward flexion velocity
- Peak lateral flexion velocity

Phase II (Picking up the object and returning to the starting position)

- Peak extension velocity
- Peak lateral flexion velocity during recovery from phase I

Phase III (Moving towards the right to place the object)

- Peak forward flexion velocity
- Peak lateral flexion velocity

Phase IV (Recovering to the starting position)

- Peak extension velocity
- Peak lateral flexion velocity during recovery from phase III

6.3.5.2 Age Effects on Peak Angular Velocity

The means and standard deviations of the velocity values are presented [Figures 6.12 to 6.15]. The between-subjects effects as tested by the MANOVA demonstrated that the angular velocities of forward flexion, extension and lateral flexion in the thoracolumbar spine in all phases significantly decreased with increasing age ($F_{2,94} = 4.63\text{-}11.21$, $p < 0.05$). The only exception was lateral flexion velocity in phase II ($F_{2,94} = 2.73$, $p = 0.07$). In the lumbar spine, forward flexion and extension angular velocities significantly decreased with advancing age in all phases ($F_{2,94} = 6.34\text{-}9.52$, $p < 0.01$). Age-related changes in lateral flexion velocity were detected during phases III and IV (phase III: $F_{2,94} = 7.97$, $p = 0.001$; phase IV: $F_{2,94} = 6.65$, $p = 0.002$). No clear age effects on the peak lateral flexion velocity during phases I and II were found in the lumbar spine.

The Schéffé test demonstrated some significant differences between age groups for peak velocities of forward flexion, extension and lateral flexion at the fast speed of motion in both the thoracolumbar and the lumbar spine [Table 6.8]. No significant differences were found between age groups at the preferred speed of motion, except for lateral flexion velocity in the lumbar spine in phase IV between the young female and elderly male groups ($p < 0.05$).

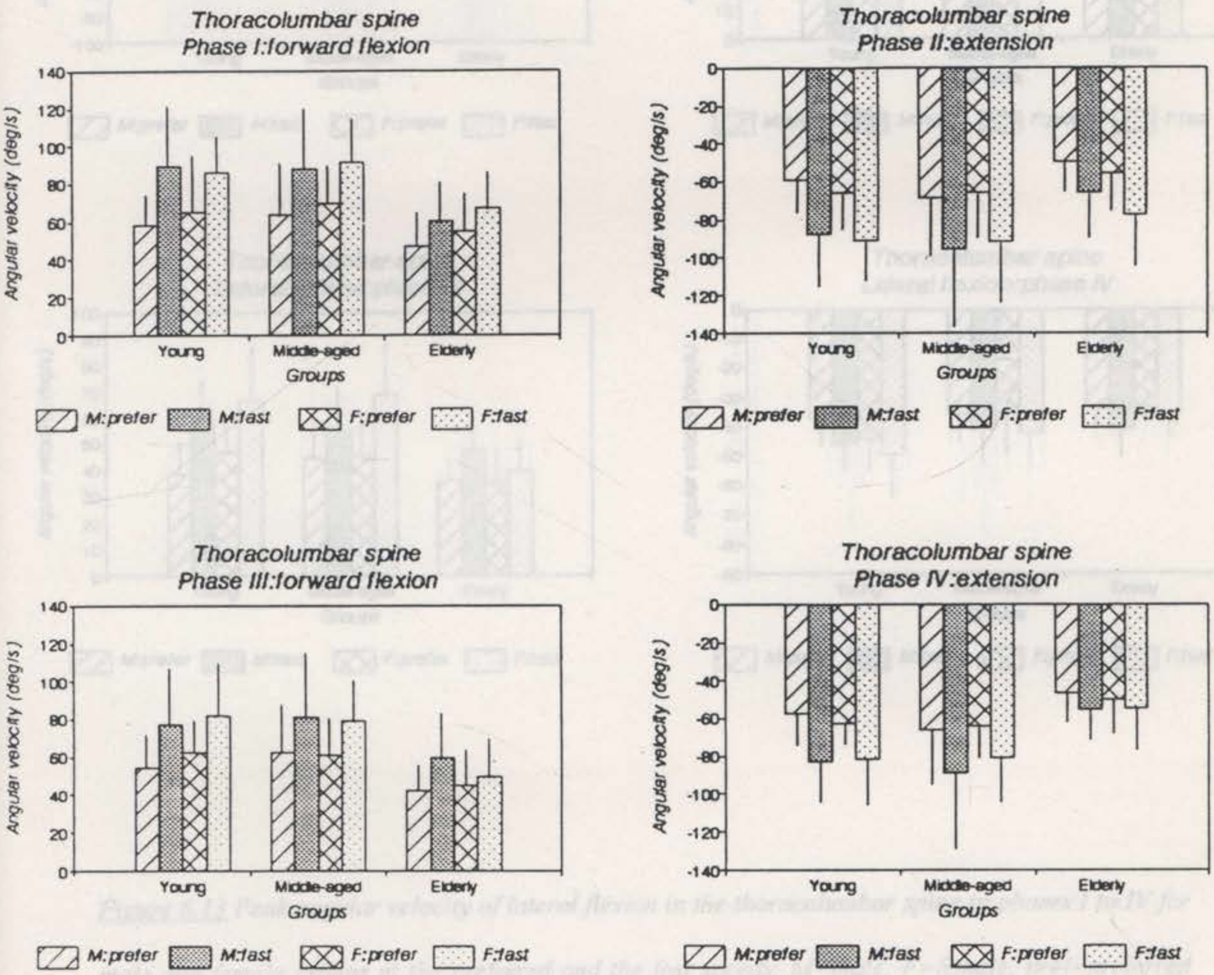


Figure 6.12 Peak angular velocity of forward flexion in the thoracolumbar spine in phases I to IV for male and female groups at the preferred and the fast speeds; M=male, F=female, pref=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].

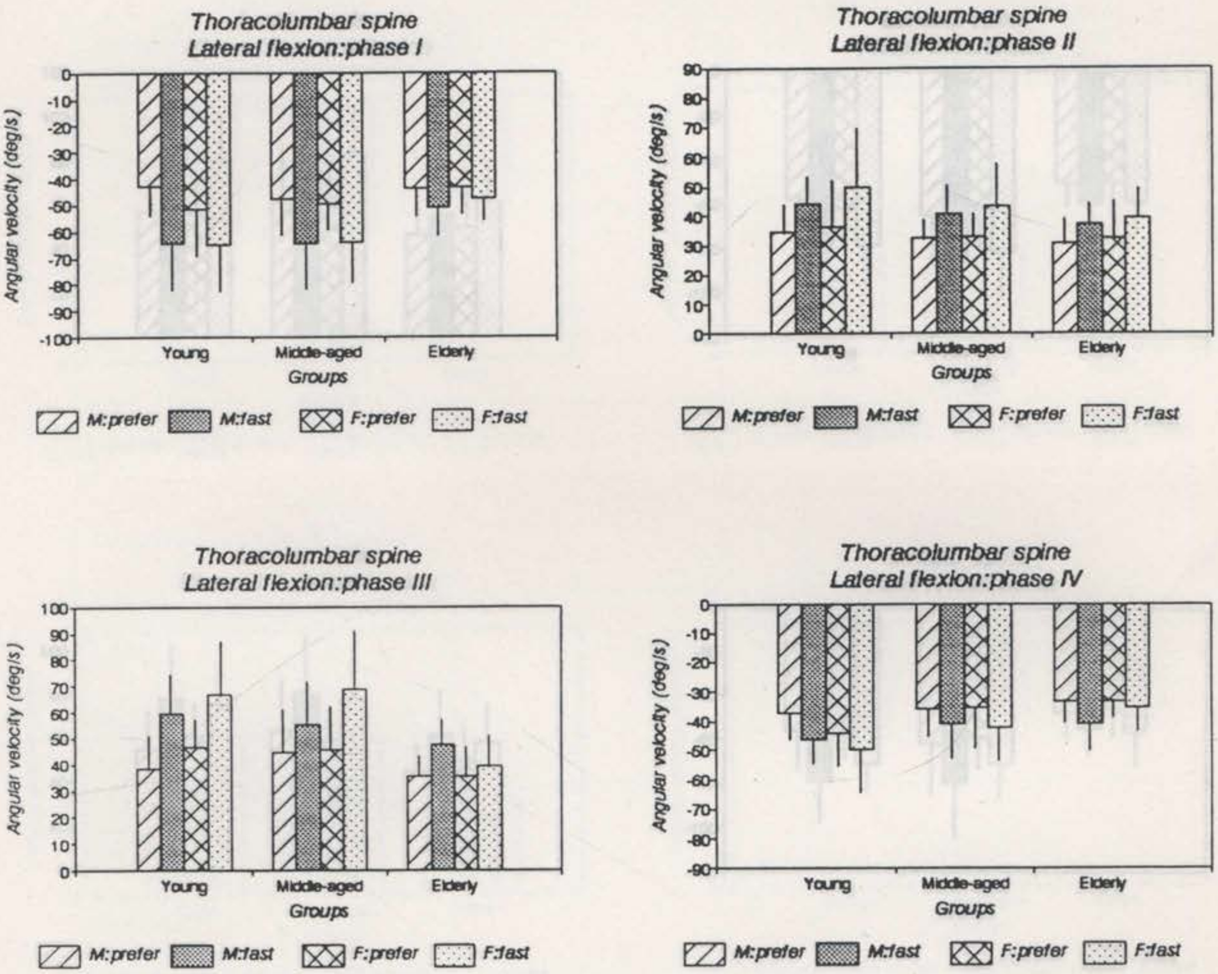
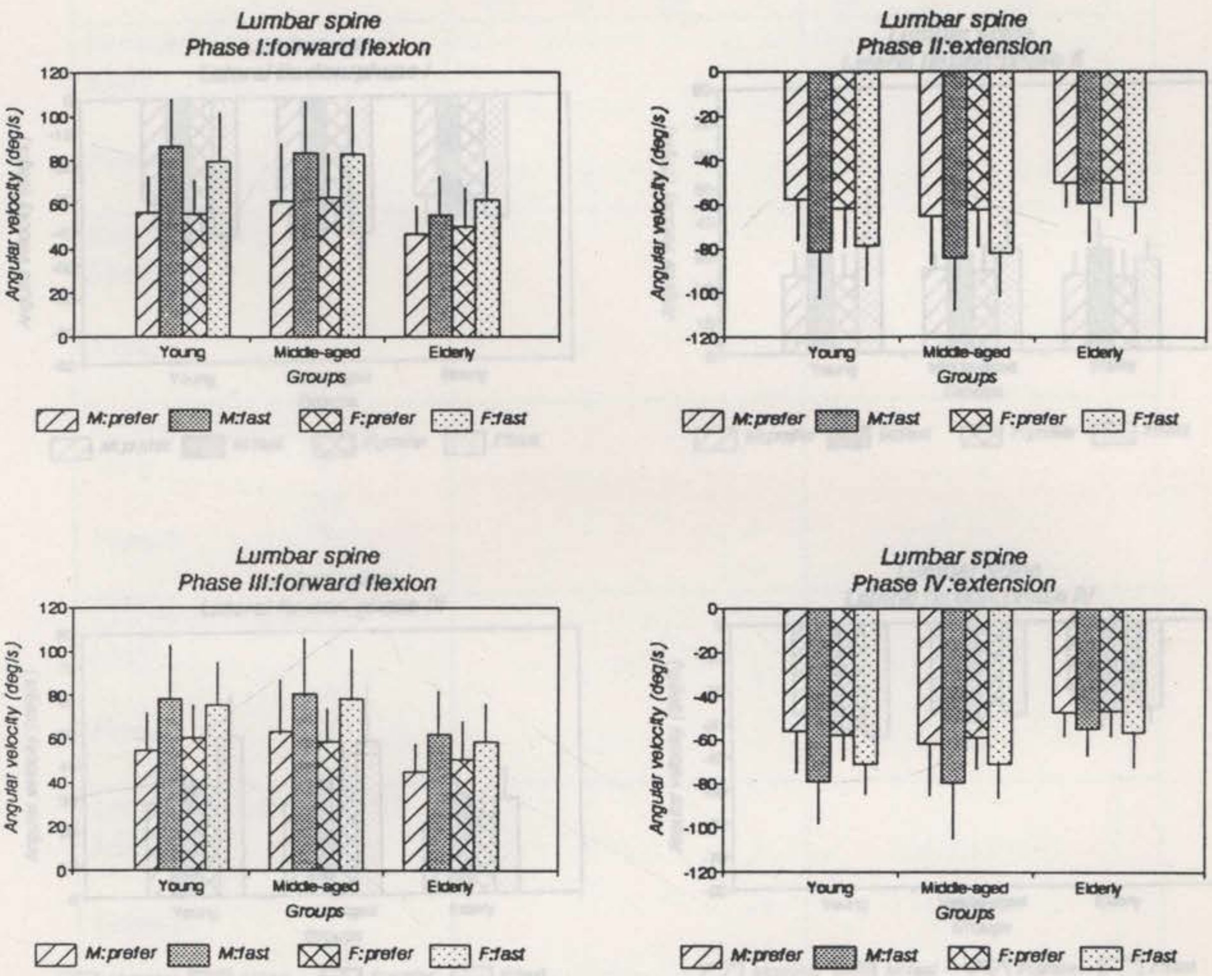


Figure 6.13 Peak angular velocity of lateral flexion in the thoracolumbar spine in phases I to IV for male and female groups at the preferred and the fast speeds; M=male, F=female, pref=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].



<u>Figure 6.14</u> Peak angular velocity of forward flexion in the lumbar spine in phases I to IV for male and female groups at the preferred and the fast speeds; M=male, F=female, pref=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].

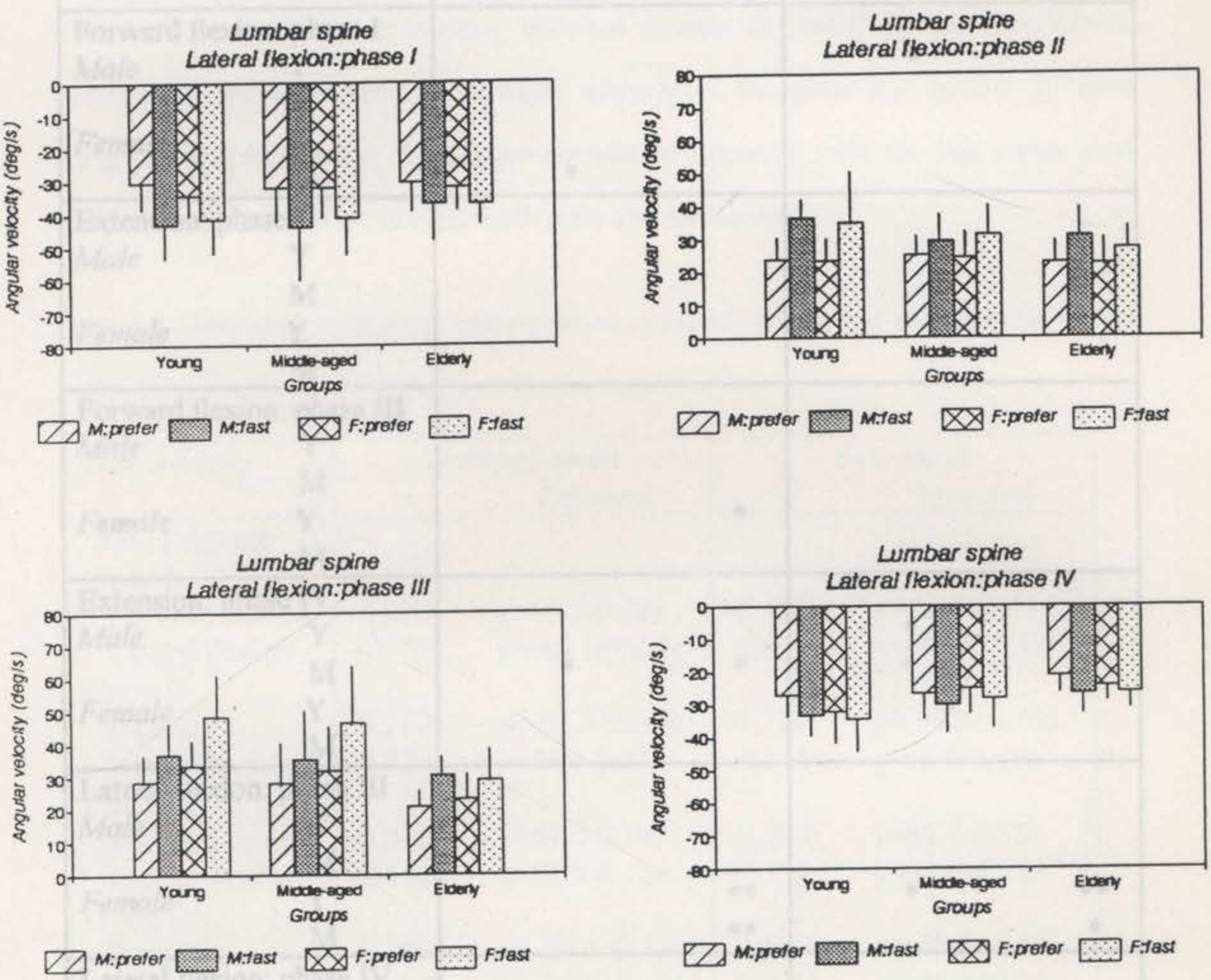


Figure 6.15 Peak angular velocity of lateral flexion in the lumbar spine in phases I to IV for male and female groups at the preferred and the fast speeds; M=male, F=female, pref=preferred speed, fast=fast speed. [Error bars represent 1 standard deviation].

Table 6.8 Scheffé multiple comparisons between age groups for peak flexion, extension and lateral flexion velocity in the thoracolumbar and lumbar spine at the fast speed of motion.

Peak velocity		Thoracolumbar spine				Lumbar spine			
		Male		*Female*		*Male*		*Female*	
		M	E	M	E	M	E	M	E
Forward flexion: phase I									
Male	Y						*		
	M								
Female	Y								
	M		*						
Extension: phase II									
Male	Y								
	M								*
Female	Y								
	M								
Forward flexion: phase III									
Male	Y								
	M								
Female	Y				*				
	M								
Extension: phase IV									
Male	Y						*		
	M		*		*		*		
Female	Y								
	M								
Lateral flexion: phase III									
Male	Y								
	M								
Female	Y				**		*		**
	M				**				*
Lateral flexion: phase IV									
Male	Y								
	M								
Female	Y				*				
	M								

Note: Y = young group, M = middle-aged group, E = elderly group.
* = $p < 0.05$, ** = $p < 0.01$

The correlations between age and peak angular velocity values for forward flexion, extension and lateral flexion indicated a reduction in peak velocity with increasing age in male and female subjects at both the total thoracolumbar and lumbar spine [Tables 6.9 and 6.10]. Although there were statistically significant differences in the mean values of peak velocity between groups as tested by the MANOVA, velocity values were variable between subjects in the same age group. In each corresponding movement, a stronger correlation occurred with the fast rather than the preferred speed of motion for both male and female subjects.

Table 6.9 Correlation coefficients and regression equations of age and peak velocity for the preferred and the fast speeds of motion in the thoracolumbar spine.

Peak velocity	Preferred speed		Fast speed	
	r	Equation	r	Equation
Male subjects				
Phase I:				
Forward flexion	-0.286#	y=65.3-0.32x	-0.415**	y=97.4-0.67x
Lateral flexion	0.070#	y=-46.1+0.05x	0.403**	y=-70.3+0.37x
Phase II:				
Extension	0.277#	y=-68.3+0.34x	0.325*	y=-99.3+0.60x
Lateral flexion	-0.326*	y=36.1-0.13x	-0.344*	y=45.8-0.19x
Phase III:				
Forward flexion	-0.332*	y=63.7-0.39x	-0.326*	y=87.7-0.55x
Lateral flexion	-0.156#	y=42.9-0.12x	-0.350*	y=62.0-0.29x
Phase IV:				
Extension	0.266#	y=-65.4+0.33x	0.361*	y=-92.5+0.63x
Lateral flexion	0.269#	y=-38.8+0.12x	0.225#	y=-46.6+0.13x
Female subjects				
Phase I:				
Forward flexion	-0.220#	y=71.3-0.31x	-0.432**	y=96.4-0.58x
Lateral flexion	0.148#	y=-51.5+0.13x	0.339*	y=-67.6+0.33x
Phase II:				
Extension	0.205#	y=-69.1+0.23x	0.192#	y=-95.1+0.32x
Lateral flexion	-0.116#	y=36.2-0.08x	-0.205#	y=49.3-0.20x
Phase III:				
Forward flexion	-0.355**	y=66.5-0.39x	-0.431**	y=88.0-0.67x
Lateral flexion	-0.303*	y=49.4-0.26x	-0.450**	y=73.9-0.60x
Phase IV:				
Extension	0.284*	y=-66.3+0.28x	0.417**	y=-88.3+0.61x
Lateral flexion	0.331*	y=-43.7+0.23x	0.429**	y=-51.7+0.35x

Note: * = $p < 0.05$, ** = $p < 0.01$, y = angular velocity (deg/s), x = age-20 (years)
= MSE/MSR ratio > 20%

Table 6.10 Correlation coefficients and regression equations of age and peak velocity for the preferred and the fast speeds of motion in the lumbar spine.

Peak velocity	Preferred speed		Fast speed	
	r	Equation	r	Equation
Male subjects				
Phase I:				
Forward flexion	-0.264#	y=62.7-0.29x	-0.461**	y=94.3-0.71x
Lateral flexion	0.088#	y=-32.1+0.05x	0.292*#	y=-47.3+0.22x
Phase II:				
Extension	0.265#	y=-65.3+0.28x	0.401**	y=-89.9+0.55x
Lateral flexion	-0.188#	y=25.4-0.06x	-0.285#	y=36.0-0.14x
Phase III:				
Forward flexion	-0.293*#	y=63.2-0.33x	-0.335*	y=86.4-0.48x
Lateral flexion	-0.355*	y=31.2-0.20x	-0.246#	y=38.7-0.17x
Phase IV:				
Extension	0.254#	y=-62.8+0.28x	0.426**	y=-86.2+0.55x
Lateral flexion	0.346*	y=-28.7+0.14x	0.289*#	y=-33.6+0.14x
Female subjects				
Phase I:				
Forward flexion	-0.220#	y=62.1-0.22x	-0.384**	y=87.9-0.50x
Lateral flexion	0.103#	y=-33.9+0.04x	0.223#	y=-43.3+0.13x
Phase II:				
Extension	0.251#	y=-64.7+0.25x	0.349**	y=-83.3+0.40x
Lateral flexion	-0.027#	y=23.7-0.01x	-0.178#	y=34.5-0.13x
Phase III:				
Forward flexion	-0.263#	y=63.2-0.25x	-0.301*	y=80.4-0.36x
Lateral flexion	-0.358**	y=35.9-0.24x	-0.454**	y=53.1-0.45x
Phase IV:				
Extension	0.330*	y=-60.8+0.24x	0.320*	y=-74.8+0.32x
Lateral flexion	0.287*#	y=-31.2+0.15x	0.363**	y=-34.7+0.20x

Note: * = $p < 0.05$, ** = $p < 0.01$, y = angular velocity (deg/s), x = age3x (years)
= MSE/MSR ratio > 20%

In the overall thoracolumbar spine, the peak velocity of forward flexion in the fast motion decreased by approximately 2 deg/s and in the lumbar spine by 1-2 deg/s every 3 years. The rate of decrease in peak lateral flexion velocity varied between 1 and 2 deg/s every 5-10 years. Thus, if a 20 year old man had a peak flexion velocity of 95 deg/s in the fast motion of the lumbar spine during the lift, at the age of 70 he would theoretically peak at 60 deg/s. The reduction in peak flexion velocity would be approximately 35%.

6.3.5.3 Gender Effects on Peak Angular Velocity

Peak angular velocities were compared [Figures 6.12 to 6.15]. There were no significant differences in the peak forward flexion and extension velocities between the genders in the same age group in either the thoracolumbar or lumbar spine. Lateral flexion velocity in phase III in the lumbar spine was the only significantly different lateral flexion value. Female subjects demonstrated an increase in lateral flexion velocity compared to male subjects in the same age group at both speeds of motion ($F_{1,94} = 4.97$, $p = 0.028$), however a two sample t-test indicated that there were significant differences only between the young male and young female groups at the fast speed of motion ($p < 0.05$).

6.3.5.4 Speed Effects on Peak Angular Velocity

Changing the speed of motion from a preferred to a faster speed had no significant effects on the nature of the overall patterns of angular velocity in the thoracolumbar or lumbar spine for male or female subjects. Plots of the patterns of angular velocity for forward flexion in the lumbar spine in the young male and elderly male groups in both speeds of motion are presented [Figures 6.16 and 6.17].

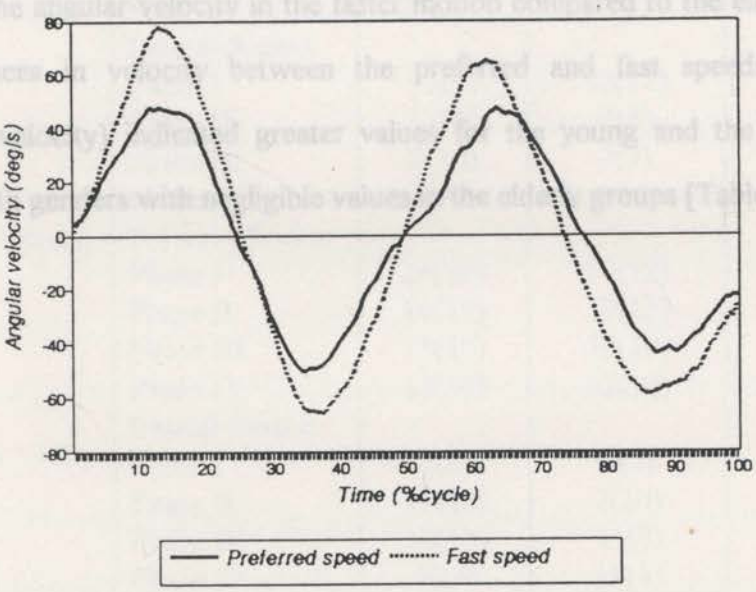


Figure 6.16 Patterns of angular velocity for the movement of forward flexion in the lumbar spine in the young male group (n=15) in both speeds of motion.

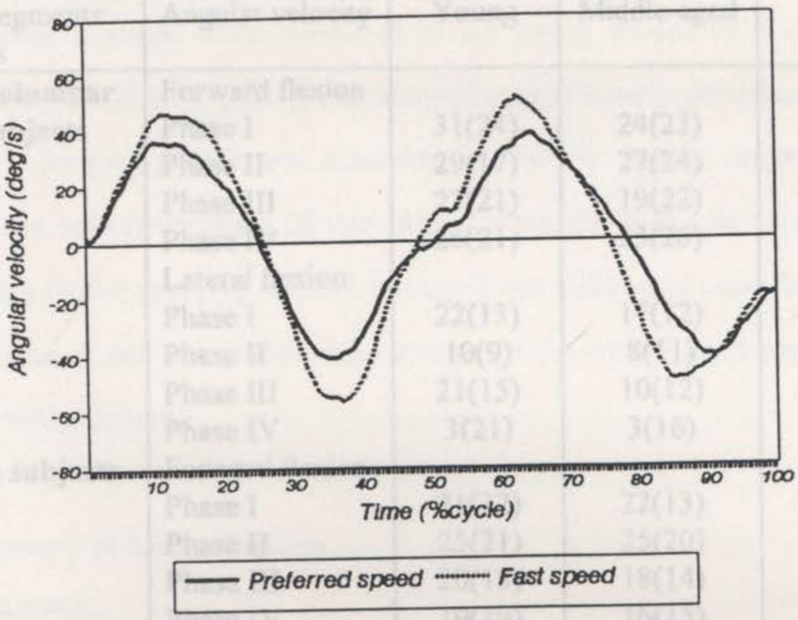


Figure 6.17 Patterns of angular velocity for the movement of forward flexion in the lumbar spine in the elderly male group (n=16) in both speeds of motion.

The young and middle-aged male and female subjects had a greater capacity to increase the angular velocity in the faster motion compared to the elderly groups. The differences in velocity between the preferred and fast speeds of motion (differential velocity) indicated greater values for the young and the middle-aged groups in both genders with negligible values in the elderly groups [Table 6.11].

Table 6.11 Means (S.D) of the differences in angular velocity (deg/s) between the preferred and fast speeds of motion in the thoracolumbar and lumbar spine for male and female subjects in each age group.

Trunk segments Subjects	Angular velocity	Young	Middle-aged	Elderly
Thoracolumbar	Forward flexion			
Male subjects	Phase I	31(24)	24(23)	13(11)*
	Phase II	29(17)	27(24)	16(13)
	Phase III	23(21)	19(22)	17(19)
	Phase IV	26(21)	23(26)	9(12)*
	Lateral flexion			
	Phase I	22(13)	17(12)	7(10)*
	Phase II	10(9)	8(11)	7(6)
	Phase III	21(15)	10(12)	12(6)*
	Phase IV	3(21)	3(16)	-6(12)
Female subjects	Forward flexion			
	Phase I	21(32)	22(13)	12(10)
	Phase II	25(21)	25(20)	21(18)
	Phase III	20(18)	18(14)	4(14)*
	Phase IV	19(19)	16(15)	5(14)*
	Lateral flexion			
	Phase I	13(13)	14(12)	5(8)
	Phase II	13(14)	10(15)	7(16)*
	Phase III	20(14)	23(10)	4(12)#
	Phase IV	3(24)	-5(15)	1(13)
Lumbar spine	Forward flexion			
Male subjects	Phase I	30(19)	22(19)	9(11)*
	Phase II	23(15)	18(15)	10(11)*
	Phase III	23(20)	17(19)	17(16)
	Phase IV	23(20)	18(18)	8(13)
	Lateral flexion			
	Phase I	13(9)	12(11)	7(7)
	Phase II	12(8)	4(5)	8(11)
	Phase III	8(10)	7(7)	9(6)
	Phase IV	4(11)	4(11)	5(8)
Female subjects	Forward flexion			
	Phase I	24(20)	19(12)	12(12)
	Phase II	16(19)	19(13)	10(11)
	Phase III	15(14)	19(12)	10(19)
	Phase IV	13(13)	12(10)	7(6)
	Lateral flexion			
	Phase I	8(6)	9(7)	7(12)
	Phase II	11(20)	7(10)	2(8)
	Phase III	15(12)	15(8)	6(8)*
	Phase IV	4(14)	1(13)	1(11)

Note: * Significant differences between the young and elderly groups at $p < 0.05$
Significant differences between the middle-aged and elderly groups at $p < 0.05$

The elderly male and female groups demonstrated significantly decreased differential velocity values for forward flexion, extension and for lateral flexion at the thoracolumbar segment when compared to the young groups ($p < 0.05$). In the lumbar spine, the elderly male group showed a significantly decreased differential velocity for forward flexion and extension ($p < 0.05$). Similar decreases in right lateral flexion velocity in phase III were found in the elderly female group compared to the young female group ($p < 0.05$). No significant differences were found between either the young and the middle-aged groups or the middle-aged and the elderly groups in male subjects.

6.3.6 Summary of Main Findings

It was found that:-

- forward flexion and lateral flexion are the major components of this lifting simulation in the overall thoracolumbar spine and in the lumbar spine.
- there are consistent patterns of forward flexion and lateral flexion at both speeds of motion and no associated pattern of axial rotation is found during the task.
- the maximum displacement of lateral flexion occurs significantly earlier than maximum forward flexion in all conditions.
- no clear age effects are shown in the ranges of forward flexion and lateral flexion.
- there are variations in the ranges of motion between subjects within the same age group.
- changing the speed of motion has no effect on the nature of the forward flexion, lateral flexion or axial rotation components.
- there are clear age-related changes in angular velocity values for the movements of forward flexion and lateral flexion.
- the young and middle-aged male and female subjects seem to have a greater ability to increase angular velocity in association with the faster speed activity.

- the elderly groups show low values of peak angular velocity in forward flexion and lateral flexion compared to the young and the middle-aged groups.
- the time history of angular velocity for forward flexion and lateral flexion are consistent in all conditions.

6.4 Discussion

6.4.1 Patterns of Movement

The study design, with a prescribed position of the object, was chosen to investigate the kinematics of the spine during a simulation of a functional task in sitting position at different speeds of movement. The main reason in studying the functional task was to investigate an activity combining movements of the spine. The task allowed the subject to perform an unconstrained, multi-axial spinal movement. Due to the standardised position of the object, it is not surprising that there was a consistency in the patterns of movement associated with the lifting simulation in all age groups. Changing the speed of the movement also had no effect on the nature of the composite movements. Therefore, it can be said that components of the movement are related to the characteristics of the task and would be expected to follow a consistent pattern for the task regardless of age or gender.

It is interesting to note that no associated patterns of rotation were detected during picking up or placing the object. It is possible that the subjects used their arms to reach the object instead of twisting with their spine. In addition, study of the patterns of anatomical movements has demonstrated that primary lateral flexion is accompanied by axial rotation to the opposite side (see section 4.4). In this part of the study, the characteristics of the task involved the subject picking an object up with two hands. During lifting phase I, the trunk was expected to rotate towards the left and phase III towards the right. The movement of axial rotation was directed to the same side as lateral flexion. The axial rotation, therefore, was in the opposite direction to that associated with the coupled axial rotation of the primary lateral flexion. The small amplitude movement may have been cancelled out. The movement of axial rotation during lifting was therefore of small amplitude and inconsistent in direction in both the overall thoracolumbar and the lumbar spine.

Ferguson et al. (1992) studied the motion characteristics of the lumbar spine during asymmetric lifting of three different weights in the standing position. In their study, the subject lifted an object from 0 degrees (sagittally symmetric) to the following asymmetric positions; 30, 60, 90, 120, 150 and 180 degrees. Ferguson et al. found that as the lifting condition became more asymmetric, the range of forward flexion decreased and the range of rotation increased, however, the range of rotation was far below the actual asymmetric angle of the task for all three weight levels. Explanations for the small range of rotation might include any combination of the following: movement of the feet, twisting with the hips or pelvis, or reaching with the arms instead of twisting with the back. In Ferguson's study, the ranges of rotation at the asymmetric angle of 30 and 60 degrees were between 10 and 15 degrees. Although the maximum range of axial rotation for each group in the present study was approximately 10 degrees, most subjects demonstrated smaller ranges of rotation (see Table 6.7). It may be that in a seated position, the subject can more easily reach the object compared with the standing position, and can also make more use of the arms.

In this study maximum lateral flexion preceded forward flexion at both speeds of lifting. This may be due to the fact that the available range of lateral flexion during lifting was less than that of forward flexion, therefore lateral flexion would reach the end of range before forward flexion. This may also suggest that the articular surfaces of the apophyseal joints impact in the direction of lateral flexion before forward flexion in this task.

The evidence of this study suggests that forward flexion and lateral flexion are the major components of the combined movement when the target is positioned 45 degrees from the midline in the front. The movement of rotation may be more important when the target is positioned more laterally (between 45 and 90 degrees to the midline).

6.4.2 Range of Motion

The stereotyped nature of the task demanded a consistent response from the subject. Since the task performed in this study did not demand a maximum range of motion and little variation was possible whether at preferred or fast speeds, it is not surprising that no clear age or speeds effects were found in range of the composite movements. However, there were variations in range of motion within age groups. A possible reason for these variations may be due to differences in the lifting technique. Range of spinal motion could be affected by differences in elbow angle during the activity. A more flexed elbow posture during picking up and placing the object would require a greater range of trunk forward flexion to allow the subject to reach the object.

In this part of the study, age-related changes in the ranges of motion were not expected, however the mean values of range of forward flexion in the elderly subjects were less than in the young and middle-aged groups and some significant differences were detected between groups for the range of lumbar forward flexion. Although the MANOVA showed no age effects on range of forward flexion in the thoracolumbar spine, the p value in phase III was close to 0.05. The result suggests that ranges of forward flexion during the lifting decrease with increasing age. This can be explained in two ways. Firstly, the young and middle-aged subjects were confident in their ability to pick the object up and may have a more flexed elbow posture than the elderly subjects. Secondly, some elderly subjects may have an anatomical limitation to trunk flexion as confirmed by the results of the earlier study (see sections 4.1.1, 4.2.1

and 4.3.1). Elderly subjects demonstrated significant decreases in the range of forward flexion compared to the young and the middle-aged groups. Although the statistical analysis demonstrated some significant differences between age groups in the range of lateral flexion during lifting, the differences in the mean values between groups may be too small to be of functional significance (see Table 6.5).

Gender effects on range of forward flexion during the combined movement were similar to those found in the monoplanar anatomical movements. Although the range of forward flexion in the task did not require maximum displacement and therefore was less than the range of the anatomical movements, the male subjects seemed to move their trunk further forward compared to female subjects in the same age group. This may be due to differences in the manner in which the object was grasped. Female subjects may have preferred to reach the object with their arms straight, leading to a reduced range of trunk flexion, while males may have preferred to keep the object closer to their body, necessitating a more flexed trunk.

6.4.3 Angular Velocity

The age effects on the spinal angular velocity values have been discussed previously in section 5.6. In the combined movement activity too, the elderly groups showed lower values of angular velocity compared to the young and middle-aged groups. With respect to the regression analysis (see Tables 6.9, 6.10), the rate of reduction in angular velocity during the fast speed lift was approximately twice that of the preferred speed. This may lead to the conclusion that a reduction in speed of movement is inevitable with advancing age, particularly with the fast movement. The main reasons for this are the changes at the neuromuscular junction, decreases in mitochondrial enzymes and impairment of excitation-contraction coupling in the elderly (Ermini, 1976; Smith and Rosesheimer, 1984). With increasing age, decline in muscle fibre cross-section and muscle mass will also limit force production capability, reaction to rapid stimuli and speed of movement (Adrian and Cooper, 1989). With advancing age, the increase in stiffness of passive tissue elements will increase resistance to the motion. This resistance could also reduce speed of motion in the elderly subjects.

Although age-related changes exist which decrease the overall speed of motion, the velocity/time profile demonstrated a similar pattern of angular velocity for the movements of forward flexion and lateral flexion across age groups. This may support the fact that the subjects who participated in the present study were healthy and normal, and therefore demonstrated normal patterns of velocity. The findings may also suggest that the subjects made up a relatively homogeneous sample.

6.5 Functional Implications

Many activities of daily living are carried out in a seated position and are associated with multiaxial movements of the spine. Epidemiological studies have indicated that lifting and axial rotation are factors associated with an increased risk of low back pain. Increasing the weight of the object lifted and increasing the frequency of lifts are also associated with an increased risk of acute back pain (Andersson, 1981; Kelsey et al., 1984). Kelsey has indicated that lifting while twisting the body should be avoided when possible because there is an increase in the risk of a prolapsed lumbar disc. Adams and Hutton (1981, 1982) have suggested that the chances of back injury are increased when a person bends forward and to the side. Wickström (1978) reported that harmful effects on the spine have been associated with deep forward flexion (greater than 70 degrees) rather than with slight or moderate degrees of forward flexion. Moderate ranges of forward flexion (30 to 40 degrees) have been found to increase the nutrition of the lumbar disc, whereas deep forward flexion, performed repeatedly over a prolonged period, influences disc nutrition negatively (Sairanen et al., 1981; Nordin et al., 1984). However, Adams and Hutton (1985, 1986) found that large amplitude of forward flexion and extension of lumbar spine were associated with maximum fluid transfer in and out of the disc.

No studies have quantified the relative forward flexion, lateral flexion and axial rotation of the spine during the performance of a functional activity while seated. This part of the study reported the movement patterns which were observed during a simulated lift of a light object. The findings of this study suggest that the movements of forward flexion and lateral flexion are the major components when the object to be lifted is positioned at 45 degrees to the midline. Since axial rotation was limited in the task, the attributes of this task activity could be desirable in the work situation. Risk factors and the incidence of work-related back problems may be reduced. It may be that the lack of axial rotation of the spine is compensated for by the use of the arms, however since shoulder motion was not measured in this study, this solution is speculative.

It would be erroneous, however, to draw too many conclusions from this study with respect to material handling in work-related situations. The characteristics of the movement and the age effects associated with the task may have been quite different if the subjects were physically challenged by a real load in the box or if the load was bulky.

Farfan (1973) has suggested that maximum shear load on the intervertebral disc occurs with torsion, since many of the fibres are maximally loaded in tension during twisting activities. This has been verified in vivo where forward flexion combined with axial rotation was seen to increase intradiscal pressure (Andersson, 1985), shear forces and compression forces (Mital and Kromodihardjo, 1986) as well as moments of force (Gagnon et al., 1993). Given the limited axial rotation associated with this study, positioning the object between 45 degrees to the left and the right of the median sagittal plane of the subject may optimise the lift and reduce shear load on the intervertebral disc.

The data reported in this study represent the kinematic demands on the spine during a simulated seated lift in normal subjects. Such a comparative study might provide useful insights into the nature of functional impairment associated with low back pain. Future research using different positions of the object may elicit different composite movement patterns, paticularly with respect to forward flexion and axial rotation. Such research may help in the development of lifting guides to optimise back motion which may prevent low back injuries when lifting objects in a seated position.

CHAPTER 7

CONCLUSION

The results of this study [illegible] age-related decreases in the ranges and angular velocities of spinal motion. In comparison of the three age groups, there were significant differences in the ranges and angular velocities of three movements in all trunk segments with the exception of the range of lumbar rotation. Differences were demonstrated between the movement characteristics of the young and the elderly groups. The results of this study, therefore rejected the hypotheses that there were no differences in range of motion, peak or average angular velocity among the young, middle-aged and the elderly groups. In addition, the hypotheses of no correlations between age and range of motion, age and peak and average angular velocity in male or female subjects have also been rejected in the present study.

The directions of most marked reduction in range were different between the lower thoracic and lumbar spine. However, there was no clear evidence for the age of onset of the changes in any of the trunk segments. It was found in this study that, with advancing age, loss of spinal range of motion is not so inevitable phenomenon and may be related to the level of functional activity demonstrated by the subjects. This means that with increasing age, range of spinal motion may be maintained and could be responsive to the requirements of daily activities. On the other hand, it could be inferred that a reduction in speed of motion is an inevitable consequence of ageing.

The reliability of the protocol using the *Motion Analysis ExpertVision™* four camera system for data collection has been thoroughly established through this study. It is believed that the data reported in the present study demonstrate accurate findings. Using skin markers, motion of the skin will inevitably affect the relationships between the motion of the markers and the kinematics of the spine. However, the methods used in the present study were accurate and reasonable to measure motion of the

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The reasons for the non significant differences in the range of lumbar rotation between the elderly groups and the young/middle-aged groups should be more thoroughly investigated. The amount and intensity of physical activity might affect the changes in spinal kinematics in the elderly. The selection of active elderly subjects would tend to limit the differences in range of motion between the age groups. Greater differences in the mean values of the range may be achievable in a less active group of elderly subjects. It would therefore be interesting to compare the differences in kinematics of the spine between active and inactive elderly people.

The results of this study rejected the hypotheses that there would be no differences in range of motion, or in peak and average angular velocities between male and female subjects. Male subjects demonstrated a greater range of maximum forward flexion and rotation compared to female subjects in the same age group in the overall thoracolumbar and the lumbar spine. Male subjects showed a reduction in the range of lateral flexion in the lower thoracic spine compared to females. Male subjects generally showed a higher value for angular velocity than female subjects of the same age in the overall thoracolumbar and the lumbar spine. The hypotheses that there would be no differences in range and angular velocity values derived from the preferred and fast speeds of movement have also been rejected. There is a general trend towards a decreasing range of lateral flexion and increasing range of rotation with the faster speed of movement in all trunk segments.

The similarity of normal time-history of the patterns observed across the range of age groups and genders in this study was remarkable in each trunk segment. Age, gender and speeds of motion had no clear effects on the nature of the movements. The study also revealed differences in amplitude and patterns of associated movements between the lower thoracic and the lumbar spine which have not previously been reported. The hypothesis that no differences between the patterns of movement derived from the lower thoracic and the lumbar spine has been rejected. It is likely that the differences in patterns of associated anatomical movements reflect the different functions and architecture of the vertebral column as well as the mechanism of movements in each region of the spine.

Due to the consistency of normal patterns of movement, it would be interesting to investigate the movement characteristics in patients with back pain or some specific spinal disorders. A spinal disorder rather than only affecting the range of motion may be primarily manifested by the patterns or rate of change of the movements. The three dimensional data might exhibit diagnostic abnormalities of range or pattern of the coupled motion.

During a simulated lifting task, designed to study the interactions of a multiaxial trunk motion, the movements of forward flexion and lateral flexion were found to be the major movement components when the target object was positioned at 45 degrees to the midline. A small amplitude of rotation was detected during performance of the task. Future research using a weighted target object in a range of positions could help in developing stategies to prevent low back injury during lifting by controlling back motion.

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APPENDICES

CONTENTS

APPENDIX A.

Subject Information Sheet

The investigation of age-related changes in three-dimensional kinematics of the spine

You are invited to participate in a study to be conducted in the Biomechanics Laboratory (H.112), Faculty of Health Sciences, the University of Sydney. The purpose of this study is to investigate the movements of the back during trunk movements, and may assist in understanding the demands placed upon the spine during everyday activities. This study will comprise the following movements: forward bending, side bending, rotation, and a combination of movements for lifting an object.

If you agree to participate in the study, you will be required to attend for one test at the Biomechanics Laboratory. The date of the tests will be arranged at a time convenient for you. The entire procedure is non-invasive, involves no discomfort in any form, and consists of video-filming while you move your trunk. In order to locate body segments, a number of markers will be attached to your back with adhesive tape. It would be helpful if you could wear either a swimsuit or shorts and a singlet for the test. The lab will be secured during the testing and your privacy will be respected; only researchers will be present.

Prior to testing you will be asked to sign a consent form which gives your agreement to take part in this study. You will also be interviewed by the researcher. The questions asked are designed to give information about your physical activities and general health. You will then be asked to perform a number of simple movements while sitting. All of these movements will be performed by yourself and will involve no forced movements. The entire procedure should not take longer than 30 minutes to complete.

You should not participate in this study if you are presently suffering back or lower limb pain or have experienced such pain in the previous six months. Age is no barrier to participation; indeed a broad selection of ages is required to fulfil the aims of this study.

If you agree to participate in the study you should understand that you are free to withdraw at any time without in any way affecting your relationship with the researchers, the Faculty of Health Sciences or the University of Sydney. All information collected will be stored in a coded form and your identity will remain confidential. Videofilm will not show the features of test subjects and will not be saved except in digital form on the computer. While the results of the study may be published, no individual will be identified in any way. Please feel free to ask the researchers if at any time you have any questions about any aspect of the study.

Thank you for agreeing to participate in this study.

Further information: Contact

Roongtiwa Vachalathiti, School of Physiotherapy 646-6549

Jack Crosbie, School of Physiotherapy 646-6549

Richard Smith, Department of Biological Sciences 646-6462

The University of Sydney
Faculty of Health Sciences

APPENDIX B.
Informed Consent

FACULTY OF OF HEALTH SCIENCES

INFORMED CONSENT

I, ______________________________ hereby voluntarily consent to participate in the research entitled:

____

____

conducted by: Roongtiwa Vachalathiti

I understand that the information obtained from this research may be used in future research, and may be published. However, my right to privacy will be retained, i.e. personal details will not be revealed.

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

I acknowledge I have the right to question any part of the procedure and can withdraw at any time without this being held against me.

I have been familiarized with the procedure.

Signed by Subject ______________________

Date ____________________________

Witness ____________________________ (Name)

____________________________ (Signature)

____________________________ (Date)

Cumberland College of Health Sciences
East Street (PO Box 170) Lidcombe NSW Australia - Phone 61 2 646 6444 - Fax 61 2 646 4853

APPENDIX C.

Subject Data Collection Sheet

(Completed by researcher)

Subject's code___________________________, Age_________years, Sex : M/F

Weight________Kg., Height________cm.

Occupation _ student _ retired _ ___________________________

____

History of Physical Activities

1. How physically active has subject been in the past six months?

_ inactive _ moderately active _ very active

2. What are subject's normal activities of daily living and how much time does he/she spend on them per week?

_ housework _________hours/week

_ gardening _________hours/week

_ walking ___________hours/week

_ other ____hours/week

_ other ____hours/week

_ other ____hours/week

3. Does subject take any exercise or participate in any activity besides daily activities?

_ no

_ yes: please describe ____________________________________

: how often/week ____________________________________

4. Does subject regularly engage in strenuous exercise or hard physical labor?

_ no _ yes (if yes: please answer No.5)

5. Does subject exercise or work hard at least three times per week?

_ no _ yes

6. Does subject have any problem of limitation of movement during daily activities?

_ no

_ yes: _ upper extremity

_ lower extremity

_ back

_ other________________________________

_ other________________________________

7. Does subject have difficulties in performing daily activities?

_ no

_ yes: please describe ________________________________

____

____

Medical History

1. Has subject presently or has subject had any problems in the following lists?

_ high blood pressure	_ none	_ previous	_ present
heart problem	_ none	_ previous	_ present
_ kidney problem	_ none	_ previous	_ present
_ diabetes	_ none	_ previous	_ present
_ urinary incontinence	_ none	_ previous	_ present
_ dizziness	_ none	_ previous	_ present
_ other______________	_ none	_ previous	_ present
_ other______________	_ none	_ previous	_ present
_ other______________	_ none	_ previous	_ present

2. Has subject taken any kind of prescription drugs regularly?

(if yes, please give the name of the drug)

_ no

_ ________________ _ previous _ present

_ ________________ _ previous _ present

_ ________________ _ previous _ present

_ ________________ _ previous _ present

3. Did subject fall during the previous year?

_ no

_ yes: No. of falls 1, 2, 3, 4, 5, or more than 5 times

: please describe the causes of falls

_ tripping _ loss of balance

_ fainting (or feeling faint) _ after rising

_ giddiness _ turning head

_ other ________________________

_ other ________________________

4. Has subject presently or has subject had any problems with joint pain?

_ cervical _ none _ previous _ present

_ thoracic _ none _ previous _ present

_ lumbar _ none _ previous _ present

_ hip _ none _ previous _ present

_ knee _ none _ previous _ present

_ other __________ _ none _ previous _ present

_ other __________ _ none _ previous _ present

_ other __________ _ none _ previous _ present

5. Has subject had any previous back pain with/without leg pain?

_ no

_ yes (if yes, please answer the following questions)

6. When was the first time subject had back pain, how severe was the pain and how long did it last?

_ ________, _ mild _ moderate _ severe

_ ________days, ________weeks, ________months.

note : ____

7. How often after the first time did the pain recur yearly?

_ 1, 2, 3, 4, 5, or more than 5 times.

8. When was the last time subject had back pain, how severe was the pain and how long did it last?

_ ________, _ mild _ moderate _ severe

_ ________days, ________weeks, ________months.

note : ____

9. During the period of back pain, how were subject's lifting activities?

_ can lift heavy weights without extra pain.

_ can lift heavy weights but it gives extra pain.

_ pain prevents from lifting heavy weights off the floor, but can manage if they are conveniently positioned, e.g. on a table.

_ pain prevents from lifting heavy weights but can manage light to medium weights if they are conveniently positioned.

_ can lift only very light weights.

_ cannot lift or carry anything at all.

note : ____

10. Has subject received any treatment during the period of back pain?

_ no treatment : normal activity of daily living (ADL)

_ no treatment : rest _ heat

_ pain killers _ back support

_ back care education _ exercise

_ manipulation and mobilisation _ other medication ____________

_ other ____

11. How beneficial were the treatments?

	help	no help	made worse
_ no treatment : normal ADL	______	______	______
_ no treatment : rest	______	______	______
_ pain killers	______	______	______
_ back care education	______	______	______
_ manipulation & mobilisation	______	______	______
_ heat	______	______	______
_ back support	______	______	______
_ exercise	______	______	______
_ ____________________	______	______	______
_ ____________________	______	______	______

12. Has subject had any previous injury producing back or leg pain?

_ no

_ yes : when ____

: type of injury ___________________________________

13. Does subject's back allow his/her to do more now than when he/she had back pain with/without leg pain?

_ no

_ yes : ____

note : ____

Subject's code___________, Age _______years, Sex : M/F, Activity __________

Current Level of Physical Activity	always	often	sometimes	never
a. Does subject walk rather than ride whenever possible?	4	3	2	1
b. Does subject exercise more than once a week?	4	3	2	1
c. Does subject make time to exercise?	4	3	2	1
d. Does subject use the stairs rather than lifts or escalators?	4	3	2	1
e. Does subject have a formal exercise plan that subject follow?	4	3	2	1
f. Does subject find time to do something active every day?	4	3	2	1
g. After work or during the day, is subject physically active instead of watching television?	4	3	2	1
h. Does subject participate in any sport at least once a week?	4	3	2	1

Scores : Activity : a_____+ d_____+ f_____+ g_____ = _____

Exercise: b_____+ c_____+ e_____+ h_____ = _____

APPENDIX D.

Experiment I

Estimation of Measurement Error under Static Conditions

Aims 1) To assess the reliability of static measurement by the ExpertVision™ system compared to known marker location.

2) To evaluate the stability of the data over time.

Procedure

Prior to the experiment, the cameras were calibrated using the calibration frame as described in section 3.5.1. The position of the cameras has been previously explained (section 3.5). To compare the system-calculated coordinates (X,Y,Z) and the coordinates of the control points (reference coordinates), five spherical, 2.5-cm-diameter retroreflective markers on the calibration frame were filmed. Data were collected for 1 second at 60 Hz to yield 60 data points for each marker. This procedure was repeated four times at 0 minute, 15 minutes, 30 minutes and 60 minutes respectively without moving the calibration frame.

Data Analysis

The ExpertVision™ software programme was used to calculate X,Y, and Z coordinates from the five markers. For each 1-second trial, the mean system-calculated values of the 60 data points was obtained. The differences between the coordinates of the reference markers and the average mean system-calculated coordinates were calculated for each marker. An error in each of the three coordinate values is calculated as a percentage of total range of camera view.

Separate correlation coefficients were calculated for each of the X,Y, and Z coordinates as well as for each of the four different times. The mean inter-trial variability for four trials at each X,Y, and Z coordinate was then calculated by averaging those standard deviation values across the four different times. Linear regressions using the mean system-calculated values and the reference values were also calculated for each of the coordinates and times.

Results

Mean system-calculated coordinates and their standard deviation for each marker at different times are presented in Tables D.1-D.3. The correlation coefficient "r" of the mean system-calculated values with respect to the reference values exceeded 0.99 for each of the X, Y, and Z coordinates. This demonstrated that the system was consistent in calculating positon from the reflective markers. Slopes of the linear regression equations comparing the average mean system-calculated position and reference position were 1, 1, and 0.822 for coordinates X, Y, and Z respectively.

Table D.1 Means (S.D) of system-calculated values (mm.) for each reference X-coordinate at different times.

Marker No.	Reference X value	0 min.	15 min.	30 min.	60 min.	Average
1.	499.0	499.19 (0.16)	499.20 (0.10)	499.17 (0.14)	499.19 (0.12)	499.19 (0.01)
2.	986.6	985.71 (0.32)	985.69 (0.37)	985.69 (0.26)	985.74 (0.32)	985.71 (0.02)
3.	493.9	493.63 (0.15)	493.64 (0.12)	493.66 (0.15)	493.63 (0.11)	493.64 (0.01)
4.	7.9	8.47 (0.35)	8.49 (0.39)	8.45 (0.33)	8.48 (0.37)	8.47 (0.02)
5.	500.2	496.88 (0.21)	496.88 (0.15)	496.87 (0.18)	496.87 (0.17)	496.88 (0.006)

Table D.2 Means (S.D) of system-calculated values (mm.) for each reference Y-coordinate at different times.

Marker No.	Reference Y value	0 min.	15 min.	30 min.	60 min.	Average
1.	10.8	10.91 (0.13)	10.90 (0.14)	10.96 (0.13)	10.91 (0.15)	10.92 (0.03)
2.	501.2	500.58 (0.49)	500.66 (0.47)	500.60 (0.55)	500.54 (0.46)	500.59 (0.05)
3.	988.5	988.17 (0.26)	988.19 (0.28)	988.22 (0.26)	988.16 (0.26)	988.19 (0.03)
4.	495.4	495.37 (0.18)	495.37 (0.22)	495.34 (0.23)	495.35 (0.18)	495.36 (0.02)
5.	500.3	504.14 (0.23)	504.10 (0.15)	504.05 (0.14)	504.06 (0.13)	504.09 (0.04)

Table D.3 Means (S.D) of system-calculated values (mm.) for each reference Z coordinate at different times.

Marker No.	Reference Z value	0 min.	15 min.	30 min.	60 min.	Average
1.	36.5	36.34 (0.13)	36.33 (0.11)	36.35 (0.11)	36.34 (0.10)	36.34 (0.008)
2.	36.3	35.98 (0.37)	35.99 (0.35)	36.06 (0.27)	35.99 (0.27)	36.01 (0.04)
3.	36.5	36.33 (0.11)	36.34 (0.12)	36.34 (0.11)	36.33 (0.11)	36.34 (0.006)
4.	38.8	38.82 (0.18)	38.89 (0.17)	38.86 (0.13)	38.88 (0.17)	38.86 (0.03)
5.	38.0	38.42 (0.19)	38.43 (0.11)	38.49 (0.11)	38.46 (0.11)	38.45 (0.03)

Table D.4 Differences (mm.) between X, Y and Z coordinates of the reference markers and the average mean system-calculated values (% of field of camera view).

Marker No.	Coordinates X (%)	Coordinates Y (%)	Coordinates Z (%)
1	0.19 (0.009)	0.12 (0.006)	0.16 (0.008)
2	0.89 (0.044)	0.61 (0.031)	0.29 (0.015)
3	0.26 (0.013)	0.31 (0.015)	0.16 (0.008)
4	0.57 (0.028)	0.04 (0.002)	0.06 (0.003)
5	3.32 (0.166)	3.79 (0.189)	0.45 (0.023)
X	1.05 (0.052)	0.97 (0.049)	0.22 (0.011)

Table D.5 Mean Inter-trial variability (mm.) across four different times for each X,Y, and Z coordinates.

Marker No.	Coordinates X	Coordinates Y	Coordinates Z
1.	0.13	0.14	0.11
2.	0.32	0.49	0.32
3.	0.13	0.27	0.11
4.	0.36	0.20	0.16
5.	0.18	0.16	0.13

Differences between the coordinates of the reference markers and the average mean system-calculated coordinates are shown in Table D.4. The range of error in detecting the position of each marker with respect to the cube's origin was between 0.04 and 0.89 millimetres. For a camera view of 2 metres, the percentages of average measurement errors were 0.05% for x, y coordinates and 0.01% for z coordinate. Only one marker (marker 5) displayed an error value of more than one millimetre for x and y coordinates [Table D.4]. This may be that marker 5 was not seen by the camera as a sphere or the centre of the sphere may have been offset, leading to an apparent movement of the marker.

The mean inter-trial variability for each coordinate is presented in Table D.5. These values are generally less than 0.5 millimetre. Although the slope of the linear regression of the Z coordinate was less than that of the X and Y coordinates, the difference in reference values and system-calculated values was between 0.06 and 0.45 millimetres, i.e. the Z axis magnitudes in absolute terms were very small.

From this experiment it can be concluded that the Motion Analysis ExpertVision™ system was accurate in measuring the position of static markers in the calibrated volume. No significant variation was found over time within 60 minutes. The average measurement error in each of the three coordinate axes was approximately 1 millimetre. However, each marker must be accurately visualised as a sphere by at least two cameras, particularly during the calibration process. Otherwise the accuracy of the system may be affected as shown by the results of marker number 5.

Experiment II

Angle Comparison between ExpertVision System and Computed Euler Angles

Eulerian geometry was used to compute relative motion between the spine and pelvis with respect to three independent rotations about each axis. In order to determine the accuracy and reliability of the ASYST programme which computed angular displacement (West, 1992), an experiment was conducted to simulate movements of the trunk about the three axes of rotations.

The aim of this study was to compare the accuracy of angle computation between the absolute angle calculated within the ExpertVision™ software and Euler angles calculated from the 3D coordinate data.

Procedure

Prior to the experiment, the system was calibrated. A model consisting of two pieces of hinged board representing a simple model of the trunk was assembled with eight retroreflective markers firmly attached. The boards were hinged to move in 3 planes at ∗. [Figure D.1]. The dimensions of the model were similar to those of a normal human trunk.

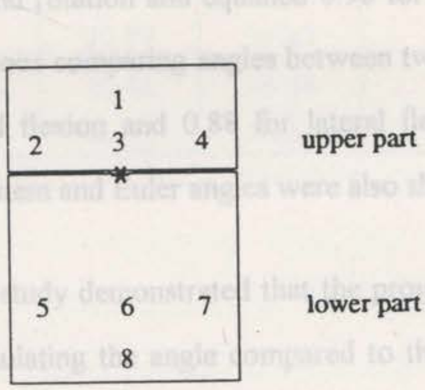


Figure D.1 Position of markers on the model.

The upper part of the model was moved in three directions; forward flexion, lateral flexion to left and right, and rotation to left and right, while the lower part was fixed. The model was moved to different angles in each direction; approximately 30, 45 and 60 degrees for forward flexion, 20 and 30 degrees for lateral flexion, and 30 and 45 degrees for rotation. Data were collected at a frequency of 60 Hz for a period of 10 seconds in each test. Automated digitisation and realisation of three dimensional coordinates of the eight markers was performed by the system.

Data Analysis

The angular displacement of the model was computed using the ExpertVision 'angle' software and by Eulerian geometry. The angular displacement calculated from the Euler angles was a dependent variable and from the ExpertVision was an independent variable. Separate correlation coefficient and linear regression values using Eulerian and system-calculated angles were derived for each of the three movements. The differences of the angle values between the two methods were also calculated.

Results

The angles obtained from the two methods are presented [Table D.6]. The correlation coefficient of the system-calculated angles and the Euler angles exceeded 0.99 for forward flexion and rotation and equalled 0.98 for lateral flexion. Slopes of the linear regression equations comparing angles between two methods were 0.99 for rotation, 0.98 for forward flexion and 0.88 for lateral flexion. The differences in angles computed by the system and Euler angles were also shown in Table D.6.

The results of this study demonstrated that the programme to compute Euler angles was reliable in calculating the angle compared to the ExpertVision software. The concordance of the angle computation was ± 0.14 degree for rotation, ± 0.45 degree for forward flexion and ± 2 degrees for lateral flexion.

Table D.6 Angular displacement (degrees) calculated from ExpertVision (EV) system and Euler angles.

Movement	Test No.	EV	Euler	EV-Euler (degrees)
Forward flexion	1	32.39	32.02	0.37
	2	31.49	31.12	0.37
	3	32.26	31.81	0.45
	4	47.24	47.08	0.16
	5	47.76	47.54	0.22
	6	47.81	47.65	0.16
	7	62.13	62.04	0.09
	8	62.02	61.97	0.05
	9	62.42	62.35	0.07
L.lateral flexion	1	19.58	18.32	1.26
	2	19.26	17.97	1.29
	3	28.75	26.66	2.09
	4	29.16	28.15	1.01
R.lateral flexion	1	24.33	25.57	-1.24
	2	22.69	23.57	-0.88
	3	34.17	35.25	-1.08
	4	33.46	34.67	-1.21
L.rotation	1	28.86	28.86	0
	2	31.95	31.98	-0.03
	3	46.89	46.91	-0.02
	4	46.96	46.98	-0.02
R.rotation	1	30.54	30.47	0.07
	2	29.99	29.85	0.14
	3	46.48	46.48	0
	4	46.62	46.63	-0.01

Experiment III

Skin Movement during Axial Rotation

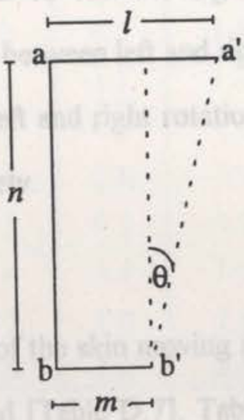
In the present study, markers were placed over the spinous processes of the vertebrae as there is less movement of the skin over the underlying bony prominences. However, the relationship between motion of the markers and the kinematics of the spine may still be affected by the motion of the skin. The errors in measuring range of forward flexion and lateral flexion using skin markers have been reported (Gracovetsky et al., 1990). During rotation, the skin is drawn across the back, displacing the marker from the spinous process, leading to an apparent angle of lateral flexion towards the same side as rotation. It is then pertinent to examine movements of the skin over the spinous process during rotation.

The aim of this experiment was to estimate the distances of the skin over the spinous processes and calculate the apparent angles of lateral flexion during rotation to the left and right in a seated position.

Procedure

The test group consisted of 10 healthy male subjects with no history of back pain in the previous six months. The mean age was 37.7 years, with the range from 27 to 53. The mean height was 174 cm (bewteen 157 and 182 cm) and the mean weight was 71 kg (from 53 to 83 kg).

Each subject sat upright on a stool with both arms crossed over his chest and was secured to the stool by two broad nylon straps, one over the thighs and one around the pelvis. The spinous processess of the 7th cervical, the 6th thoracic, the 12th thoracic and the 5th lumbar vertebrae were identified with skin markers. The subject was then asked to turn his head and trunk together as far as possible to the left, then to the right. Points were marked again at the spinous processes of the aforementioned vertebrae at the end of the range of rotation. There were three dots at each of the levels of C7, T6, T12 and L5. Distances between dots at the neutral position and the end of range were measured for both sides using vernier calipers (sensitivity ± 0.05 mm). Distances between the spinous processes of C7 and T6, T6 and T12, and T12 and L5 were also measured.



$$\theta = \tan^{-1}\frac{l-m}{n}$$

<u>Figure D.2</u> Diagram representations of an angle (θ) occurring from movements of the skin in the upper thoracic spine during right rotation.

In order to calculate the angle associated with movement of the skin, the displacements of the skin during rotation to the left and right and the distances between the adjacent vertebrae were used. The following method was used to calculate an apparent angle at the upper thoracic spine [Figure D.2]. a and b are mark the spinous processes of the 7th cervical and the 6th thoracic vertebrae at the neutral position, and a′ and b′ mark the end of range of right rotation. l and m are distances of the skin movement over the spinous processes of C7 and T6 respectively. n is the distance from the spinous process of C7 to T6. θ is the angle associated with movement of the skin during right rotation which is $\tan^{-1}((\mathbf{l}-\mathbf{m})/\mathbf{n})$. The apparent angles of lateral flexion associated with left and right rotation in the upper thoracic, lower thoracic and lumbar spinal segments were calculated for each subject.

Data Analysis

The means and standard deviations of movements of the skin over the spinous processes of C7, T6, T12 and L5 were calculated for the left and right rotation. Means and standard deviations of apparent angles in the upper thoracic, lower thoracic and the lumbar spine were also calculated during rotation to both sides. A paired t-test was used to test for significant differences in the mean values of movements of the skin between left and right rotation at each level as well as angles of lateral flexion during left and right rotation in the upper thoracic, lower thoracic and lumbar spine respectively.

Results

The distances of the skin moving across the midline during rotation to the left and right are presented [Table D.7]. Table D.8 shows the apparent angles of lateral flexion in the upper thoracic (C7-T6), lower thoracic (T6-T12) and the lumbar spine (T12-L5) during rotation to the left and right.

Table D.7 Skin distances (mm.) at the spinous processes of C7, T6 and T12 for left and right rotation.

Subjects	C7		T6		T12	
	Left	Right	Left	Right	Left	Right
1	10.7	9.9	7.2	8.0	6.0	5.5
2	11.0	10.9	9.3	7.5	5.7	6.4
3	9.4	8.8	8.8	7.1	5.5	4.2
4	10.2	10.1	9.2	7.6	6.0	4.9
5	9.6	8.5	8.8	6.8	6.0	4.2
6	13.0	9.6	10.5	7.7	6.0	5.0
7	10.3	9.4	6.0	8.5	5.8	5.3
8	9.5	10.3	8.5	6.7	4.8	6.0
9	10.0	11.5	9.2	8.5	6.4	5.5
10	10.2	12.5	8.5	8.7	6.5	5.8
$\overline{X}$	10.4	10.2	8.6	7.7	5.9	5.3
S.D.	1.0	1.2	1.2	0.7	0.5	0.7

Table D.8 Apparent angles of lateral flexion (degrees) in the upper thoracic (C7-T6), lower thoracic (T6-T12), and the lumbar spine (T12-L5) for left and right rotation.

Subjects	C7-T6		T6-T12		T12-L5	
	Left	Right	Left	Right	Left	Right
1	1.2	0.7	0.5	1.1	2.7	2.4
2	0.7	1.4	1.4	0.4	2.3	2.5
3	0.2	0.7	1.4	1.3	2.0	1.6
4	0.4	1.1	1.3	1.1	2.5	2.1
5	0.3	0.6	1.1	1.0	2.3	1.6
6	0.8	0.6	1.9	1.2	2.1	1.8
7	1.5	0.3	0.1	1.5	2.2	2.0
8	0.4	1.4	1.6	0.3	1.9	2.3
9	0.3	1.0	1.1	1.2	2.5	2.2
10	0.6	1.4	0.8	1.2	2.5	2.3
$\overline{X}$	0.6	0.9	1.0	1.0	2.3	2.1
S.D.	0.4	0.4	0.5	0.4	0.3	0.3

Movements of the skin over the spinous processes varied between 8.5 and 13.0 millimetres at C7, 6.0 and 10.5 at T6, and 4.2 and 6.5 at T12. No movements of the skin over the 5th lumbar spinous process were detected in any subject. The maximum errors obtained from movements of the skin were 13, 10.5 and 6.5 millimetres at C7, T6 and T12 respectively and the greatest angles were 1.5, 1.9 and 2.7 degrees for the upper thoracic, lower thoracic and the lumbar spine respectively. No significant differences were found between left and right sides either in movements of the skin or angles at any level of the spine ($p > 0.05$).

The results of this study demonstrated that the error, introduced by movement of the skin relative to underlying bony structures, produced apparent angles of lateral flexion of approximately 1, 1 and 2 degrees in both directions in the upper thoracic, lower thoracic and lumbar spine respectively.

Experiment IV

Determination of Reaching Distance

The aim of this experiment was to determine the position of the object for the lifting simulation. Lifting and placing an object is an activity often seen in certain work practices which involve movements of the spine. It has been reported that flexibility of the spine is related to the subject's height (Batti'e et al., 1987). A taller person may have less difficulty reaching their toes. In order to eliminate the differences between subjects' height which could influence the reaching distance during lifting, the position of the object needs to be standardised. An experiment was conducted to simulate the movements of the lifting in a direction 45 degrees to the median plane of the subject in a seated position.

Procedure

The test group consisted of 20 healthy volunteer subjects (10 males and 10 females) with no recent history of back pain. Their mean age was 36.6 years for males and 36.1 years for females, with a range from 21 to 44. The mean height was 170 cm for males and 157 cm for females and the mean weight was 69 kg and 54 kg for male and female subjects respectively.

Subjects sat upright on a stool. Two lines were drawn on the floor in a direction 45 degrees to the mid line from the front legs of the stool to the left and right. The subject was asked to reach to the left and right, with both arms straight, along the direction of the lines. The subject was instructed to reach as far as possible and stop when his/her bottom start lifting from the stool. After reaching to the left, the subject was asked to return to the neutral position, then, to reach to the right. Reaching distances were recorded using a tape measure.

Data Analysis

To determine the relationship between reaching distance and height, the ratio of reaching distance to the left and right sides to total height were calculated for each subject. The means and standard deviations of the ratio were also calculated for the male and female groups. A paired t-test was used to test for significant differences in the mean values of the ratio between left and right sides in each group and an independent t-test for the mean values of the ratio between male and female groups.

Results

Tables D.9 and D.10 show the reaching distance to the left and right sides in the sitting position. The percentages of the mean ratio of the reaching distance to height in male and female subjects are also reported.

Table D.9 Reaching distance (cm.) and the ratio of reaching distance to height (%) in male subjects.

Subject	Left distance	Right distance	L. distance/Ht (%)	R. distance/Ht (%)
1	35	27	20.83	16.07
2	23	23	14.11	14.11
3	41	41	20.19	20.19
4	35	30	21.60	18.52
5	22	20	13.33	12.12
6	30	33	16.85	18.54
7	23	25	14.56	15.82
8	36	40	21.30	23.67
9	22	35	13.58	21.60
10	28	25	16.47	14.71
$\overline{X}$	29.50	29.90	17.28	17.54
S.D.	6.95	7.17	3.39	3.61

Table D.10 Reaching distance (cm.) and the ratio of reaching distance to height (%) in female subjects.

Subject	Left distance	Right distance	L. distance/Ht (%)	R. distance/Ht (%)
1	34	33	19.10	18.54
2	25	22	16.45	14.47
3	35	34	23.03	22.37
4	30	30	19.74	19.74
5	25	23	16.67	15.33
6	28	22	16.97	13.33
7	23.5	24	15.26	15.58
8	27	31	17.53	20.13
9	25	23	16.45	15.13
10	28	33	17.50	20.63
$\bar{X}$	28.05	27.50	17.87	17.53
S.D.	3.90	5.10	2.24	3.11

Reaching distance varied between 12.12 and 23.67 cm in male subjects and in the range of 13.33 to 23.03 cm in female subjects. It is interesting to see that the mean ratio was approximately 17% in all conditions. No significant differences were found between these ratios in either left or right side or genders ($p > 0.05$). It can be noted that regardless of gender the distance is proportional to the height. Therefore, in the lifting simulation of this study the distance of the object from the front leg of the stool was set at 17 percent of the height of each subject.

APPENDIX E.

Pattern of Lateral Flexion in the Elderly Subject

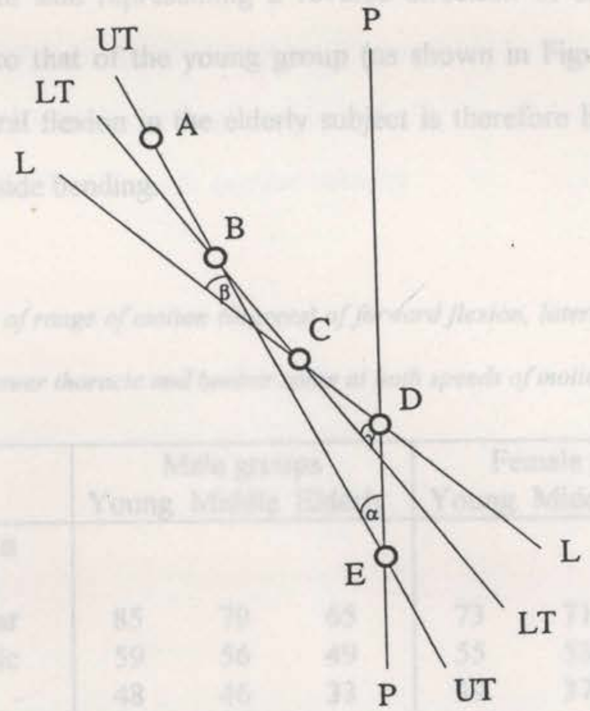


Figure E.1 Geometrical representation of angulation in the thoracolumbar (α), lower thoracic (β) and lumbar spine (γ) during lateral flexion in the elderly group.

The line, UT, joining markers at C7 (A) and T6 (B) represents the vector of the upper thoracic segment. The line, LT, joining markers at T6 (B) and T12 (C) represents the vector of the lower thoracic segment. The line, L, joining markers at T12 (C) and L5 (D) represents the vector of the lumbar segment. The line, P, joining markers at L5 (D) and sacrum (E) represents the vector of the pelvic segment. The angle of the thoracolumbar spine (α) is the angle between UT and P. The angle of the lower thoracic spine (β) is the angle between UT and L. The angle of the lumbar spine (γ) is the angle between LT and P.

In the elderly groups, range of lateral flexion in the thoracolumbar spine was equal to or less than that in the lumbar spine [Table E.1]. To demonstrate the pattern of movement in the elderly group, Figure E.1 shows the angle of lateral flexion at the thoracolumbar (α), lower thoracic (β) and the lumbar spine (γ) which α is less than γ. The upper thoracic segment of the elderly subject, segment AB, tends to move towards the opposite side representing a reverse direction of side bending of the segment compared to that of the young group (as shown in Figure 3.10, page 50). The patterns of lateral flexion in the elderly subject is therefore like swaying to one side instead of fully side bending.

Table E.1 Mean values of range of motion (degrees) of forward flexion, lateral flexion and rotation in the thoracolumbar, lower thoracic and lumbar spine at both speeds of motion.

Movements	Male groups			Female groups		
	Young	Middle	Elderly	Young	Middle	Elderly
Forward flexion						
Preferred speed						
Thoracolumbar	85	79	65	73	71	66
Lower thoracic	59	56	49	55	53	50
Lumbar	48	46	33	39	37	32
Fast speed						
Thoracolumbar	86	80	65	73	70	65
Lower thoracic	60	57	49	55	53	50
Lumbar	49	47	33	39	37	31
Lateral flexion						
Preferred speed						
Thoracolumbar	69	66	50	73	69	50
Lower thoracic	47	42	29	56	49	31
Lumbar	66	63	53	66	62	49
Fast speed						
Thoracolumbar	68	63	48	66	66	47
Lower thoracic	47	40	28	52	48	31
Lumbar	63	59	52	59	58	46
Rotation						
Preferred speed						
Thoracolumbar	79	77	63	75	73	52
Lower thoracic	36	30	20	36	33	16
Lumbar	44	46	42	38	40	36
Fast speed						
Thoracolumbar	89	83	66	83	78	54
Lower thoracic	38	31	20	39	34	16
Lumbar	50	50	44	42	43	38

APPENDIX F.

Data for Range and Angular Velocity of Anatomical Movements

Tables F.1-F.9 MANOVA for range of motion

Tables F.10-F.18 MANOVA for average angular velovity

Tables F.19-F.33 MANOVA for peak angular velocity

Table F.1 Multivariate Analysis of Variance for range of forward flexion in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	84.869	14.368	15	76.913	92.826
middle-aged	79.119	11.376	15	72.819	85.419
elderly	65.183	9.950	16	59.880	70.485
FEMALE					
young	73.162	8.211	20	69.319	77.005
middle-aged	70.784	12.110	18	64.762	76.807
elderly	65.856	6.381	16	62.455	69.256
For entire sample	72.938	12.362	100	70.485	75.391

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	85.643	12.753	15	78.580	92.705
middle-aged	79.929	11.573	15	73.520	86.338
elderly	65.016	10.652	16	59.339	70.692
FEMALE					
young	73.176	11.141	20	67.962	78.390
middle-aged	70.112	12.539	18	63.876	76.347
elderly	64.902	6.568	16	61.402	68.402
For entire sample	72.878	13.053	100	70.288	75.468

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	21706.73	94	230.92		
GENDER	2396.94	1	2396.94	10.38	.002
AGEC	6741.96	2	3370.98	14.60	.000
GENDER BY AGEC	1361.59	2	680.80	2.95	.057

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	397.69	94	4.23		
SPEED(1)	.05	1	.05	.01	.912
GENDER BY SPEED(1)	12.61	1	12.61	2.98	.088
AGEC BY SPEED(1)	7.73	2	3.87	.91	.404
GENDER BY AGEC BY SP EED(1)	1.39	2	.69	.16	.849

Table F.2 Multivariate Analysis of Variance for range of lateral flexion in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	69.399	15.992	15	60.543	78.255
middle-aged	65.596	14.774	15	57.415	73.777
elderly	50.089	12.392	16	43.486	56.693
FEMALE					
young	72.536	13.066	20	66.421	78.651
middle-aged	69.000	13.540	18	62.267	75.733
elderly	50.033	12.497	16	43.373	56.692
For entire sample	63.196	16.261	100	59.969	66.423

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	67.733	18.028	15	57.750	77.717
middle-aged	63.310	14.965	15	55.023	71.597
elderly	47.897	9.739	16	42.707	53.086
FEMALE					
young	65.867	12.455	20	60.037	71.696
middle-aged	65.475	11.428	18	59.792	71.158
elderly	47.356	10.510	16	41.756	52.957
For entire sample	59.856	15.283	100	56.823	62.888

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	32023.41	94	340.67		
GENDER	53.52	1	53.52	.16	.693
AGEC	15224.09	2	7612.04	22.34	.000
GENDER BY AGEC	81.29	2	40.64	.12	.888

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	1552.37	94	16.51		
SPEED(1)	496.83	1	496.83	30.08	.000
GENDER BY SPEED(1)	62.17	1	62.17	3.76	.055
AGEC BY SPEED(1)	26.85	2	13.42	.81	.447
GENDER BY AGEC BY SP EED(1)	49.12	2	24.56	1.49	.231

Table F.3 Multivariate Analysis of Variance for range of rotation in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	79.365	12.035	15	72.700	86.029
middle-aged	77.168	17.355	15	67.557	86.779
elderly	62.874	14.467	16	55.165	70.583
FEMALE					
young	74.649	9.436	20	70.233	79.065
middle-aged	72.749	15.584	18	65.000	80.499
elderly	51.871	15.552	16	43.583	60.158
For entire sample	69.864	16.684	100	66.553	73.174

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	89.250	17.282	15	79.679	98.821
middle-aged	83.009	19.607	15	72.150	93.867
elderly	65.709	13.789	16	58.362	73.057
FEMALE					
young	83.105	13.534	20	76.771	89.439
middle-aged	78.380	15.163	18	70.839	85.921
elderly	54.293	17.958	16	44.724	63.861
For entire sample	75.768	19.682	100	71.863	79.674

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	40783.55	94	433.87		
GENDER	2461.81	1	2461.81	5.67	.019
AGEC	19698.46	2	9849.23	22.70	.000
GENDER BY AGEC	426.17	2	213.09	.49	.613

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	2690.65	94	28.62		
SPEED(1)	1689.95	1	1689.95	59.04	.000
GENDER BY SPEED(1)	5.79	1	5.79	.20	.654
AGEC BY SPEED(1)	355.02	2	177.51	6.20	.003
GENDER BY AGEC BY SPEED(1)	3.59	2	1.79	.06	.939

Table F.4 Multivariate Analysis of Variance for range of forward flexion in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	58.765	10.489	15	52.956	64.573
	middle-aged	55.554	7.361	15	51.478	59.630
	elderly	49.253	6.735	16	45.664	52.842
FEMALE						
	young	54.800	6.115	20	51.937	57.662
	middle-aged	53.014	9.013	18	48.533	57.496
	elderly	49.946	6.897	16	46.271	53.621
For entire sample		53.522	8.283	100	51.879	55.166

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	59.825	9.736	15	54.434	65.217
	middle-aged	57.055	6.885	15	53.242	60.867
	elderly	49.249	6.880	16	45.583	52.915
FEMALE						
	young	55.093	8.248	20	51.233	58.953
	middle-aged	52.986	9.573	18	48.225	57.746
	elderly	50.041	7.669	16	45.954	54.127
For entire sample		53.974	8.840	100	52.220	55.728

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	11874.64	94	126.33		
GENDER	262.52	1	262.52	2.08	.153
AGEC	1919.39	2	959.70	7.60	.001
GENDER BY AGEC	236.34	2	118.17	.94	.396

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	342.87	94	3.65		
SPEED(1)	11.69	1	11.69	3.21	.077
GENDER BY SPEED(1)	6.64	1	6.64	1.82	.181
AGEC BY SPEED(1)	4.75	2	2.37	.65	.524
GENDER BY AGEC BY SP EED(1)	5.37	2	2.68	.74	.482

Table F.5 Multivariate Analysis of Variance for range of lateral flexion in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	46.920	12.274	15	40.123	53.717
	middle-aged	41.919	15.209	15	33.496	50.341
	elderly	28.664	10.944	16	22.832	34.495
FEMALE						
	young	55.874	11.917	20	50.296	61.451
	middle-aged	48.662	13.908	18	41.745	55.578
	elderly	31.130	10.913	16	25.315	36.945
For entire sample		42.827	15.762	100	39.699	45.954

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	47.075	13.870	15	39.394	54.756
	middle-aged	40.395	14.332	15	32.458	48.332
	elderly	27.740	9.752	16	22.544	32.936
FEMALE						
	young	52.032	11.960	20	46.435	57.629
	middle-aged	47.595	11.207	18	42.022	53.168
	elderly	31.161	10.432	16	25.602	36.720
For entire sample		41.518	14.768	100	38.588	44.449

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	26873.40	94	285.89		
GENDER	1564.17	1	1564.17	5.47	.021
AGEC	15100.62	2	7550.31	26.41	.000
GENDER BY AGEC	174.97	2	87.48	.31	.737

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	1524.21	94	16.21		
SPEED(1)	70.62	1	70.62	4.36	.040
GENDER BY SPEED(1)	9.19	1	9.19	.57	.453
AGEC BY SPEED(1)	16.31	2	8.16	.50	.606
GENDER BY AGEC BY SP EED(1)	62.38	2	31.19	1.92	.152

Table F.6 Multivariate Analysis of Variance for range of rotation in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	35.911	11.193	15	29.712	42.109
middle-aged	29.537	8.227	15	24.981	34.093
elderly	20.248	9.476	16	15.198	25.297
FEMALE					
young	35.924	7.418	20	32.452	39.395
middle-aged	32.515	9.765	18	27.659	37.371
elderly	15.946	8.771	16	11.272	20.619
For entire sample	28.645	11.768	100	26.310	30.980

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	37.450	10.453	15	31.661	43.239
middle-aged	30.837	9.176	15	25.756	35.919
elderly	19.803	8.220	16	15.423	24.183
FEMALE					
young	39.091	10.236	20	34.300	43.881
middle-aged	33.852	9.474	18	29.141	38.563
elderly	15.518	9.170	16	10.631	20.404
For entire sample	29.806	12.823	100	27.262	32.350

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	15562.10	94	165.55		
GENDER	1.22	1	1.22	.01	.932
AGEC	12878.21	2	6439.10	38.89	.000
GENDER BY AGEC	453.03	2	226.51	1.37	.260

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	806.73	94	8.58		
SPEED(1)	57.55	1	57.55	6.71	.011
GENDER BY SPEED(1)	3.88	1	3.88	.45	.503
AGEC BY SPEED(1)	65.46	2	32.73	3.81	.026
GENDER BY AGEC BY SP EED(1)	7.18	2	3.59	.42	.659

Table F.7 Multivariate Analysis of Variance for range of forward flexion in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	48.161	10.911	15	42.118	54.203
	middle-aged	46.131	10.993	15	40.044	52.219
	elderly	33.177	9.225	16	28.261	38.093
FEMALE						
	young	39.200	9.168	20	34.909	43.490
	middle-aged	37.077	11.480	18	31.368	42.786
	elderly	32.176	6.763	16	28.572	35.780
For entire sample		39.114	11.252	100	36.881	41.347

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	48.741	9.632	15	43.407	54.075
	middle-aged	47.216	11.444	15	40.878	53.554
	elderly	33.107	9.763	16	27.904	38.309
FEMALE						
	young	38.621	9.389	20	34.226	43.015
	middle-aged	36.568	11.135	18	31.031	42.105
	elderly	31.434	6.438	16	28.003	34.864
For entire sample		39.026	11.452	100	36.754	41.299

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	17908.78	94	190.52		
GENDER	2361.66	1	2361.66	12.40	.001
AGEC	4687.62	2	2343.81	12.30	.000
GENDER BY AGEC	756.84	2	378.42	1.99	.143

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	216.93	94	2.31		
SPEED(1)	.08	1	.08	.03	.856
GENDER BY SPEED(1)	16.12	1	16.12	6.98	.010
AGEC BY SPEED(1)	3.93	2	1.97	.85	.430
GENDER BY AGEC BY SPEED(1)	1.72	2	.86	.37	.690

Table F.8 Multivariate Analysis of Variance for range of lateral flexion in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	66.159	14.255	15	58.264	74.053
middle-aged	62.477	12.692	15	55.449	69.506
elderly	53.395	13.199	16	46.362	60.428
FEMALE					
young	65.552	8.959	20	61.359	69.744
middle-aged	62.073	10.541	18	56.831	67.315
elderly	49.234	10.900	16	43.426	55.042
For entire sample	60.000	13.033	100	57.413	62.586

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	62.861	15.469	15	54.295	71.428
middle-aged	59.035	12.714	15	51.995	66.076
elderly	51.715	10.845	16	45.936	57.494
FEMALE					
young	58.878	7.764	20	55.244	62.512
middle-aged	57.909	9.029	18	53.419	62.399
elderly	46.334	8.005	16	42.069	50.600
For entire sample	56.172	11.777	100	53.835	58.508

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	22633.01	94	240.78		
GENDER	337.09	1	337.09	1.40	.240
AGEC	6262.39	2	3131.20	13.00	.000
GENDER BY AGEC	132.08	2	66.04	.27	.761

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	1146.20	94	12.19		
SPEED(1)	674.54	1	674.54	55.32	.000
GENDER BY SPEED(1)	38.86	1	38.86	3.19	.077
AGEC BY SPEED(1)	60.30	2	30.15	2.47	.090
GENDER BY AGEC BY SPEED(1)	16.75	2	8.37	.69	.506

Table F.9 Multivariate Analysis of Variance for range of rotation in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE	young	44.024	6.998	15	40.149	47.899
	middle-aged	45.453	10.690	15	39.533	51.372
	elderly	41.741	7.316	16	37.842	45.639
FEMALE	young	38.381	8.568	20	34.371	42.391
	middle-aged	39.742	12.850	18	33.352	46.132
	elderly	36.076	9.869	16	30.818	41.335
For entire sample		40.702	9.918	100	38.734	42.670

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE	young	49.969	11.436	15	43.636	56.302
	middle-aged	49.655	10.952	15	43.589	55.720
	elderly	44.078	7.400	16	40.135	48.021
FEMALE	young	42.316	10.130	20	37.574	47.057
	middle-aged	43.436	14.015	18	36.466	50.405
	elderly	37.522	11.293	16	31.504	43.539
For entire sample		44.281	11.579	100	41.983	46.579

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	19393.21	94	206.31		
GENDER	1926.78	1	1926.78	9.34	.003
AGEC	812.04	2	406.02	1.97	.145
GENDER BY AGEC	4.36	2	2.18	.01	.989

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	890.73	94	9.48		
SPEED(1)	638.59	1	638.59	67.39	.000
GENDER BY SPEED(1)	15.98	1	15.98	1.69	.197
AGEC BY SPEED(1)	79.41	2	39.70	4.19	.018
GENDER BY AGEC BY SPEED(1)	5.12	2	2.56	.27	.764

Table F.10 Multivariate Analysis of Variance for average angular velocity of forward flexion in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	111.882	21.981	15	99.709	124.055
middle-aged	103.213	31.891	15	85.553	120.874
elderly	78.316	26.627	16	64.127	92.504
FEMALE					
young	93.671	21.810	20	83.464	103.878
middle-aged	92.611	26.497	18	79.434	105.787
elderly	76.031	27.574	16	61.338	90.724
For entire sample	92.364	28.241	100	86.760	97.967

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	146.155	28.559	15	130.340	161.971
middle-aged	134.991	40.910	15	112.336	157.646
elderly	94.377	29.576	16	78.617	110.137
FEMALE					
young	120.614	24.107	20	109.332	131.897
middle-aged	119.012	29.908	18	104.139	133.885
elderly	93.234	25.014	16	79.905	106.563
For entire sample	117.735	34.629	100	110.864	124.606

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	133925.16	94	1424.74		
GENDER	7475.80	1	7475.80	5.25	.024
AGEC	39641.11	2	19820.56	13.91	.000
GENDER BY AGEC	3378.69	2	1689.35	1.19	.310

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	13693.93	94	145.68		
SPEED(1)	32022.35	1	32022.35	219.81	.000
GENDER BY SPEED(1)	183.77	1	183.77	1.26	.264
AGEC BY SPEED(1)	1916.14	2	958.07	6.58	.002
GENDER BY AGEC BY SP EED(1)	160.96	2	80.48	.55	.577

Table F.11 Multivariate Analysis of Variance for average angular velocity of lateral flexion in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	51.736	13.608	15	44.200	59.272
middle-aged	48.511	18.122	15	38.476	58.547
elderly	33.218	11.712	16	26.976	39.459
FEMALE					
young	50.232	12.730	20	44.274	56.189
middle-aged	47.752	9.702	18	42.927	52.577
elderly	30.653	10.918	16	24.836	36.471
For entire sample	43.898	15.128	100	40.896	46.900

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	77.459	16.905	15	68.097	86.820
middle-aged	68.017	21.306	15	56.218	79.816
elderly	46.812	14.831	16	38.909	54.715
FEMALE					
young	71.776	12.973	20	65.704	77.848
middle-aged	68.193	12.574	18	61.940	74.446
elderly	41.258	11.339	16	35.215	47.300
For entire sample	62.543	19.783	100	58.617	66.468

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	32119.09	94	341.69		
GENDER	346.92	1	346.92	1.02	.316
AGEC	22719.20	2	11359.60	33.25	.000
GENDER BY AGEC	138.04	2	69.02	.20	.817

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	5066.00	94	53.89		
SPEED(1)	17056.01	1	17056.01	316.48	.000
GENDER BY SPEED(1)	53.37	1	53.37	.99	.322
AGEC BY SPEED(1)	1140.91	2	570.45	10.58	.000
GENDER BY AGEC BY SP EED(1)	59.38	2	29.69	.55	.578

Table F.12 Multivariate Analysis of Variance for average angular velocity of rotation in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE	young	74.175	41.347	15	51.278	97.073
	middle-aged	76.266	31.206	15	58.985	93.547
	elderly	50.705	23.982	16	37.926	63.484
FEMALE	young	67.129	24.891	20	55.479	78.778
	middle-aged	59.808	23.436	18	48.154	71.463
	elderly	38.643	12.325	16	32.075	45.210
For entire sample		61.053	29.500	100	55.200	66.906

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE	young	146.223	56.093	15	115.160	177.287
	middle-aged	124.445	50.007	15	96.752	152.138
	elderly	80.430	35.928	16	61.285	99.575
FEMALE	young	120.915	45.208	20	99.756	142.073
	middle-aged	106.017	36.198	18	88.017	124.018
	elderly	57.080	21.186	16	45.791	68.369
For entire sample		105.868	50.134	100	95.920	115.816

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	205011.48	94	2180.97		
GENDER	14479.46	1	14479.46	6.64	.012
AGEC	73953.56	2	36976.78	16.95	.000
GENDER BY AGEC	22.38	2	11.19	.01	.995

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	30832.67	94	328.01		
SPEED(1)	98973.01	1	98973.01	301.74	.000
GENDER BY SPEED(1)	1365.12	1	1365.12	4.16	.044
AGEC BY SPEED(1)	12582.05	2	6291.03	19.18	.000
GENDER BY AGEC BY SPEED(1)	558.13	2	279.06	.85	.430

Table F.13 Multivariate Analysis of Variance for average angular velocity of forward flexion in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	77.844	17.384	15	68.217	87.471
middle-aged	73.281	24.929	15	59.476	87.087
elderly	59.058	18.557	16	49.170	68.946
FEMALE					
young	70.607	19.216	20	61.613	79.600
middle-aged	69.485	19.629	18	59.724	79.246
elderly	57.152	19.809	16	46.596	67.707
For entire sample	67.891	20.782	100	63.767	72.015

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	102.333	21.367	15	90.500	114.166
middle-aged	97.123	31.038	15	79.935	114.311
elderly	71.299	19.669	16	60.818	81.780
FEMALE					
young	91.219	21.312	20	81.245	101.193
middle-aged	90.178	23.176	18	78.653	101.704
elderly	71.719	20.112	16	61.003	82.436
For entire sample	87.277	25.183	100	82.280	92.274

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	79365.70	94	844.32		
GENDER	1284.76	1	1284.76	1.52	.220
AGEC	16326.78	2	8163.39	9.67	.000
GENDER BY AGEC	589.33	2	294.66	.35	.706

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	7692.86	94	81.84		
SPEED(1)	18631.17	1	18631.17	227.66	.000
GENDER BY SPEED(1)	30.33	1	30.33	.37	.544
AGEC BY SPEED(1)	879.45	2	439.72	5.37	.006
GENDER BY AGEC BY SPEED(1)	93.69	2	46.84	.57	.566

Table F.14 Multivariate Analysis of Variance for average angular velocity of lateral flexion in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf.	Interval
MALE						
	young	35.104	10.725	15	29.165	41.043
	middle-aged	31.853	16.752	15	22.576	41.131
	elderly	19.482	9.607	16	14.363	24.601
FEMALE						
	young	38.352	9.147	20	34.071	42.633
	middle-aged	33.274	8.022	18	29.285	37.263
	elderly	18.937	7.825	16	14.767	23.106
For entire sample		29.850	12.824	100	27.306	32.395

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf.	Interval
MALE						
	young	53.881	12.437	15	46.994	60.769
	middle-aged	44.796	21.356	15	32.970	56.622
	elderly	28.026	13.277	16	20.951	35.101
FEMALE						
	young	56.409	11.071	20	51.227	61.591
	middle-aged	49.419	10.965	18	43.966	54.872
	elderly	27.336	10.663	16	21.654	33.017
For entire sample		43.837	17.661	100	40.332	47.341

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	23846.76	94	253.69		
GENDER	153.91	1	153.91	.61	.438
AGEC	17737.39	2	8868.70	34.96	.000
GENDER BY AGEC	138.24	2	69.12	.27	.762

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	3951.74	94	42.04		
SPEED(1)	9435.06	1	9435.06	224.43	.000
GENDER BY SPEED(1)	7.50	1	7.50	.18	.674
AGEC BY SPEED(1)	828.04	2	414.02	9.85	.000
GENDER BY AGEC BY SPEED(1)	37.07	2	18.54	.44	.645

Table F.15 Multivariate Analysis of Variance for average angular velocity of rotation in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	33.361	20.376	15	22.077	44.645
	middle-aged	28.915	13.049	15	21.688	36.141
	elderly	16.393	10.963	16	10.551	22.235
FEMALE						
	young	32.552	14.156	20	25.926	39.177
	middle-aged	25.873	7.711	18	22.039	29.708
	elderly	11.781	6.353	16	8.396	15.166
For entire sample		25.017	14.852	100	22.070	27.964

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	60.711	26.394	15	46.094	75.327
	middle-aged	45.641	19.663	15	34.752	56.530
	elderly	24.448	15.040	16	16.434	32.462
FEMALE						
	young	57.164	24.233	20	45.823	68.505
	middle-aged	45.303	15.143	18	37.773	52.833
	elderly	16.240	9.994	16	10.914	21.566
For entire sample		42.050	24.803	100	37.129	46.972

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	44952.95	94	478.22		
GENDER	580.59	1	580.59	1.21	.273
AGEC	28157.95	2	14078.97	29.44	.000
GENDER BY AGEC	218.41	2	109.20	.23	.796

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	5583.17	94	59.40		
SPEED(1)	13914.42	1	13914.42	234.27	.000
GENDER BY SPEED(1)	18.10	1	18.10	.30	.582
AGEC BY SPEED(1)	3248.33	2	1624.16	27.34	.000
GENDER BY AGEC BY SP EED(1)	95.42	2	47.71	.80	.451

Table F.16 Multivariate Analysis of Variance for average angular velocity of forward flexion in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	63.331	15.317	15	54.848	71.813
middle-aged	59.446	20.229	15	48.244	70.648
elderly	39.721	17.778	16	30.247	49.194
FEMALE					
young	50.351	15.005	20	43.329	57.373
middle-aged	48.561	17.967	18	39.626	57.496
elderly	37.455	16.434	16	28.698	46.212
For entire sample	49.576	19.018	100	45.802	53.349

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	83.261	20.160	15	72.097	94.425
middle-aged	79.053	26.567	15	64.341	93.765
elderly	48.084	21.049	16	36.868	59.300
FEMALE					
young	63.753	16.881	20	55.852	71.654
middle-aged	61.486	18.836	18	52.119	70.853
elderly	45.286	15.169	16	37.202	53.369
For entire sample	63.104	23.734	100	58.395	67.814

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	59801.45	94	636.19		
GENDER	5986.04	1	5986.04	9.41	.003
AGEC	19509.91	2	9754.96	15.33	.000
GENDER BY AGEC	1787.90	2	893.95	1.41	.250

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	4883.70	94	51.95		
SPEED(1)	9252.32	1	9252.32	178.09	.000
GENDER BY SPEED(1)	259.53	1	259.53	5.00	.028
AGEC BY SPEED(1)	760.63	2	380.32	7.32	.001
GENDER BY AGEC BY SP EED(1)	99.81	2	49.90	.96	.386

Table F.17 Multivariate Analysis of Variance for average angular velocity of lateral flexion in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	49.557	13.379	15	42.148	56.966
middle-aged	46.323	17.158	15	36.822	55.825
elderly	35.366	12.269	16	28.829	41.904
FEMALE					
young	45.972	13.136	20	39.824	52.119
middle-aged	43.285	9.482	18	38.570	48.000
elderly	29.910	8.937	16	25.148	34.672
For entire sample	41.812	14.003	100	39.033	44.590

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	72.091	14.679	15	63.963	80.220
middle-aged	63.161	17.606	15	53.412	72.911
elderly	50.333	15.342	16	42.158	58.509
FEMALE					
young	64.487	10.315	20	59.659	69.315
middle-aged	60.288	10.423	18	55.105	65.472
elderly	40.474	9.758	16	35.275	45.674
For entire sample	58.566	16.305	100	55.331	61.802

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	27684.94	94	294.52		
GENDER	1443.89	1	1443.89	4.90	.029
AGEC	12811.06	2	6405.53	21.75	.000
GENDER BY AGEC	179.96	2	89.98	.31	.737

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	3389.27	94	36.06		
SPEED(1)	13856.70	1	13856.70	384.31	.000
GENDER BY SPEED(1)	93.65	1	93.65	2.60	.110
AGEC BY SPEED(1)	498.46	2	249.23	6.91	.002
GENDER BY AGEC BY SP EED(1)	52.59	2	26.29	.73	.485

Table F.18 Multivariate Analysis of Variance for average angular velocity of rotation in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	40.669	21.328	15	28.858	52.481
middle-aged	45.091	18.290	15	34.962	55.220
elderly	33.458	13.791	16	26.109	40.807
FEMALE					
young	34.190	13.086	20	28.065	40.314
middle-aged	33.351	18.645	18	24.079	42.623
elderly	27.073	9.162	16	22.190	31.955
For entire sample	35.390	16.645	100	32.087	38.693

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	81.789	32.479	15	63.803	99.775
middle-aged	74.419	28.674	15	58.540	90.298
elderly	53.436	20.861	16	42.320	64.552
FEMALE					
young	60.926	24.379	20	49.516	72.336
middle-aged	59.264	28.603	18	45.040	73.488
elderly	39.222	13.469	16	32.045	46.399
For entire sample	61.109	28.153	100	55.523	66.696

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	73999.77	94	787.23		
GENDER	7695.69	1	7695.69	9.78	.002
AGEC	10376.40	2	5188.20	6.59	.002
GENDER BY AGEC	115.66	2	57.83	.07	.929

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	11056.05	94	117.62		
SPEED(1)	33107.55	1	33107.55	281.48	.000
GENDER BY SPEED(1)	902.48	1	902.48	7.67	.007
AGEC BY SPEED(1)	2699.96	2	1349.98	11.48	.000
GENDER BY AGEC BY SP EED(1)	255.66	2	127.83	1.09	.341

Table F.19 Multivariate Analysis of Variance for peak angular velocity of forward flexion in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	128.073	29.135	15	111.939	144.208
middle-aged	110.625	50.918	15	82.428	138.823
elderly	88.099	29.928	16	72.151	104.047
FEMALE					
young	126.811	33.265	20	111.242	142.379
middle-aged	120.398	28.336	18	106.307	134.489
elderly	84.269	25.388	16	70.741	97.798
For entire sample	110.417	37.161	100	103.044	117.791

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	172.049	50.033	15	144.342	199.757
middle-aged	154.109	55.707	15	123.259	184.958
elderly	106.652	32.513	16	89.327	123.977
FEMALE					
young	163.702	38.082	20	145.878	181.525
middle-aged	161.838	38.142	18	142.871	180.806
elderly	96.978	27.418	16	82.368	111.588
For entire sample	143.376	49.481	100	133.558	153.194

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	232112.21	94	2469.28		
GENDER	43.27	1	43.27	.02	.895
AGEC	105158.83	2	52579.42	21.29	.000
GENDER BY AGEC	2333.32	2	1166.66	.47	.625

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	31758.78	94	337.86		
SPEED(1)	53353.91	1	53353.91	157.92	.000
GENDER BY SPEED(1)	308.01	1	308.01	.91	.342
AGEC BY SPEED(1)	7238.84	2	3619.42	10.71	.000
GENDER BY AGEC BY SP EED(1)	57.25	2	28.63	.08	.919

Table F.20 Multivariate Analysis of Variance for peak angular velocity of extension in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	-146.185	31.408	15	-163.579	-128.792
middle-aged	-131.148	55.447	15	-161.853	-100.443
elderly	-105.857	39.671	16	-126.996	-84.717
FEMALE					
young	-157.401	36.750	20	-174.601	-140.201
middle-aged	-145.794	32.260	18	-161.837	-129.752
elderly	-92.656	27.596	16	-107.360	-77.951
For entire sample	-131.085	43.833	100	-139.783	-122.388

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	-180.291	36.316	15	-200.403	-160.180
middle-aged	-166.645	49.823	15	-194.236	-139.054
elderly	-128.003	45.437	16	-152.214	-103.791
FEMALE					
young	-188.830	44.346	20	-209.584	-168.075
middle-aged	-170.663	30.167	18	-185.665	-155.661
elderly	-121.992	27.203	16	-136.487	-107.497
For entire sample	-160.525	46.395	100	-169.731	-151.319

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	259399.89	94	2759.57		
GENDER	506.87	1	506.87	.18	.669
AGEC	110784.44	2	55392.22	20.07	.000
GENDER BY AGEC	4001.48	2	2000.74	.73	.487

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	23953.69	94	254.83		
SPEED(1)	43233.78	1	43233.78	169.66	.000
GENDER BY SPEED(1)	51.39	1	51.39	.20	.654
AGEC BY SPEED(1)	415.72	2	207.86	.82	.445
GENDER BY AGEC BY SP EED(1)	644.24	2	322.12	1.26	.287

Table F.21 Multivariate Analysis of Variance for peak angular velocity of lateral flexion in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	97.140	24.911	15	83.345	110.935
	middle-aged	94.305	42.075	15	71.005	117.605
	elderly	63.940	19.785	16	53.397	74.483
FEMALE						
	young	89.934	26.684	20	77.446	102.423
	middle-aged	90.892	20.516	18	80.690	101.094
	elderly	57.533	19.351	16	47.222	67.845
For entire sample		82.500	29.951	100	76.557	88.443

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	135.948	37.160	15	115.369	156.527
	middle-aged	126.537	44.902	15	101.671	151.403
	elderly	87.896	31.642	16	71.035	104.756
FEMALE						
	young	132.841	28.733	20	119.393	146.288
	middle-aged	128.073	32.200	18	112.061	144.086
	elderly	74.801	21.753	16	63.209	86.392
For entire sample		115.025	40.028	100	107.083	122.968

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	141298.81	94	1503.18		
GENDER	1380.06	1	1380.06	.92	.340
AGEC	73222.43	2	36611.22	24.36	.000
GENDER BY AGEC	628.47	2	314.23	.21	.812

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	27332.55	94	290.77		
SPEED(1)	50837.73	1	50837.73	174.84	.000
GENDER BY SPEED(1)	7.65	1	7.65	.03	.871
AGEC BY SPEED(1)	3535.90	2	1767.95	6.08	.003
GENDER BY AGEC BY SP EED(1)	341.26	2	170.63	.59	.558

Table F.22 Multivariate Analysis of Variance for peak angular velocity of rotation from left to right in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	130.117	69.119	15	91.840	168.394
middle-aged	138.277	57.548	15	106.408	170.146
elderly	105.711	43.101	16	82.744	128.677
FEMALE					
young	125.046	45.028	20	103.972	146.119
middle-aged	119.571	37.939	18	100.705	138.438
elderly	85.254	24.539	16	72.178	98.331
For entire sample	117.345	49.449	100	107.534	127.157

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	256.187	98.145	15	201.836	310.538
middle-aged	223.066	85.367	15	175.791	270.341
elderly	161.985	64.097	16	127.830	196.140
FEMALE					
young	214.283	86.128	20	173.974	254.591
middle-aged	200.829	66.844	18	167.588	234.070
elderly	114.110	40.604	16	92.474	135.746
For entire sample	195.069	86.357	100	177.934	212.204

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	638934.61	94	6797.18		
GENDER	33546.29	1	33546.29	4.94	.029
AGEC	156271.73	2	78135.87	11.50	.000
GENDER BY AGEC	1674.96	2	837.48	.12	.884

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	114342.08	94	1216.41		
SPEED(1)	299000.86	1	299000.86	245.81	.000
GENDER BY SPEED(1)	6312.91	1	6312.91	5.19	.025
AGEC BY SPEED(1)	35565.79	2	17782.89	14.62	.000
GENDER BY AGEC BY SPEED(1)	2448.16	2	1224.08	1.01	.369

Table F.23 Multivariate Analysis of Variance for peak angular velocity of rotation from right to left in the thoracolumbar spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	-130.748	77.656	15	-173.753	-87.743
	middle-aged	-137.965	53.683	15	-167.693	-108.236
	elderly	-105.978	45.531	16	-130.240	-81.716
FEMALE						
	young	-124.631	40.451	20	-143.562	-105.699
	middle-aged	-114.072	38.159	18	-133.048	-95.096
	elderly	-82.036	26.355	16	-96.079	-67.992
For entire sample		-115.848	50.677	100	-125.904	-105.793

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	-245.963	94.295	15	-298.181	-193.744
	middle-aged	-210.833	75.987	15	-252.914	-168.753
	elderly	-160.972	60.827	16	-193.384	-128.559
FEMALE						
	young	-208.742	76.371	20	-244.485	-172.999
	middle-aged	-198.630	57.530	18	-227.239	-170.021
	elderly	-108.550	38.944	16	-129.302	-87.798
For entire sample		-189.145	79.903	100	-204.999	-173.290

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	587168.94	94	6246.48		
GENDER	33352.37	1	33352.37	5.34	.023
AGEC	146688.68	2	73344.34	11.74	.000
GENDER BY AGEC	3729.00	2	1864.50	.30	.743

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	85611.86	94	910.76		
SPEED(1)	263916.37	1	263916.37	289.77	.000
GENDER BY SPEED(1)	3151.76	1	3151.76	3.46	.066
AGEC BY SPEED(1)	29333.90	2	14666.95	16.10	.000
GENDER BY AGEC BY SP EED(1)	4736.83	2	2368.41	2.60	.080

Table F.24 Multivariate Analysis of Variance for peak angular velocity of forward flexion in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	92.899	22.878	15	80.229	105.568
middle-aged	72.925	36.028	15	52.973	92.877
elderly	64.033	24.728	16	50.856	77.210
FEMALE					
young	101.152	25.424	20	89.253	113.051
middle-aged	91.464	21.115	18	80.964	101.965
elderly	56.580	15.717	16	48.205	64.955
For entire sample	80.866	29.401	100	75.032	86.699

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	127.800	38.748	15	106.342	149.258
middle-aged	104.265	38.292	15	83.059	125.470
elderly	78.317	30.835	16	61.886	94.748
FEMALE					
young	126.413	28.893	20	112.891	139.935
middle-aged	124.661	31.316	18	109.088	140.234
elderly	69.958	21.664	16	58.413	81.502
For entire sample	106.255	38.951	100	98.527	113.984

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	132957.98	94	1414.45		
GENDER	1235.82	1	1235.82	.87	.352
AGEC	69313.49	2	34656.74	24.50	.000
GENDER BY AGEC	6132.33	2	3066.17	2.17	.120

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	20663.48	94	219.82		
SPEED(1)	31896.61	1	31896.61	145.10	.000
GENDER BY SPEED(1)	103.76	1	103.76	.47	.494
AGEC BY SPEED(1)	3288.06	2	1644.03	7.48	.001
GENDER BY AGEC BY SP EED(1)	303.00	2	151.50	.69	.505

Table F.25 Multivariate Analysis of Variance for peak angular velocity of extension in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	-107.390	34.590	15	-126.545	-88.235
middle-aged	-93.394	60.589	15	-126.947	-59.841
elderly	-76.229	37.482	16	-96.202	-56.257
FEMALE					
young	-123.800	31.322	20	-138.459	-109.141
middle-aged	-112.481	25.714	18	-125.268	-99.694
elderly	-65.045	21.715	16	-76.616	-53.474
For entire sample	-97.728	41.421	100	-105.947	-89.509

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	-138.753	36.546	15	-158.992	-118.515
middle-aged	-126.132	53.287	15	-155.641	-96.623
elderly	-95.643	42.573	16	-118.329	-72.958
FEMALE					
young	-153.822	38.905	20	-172.030	-135.614
middle-aged	-141.393	29.813	18	-156.219	-126.568
elderly	-85.041	28.736	16	-100.353	-69.728
For entire sample	-124.857	45.564	100	-133.898	-115.816

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	245936.63	94	2616.35		
GENDER	2665.02	1	2665.02	1.02	.315
AGEC	90326.10	2	45163.05	17.26	.000
GENDER BY AGEC	8107.79	2	4053.90	1.55	.218

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	22127.66	94	235.40		
SPEED(1)	36258.81	1	36258.81	154.03	.000
GENDER BY SPEED(1)	28.89	1	28.89	.12	.727
AGEC BY SPEED(1)	1323.03	2	661.51	2.81	.065
GENDER BY AGEC BY SP EED(1)	39.55	2	19.78	.08	.919

Table F.26 Multivariate Analysis of Variance for peak angular velocity of lateral flexion in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE	young	66.953	18.583	15	56.662	77.244
	middle-aged	63.055	33.190	15	44.675	81.435
	elderly	38.766	16.846	16	29.790	47.743
FEMALE	young	69.131	18.579	20	60.435	77.826
	middle-aged	65.214	17.810	18	56.358	74.071
	elderly	36.808	14.659	16	28.997	44.619
For entire sample		57.158	24.146	100	52.367	61.949

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE	young	97.972	27.109	15	82.959	112.985
	middle-aged	87.117	40.201	15	64.855	109.380
	elderly	54.397	24.192	16	41.506	67.288
FEMALE	young	107.558	24.910	20	95.900	119.216
	middle-aged	92.549	26.988	18	79.128	105.970
	elderly	46.693	16.637	16	37.828	55.558
For entire sample		82.108	35.024	100	75.159	89.058

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	89219.44	94	949.14		
GENDER	129.09	1	129.09	.14	.713
AGEC	62076.00	2	31038.00	32.70	.000
GENDER BY AGEC	1054.05	2	527.03	.56	.576

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	20485.46	94	217.93		
SPEED(1)	29433.34	1	29433.34	135.06	.000
GENDER BY SPEED(1)	33.46	1	33.46	.15	.696
AGEC BY SPEED(1)	4020.31	2	2010.16	9.22	.000
GENDER BY AGEC BY SP EED(1)	371.41	2	185.70	.85	.430

Table F.27 Multivariate Analysis of Variance for peak angular velocity of rotation from left to right in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	70.594	41.683	15	47.511	93.677
middle-aged	68.583	30.733	15	51.564	85.603
elderly	45.924	23.826	16	33.228	58.620
FEMALE					
young	72.388	27.989	20	59.288	85.487
middle-aged	64.736	19.381	18	55.097	74.374
elderly	35.491	17.162	16	26.345	44.636
For entire sample	60.033	30.284	100	54.024	66.042

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	130.964	57.819	15	98.945	162.983
middle-aged	106.689	38.980	15	85.102	128.275
elderly	60.397	31.314	16	43.711	77.083
FEMALE					
young	117.611	45.352	20	96.385	138.836
middle-aged	104.687	40.687	18	84.453	124.920
elderly	42.025	19.243	16	31.771	52.279
For entire sample	94.401	50.547	100	84.371	104.431

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	195114.40	94	2075.69		
GENDER	2934.69	1	2934.69	1.41	.237
AGEC	97085.19	2	48542.60	23.39	.000
GENDER BY AGEC	1154.80	2	577.40	.28	.758

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	32196.77	94	342.52		
SPEED(1)	57551.17	1	57551.17	168.02	.000
GENDER BY SPEED(1)	619.88	1	619.88	1.81	.182
AGEC BY SPEED(1)	15287.14	2	7643.57	22.32	.000
GENDER BY AGEC BY SP EED(1)	607.59	2	303.79	.89	.415

Table F.28 Multivariate Analysis of Variance for peak angular velocity of rotation from right to left in the lower thoracic spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	-66.988	42.890	15	-90.739	-43.237
	middle-aged	-64.861	29.792	15	-81.359	-48.363
	elderly	-46.717	28.147	16	-61.715	-31.718
FEMALE						
	young	-72.052	25.728	20	-84.093	-60.011
	middle-aged	-62.447	19.713	18	-72.250	-52.643
	elderly	-33.595	16.116	16	-42.183	-25.007
For entire sample		-58.278	30.305	100	-64.291	-52.265

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE						
	young	-122.031	46.467	15	-147.763	-96.298
	middle-aged	-101.045	42.545	15	-124.606	-77.485
	elderly	-60.446	29.303	16	-76.060	-44.831
FEMALE						
	young	-115.819	47.493	20	-138.046	-93.591
	middle-aged	-103.768	35.051	18	-121.198	-86.337
	elderly	-42.304	25.717	16	-56.008	-28.601
For entire sample		-91.743	47.794	100	-101.227	-82.260

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	184743.63	94	1965.36		
GENDER	1416.08	1	1416.08	.72	.398
AGEC	84251.92	2	42125.96	21.43	.000
GENDER BY AGEC	2577.03	2	1288.51	.66	.521

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	30510.31	94	324.58		
SPEED(1)	54278.63	1	54278.63	167.23	.000
GENDER BY SPEED(1)	171.10	1	171.10	.53	.470
AGEC BY SPEED(1)	12730.86	2	6365.43	19.61	.000
GENDER BY AGEC BY SP EED(1)	572.18	2	286.09	.88	.418

Table F.29 Multivariate Analysis of Variance for peak angular velocity of forward flexion in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	100.580	21.926	15	88.438	112.722
middle-aged	88.335	37.837	15	67.381	109.288
elderly	71.842	24.873	16	58.588	85.096
FEMALE					
young	95.793	26.603	20	83.343	108.243
middle-aged	90.053	20.684	18	79.767	100.339
elderly	71.597	20.265	16	60.798	82.395
For entire sample	86.656	27.506	100	81.198	92.113

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	135.168	34.551	15	116.034	154.302
middle-aged	121.900	41.785	15	98.760	145.040
elderly	84.286	24.157	16	71.413	97.158
FEMALE					
young	124.086	34.892	20	107.755	140.416
middle-aged	123.709	29.212	18	109.182	138.235
elderly	85.299	20.741	16	74.247	96.351
For entire sample	112.779	36.590	100	105.518	120.039

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	139373.75	94	1482.70		
GENDER	184.04	1	184.04	.12	.725
AGEC	45866.16	2	22933.08	15.47	.000
GENDER BY AGEC	926.48	2	463.24	.31	.732

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	17560.37	94	186.81		
SPEED(1)	33545.03	1	33545.03	179.57	.000
GENDER BY SPEED(1)	33.62	1	33.62	.18	.672
AGEC BY SPEED(1)	4126.37	2	2063.18	11.04	.000
GENDER BY AGEC BY SP EED(1)	138.61	2	69.31	.37	.691

Table F.30 Multivariate Analysis of Variance for peak angular velocity of extension in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	-110.945	20.375	15	-122.228	-99.661
middle-aged	-101.659	39.032	15	-123.274	-80.044
elderly	-83.279	26.736	16	-97.525	-69.032
FEMALE					
young	-111.039	25.225	20	-122.845	-99.233
middle-aged	-107.668	26.509	18	-120.850	-94.485
elderly	-79.706	18.746	16	-89.695	-69.717
For entire sample	-99.556	29.050	100	-105.320	-93.792

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	-130.187	18.507	15	-140.436	-119.938
middle-aged	-126.695	38.294	15	-147.902	-105.489
elderly	-98.220	30.647	16	-114.550	-81.890
FEMALE					
young	-128.405	28.549	20	-141.766	-115.043
middle-aged	-125.156	24.828	18	-137.502	-112.809
elderly	-93.499	20.814	16	-104.590	-82.408
For entire sample	-117.416	30.839	100	-123.535	-111.297

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	127737.03	94	1358.90		
GENDER	41.75	1	41.75	.03	.861
AGEC	37466.49	2	18733.24	13.79	.000
GENDER BY AGEC	329.52	2	164.76	.12	.886

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	11308.44	94	120.30		
SPEED(1)	15987.03	1	15987.03	132.89	.000
GENDER BY SPEED(1)	153.64	1	153.64	1.28	.261
AGEC BY SPEED(1)	386.91	2	193.46	1.61	.206
GENDER BY AGEC BY SPEED(1)	100.47	2	50.24	.42	.660

Table F.31 Multivariate Analysis of Variance for peak angular velocity of lateral flexion in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE	young	96.998	26.161	15	82.510	111.486
	middle-aged	91.794	37.510	15	71.022	112.566
	elderly	68.228	21.919	16	56.547	79.908
FEMALE	young	90.507	30.977	20	76.009	105.005
	middle-aged	81.721	15.609	18	73.958	89.483
	elderly	57.313	16.166	16	48.699	65.927
For entire sample		81.216	28.739	100	75.514	86.919

Fast Speed

		Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE	young	132.928	32.207	15	115.092	150.764
	middle-aged	123.173	39.335	15	101.390	144.956
	elderly	100.724	35.892	16	81.598	119.849
FEMALE	young	123.040	25.806	20	110.963	135.117
	middle-aged	116.361	22.369	18	105.237	127.484
	elderly	74.429	18.994	16	64.308	84.550
For entire sample		111.992	34.512	100	105.144	118.840

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	127032.87	94	1351.41		
GENDER	6824.30	1	6824.30	5.05	.027
AGEC	46238.22	2	23119.11	17.11	.000
GENDER BY AGEC	1147.48	2	573.74	.42	.655

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	17825.74	94	189.64		
SPEED(1)	46567.01	1	46567.01	245.56	.000
GENDER BY SPEED(1)	330.81	1	330.81	1.74	.190
AGEC BY SPEED(1)	856.58	2	428.29	2.26	.110
GENDER BY AGEC BY SPEED(1)	721.19	2	360.59	1.90	.155

Table F.32 Multivariate Analysis of Variance for peak angular velocity of rotation from left to right in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	74.713	31.626	15	57.199	92.227
middle-aged	83.248	36.522	15	63.023	103.473
elderly	73.288	29.223	16	57.715	88.860
FEMALE					
young	64.106	25.093	20	52.361	75.850
middle-aged	67.597	32.433	18	51.469	83.726
elderly	62.241	18.709	16	52.271	72.210
For entire sample	70.367	29.383	100	64.537	76.197

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	143.759	52.704	15	114.572	172.945
middle-aged	132.977	55.229	15	102.393	163.562
elderly	110.168	42.071	16	87.750	132.586
FEMALE					
young	107.842	47.377	20	85.668	130.015
middle-aged	111.936	57.321	18	83.431	140.441
elderly	83.076	26.819	16	68.785	97.366
For entire sample	114.146	50.501	100	104.126	124.167

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	252000.72	94	2680.86		
GENDER	20236.08	1	20236.08	7.55	.007
AGEC	11237.03	2	5618.51	2.10	.129
GENDER BY AGEC	237.13	2	118.57	.04	.957

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	46017.34	94	489.55		
SPEED(1)	96175.97	1	96175.97	196.46	.000
GENDER BY SPEED(1)	3002.47	1	3002.47	6.13	.015
AGEC BY SPEED(1)	6443.23	2	3221.61	6.58	.002
GENDER BY AGEC BY SPEED(1)	831.02	2	415.51	.85	.431

Table F.33 Multivariate Analysis of Variance for peak angular velocity of rotation from right to left in the lumbar spine over preferred and fast speeds of motion.

Preferred Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	-74.952	38.931	15	-96.511	-53.393
middle-aged	-82.887	34.873	15	-102.199	-63.575
elderly	-71.967	27.069	16	-86.391	-57.543
FEMALE					
young	-65.853	20.177	20	-75.296	-56.409
middle-aged	-66.139	30.215	18	-81.164	-51.114
elderly	-59.391	21.471	16	-70.832	-47.950
For entire sample	-69.769	29.256	100	-75.574	-63.964

Fast Speed

	Mean	Std. Dev.	N	95 percent Conf. Interval	
MALE					
young	-139.578	57.290	15	-171.304	-107.852
middle-aged	-131.294	49.005	15	-158.432	-104.156
elderly	-112.616	37.719	16	-132.715	-92.517
FEMALE					
young	-107.142	38.507	20	-125.164	-89.120
middle-aged	-111.499	50.898	18	-136.810	-86.188
elderly	-77.099	25.273	16	-90.566	-63.632
For entire sample	-112.483	47.102	100	-121.830	-103.137

Tests of Between-Subjects Effects.

Tests of Significance for T1 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	225705.31	94	2401.12		
GENDER	21874.01	1	21874.01	9.11	.003
AGEC	12759.74	2	6379.87	2.66	.075
GENDER BY AGEC	271.23	2	135.61	.06	.945

Tests involving 'SPEED(1)' Within-Subject Effect.

Tests of Significance for T2 using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN CELLS	36404.00	94	387.28		
SPEED(1)	91489.67	1	91489.67	236.24	.000
GENDER BY SPEED(1)	3343.00	1	3343.00	8.63	.004
AGEC BY SPEED(1)	4999.70	2	2499.85	6.45	.002
GENDER BY AGEC BY SPEED(1)	1106.72	2	553.36	1.43	.245

APPENDIX G.

Data for Range of Primary and Associated Movements

Ranges of primary and associated movements are presented [Tables G.1 to G.12]. The associated movements could be either positive or negative in each plane of movement. For example, the associated movement in the sagittal plane can be either forward flexion or extension. Therefore, the number of subjects showing each direction of the associated movements are also presented.

Table G.1 Means (S.D) of range of motion for primary and associated movements.

Subjects: Male; Segment: Thoracolumbar spine; Speed of motion: Preferred

Primary mvt Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**84.9(14.4)**		**79.1(11.4)**		**65.2(9.9)**	
Lateral flexion	3.9(2.4)	7	2.1(1.7)	9	2.0(1.9)	5
	-2.0(1.8)	8	-1.6(0.9)	6	-3.6(1.9)	11
Rotation	1.8(1.9)	10	3.7(2.9)	7	2.3(1.6)	12
	-2.2(0.5)	5	-3.6(2.9)	8	-0.3(0.2)	4
Left lateral flexion	**33.8(8.4)**		**32.5(9.4)**		**28.9(7.1)**	
Forward flexion	16.1(7.6)	14	16.4(8.6)	15	10.4(6.1)	16
	-2.1	1	-			
Rotation	28.8(9.3)	15	24.6(7.5)	15	21.5(5.3)	16
	-		-		-	
Right lateral flexion	**35.6(9.2)**		**33.1(7.6)**		**21.2(7.4)**	
Forward flexion	17.9(9.0)	15	20.5(8.4)	15	12.9(6.5)	16
	-		-		-	
Rotation	-		-		-	
	-26.4(8.5)	15	-26.4(9.8)	15	-19.2(6.7)	16
Left rotation	**39.1(5.8)**		**38.8(9.4)**		**31.1(7.7)**	
Forward flexion	4.0(2.8)		5.0(3.0)	14	2.4(1.8)	12
	-1.8(1.1)	11	-5.6	1	-2.4(1.8)	4
Lateral flexion	-	4	-		-	
	-18.4(6.4)		-17.5(8.2)	15	-19.7(6.4)	16
Right rotation	**40.3(7.9)**	15	**38.4(9.7)**		**31.8(7.9)**	
Forward flexion	4.7(4.8)		5.9(4.7)	10	3.5(2.6)	15
	-7.1(1.9)	12	-3.9(2.9)	5	-3.7	1
Lateral flexion	18.9(6.2	3	18.3(9.6)	15	18.9(5.8)	16
	-	15	-		-	

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

Table G.2 Means (S.D) of range of motion for primary and associated movements.

Subjects: Male

Segment: Thoracolumbar spine

Speed of motion: Fast

Primary mvt Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**85.6(12.8)**		**79.9(11.6)**		**65.0(10.7)**	
Lateral flexion	3.3(1.8)	9	1.6(1.2)	10	4.6(2.4)	2
	-2.6(0.8)	6	-0.8(0.9)	5	-3.2(2.3)	14
Rotation	2.0(1.9)	8	3.3(3.8)	6	2.1(1.5)	12
	-2.0(0.9)	7	-3.3(2.4)	9	-1.1(0.7)	4
Left lateral flexion	**32.2(8.9)**		**31.3(9.6)**		**27.0(6.6)**	
Forward flexion	15.3(7.5)	14	14.1(7.1)	15	10.0(4.4)	16
	-1.4	1	-		-	
Rotation	28.2(11.6)	15	22.0(6.9)	15	21.8(7.5)	16
	-		-		-	
Right lateral flexion	**35.5(10.5)**		**32.0(7.1)**		**20.8(6.5)**	
Forward flexion	16.4(7.4)	15	18.0(10.7)	15	13.3(6.6)	16
	-		-		-	
Rotation	-		-		-	
	-24.8(8.5)	15	-23.1(9.7)	15	-19.0(7.3)	16
Left rotation	**43.3(7.7)**		**41.9(10.1)**		**32.1(8.6)**	
Forward flexion	6.4(3.3)	12	6.1(3.2)	14	3.4(2.1)	11
	-2.1(1.3)	3	-1.3	1	-1.7(1.8)	5
Lateral flexion	-		-		-	
	-19.0(6.3)	15	-18.8(8.7)	15	-17.6(7.2)	16
Right rotation	**46.0(10.6)**		**41.1(11.3)**		**33.6(7.4)**	
Forward flexion	5.1(2.8)	12	6.4(3.6)	11	3.5(2.4)	14
	-5.6(2.5)	3	-4.1(2.1)	4	-0.5(0.04)	2
Lateral flexion	19.3(4.5)	15	19.7(8.6)	15	20.3(5.6)	16
	-		-		-	

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

Table G.3 Means (S.D) of range of motion for primary and associated movements.

Subjects: Female

Segment: Thoracolumbar spine

Speed of motion: Preferred

Primary mvt Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**73.2(8.2)**		**70.8(12.1)**		**65.9(6.4)**	
Lateral flexion	3.8(3.6)	11	3.3(2.3)	8	1.7(1.3)	4
	-2.8(2.9)	9	-3.2(1.9)	10	-3.2(2.0)	12
Rotation	1.6(1.1)	11	1.9(1.4)	12	3.9(2.6)	8
	-3.5(1.7)	9	-2.5(2.2)	6	-2.8(1.7)	8
Left lateral flexion	**35.4(6.3)**		**34.5(7.7)**		**28.0(7.5)**	
Forward flexion	20.8(7.9)	20	19.6(8.5)	17	11.1(6.1)	16
	-		-3.8	1	-	
Rotation	27.4(7.5)	20	23.4(8.4)	18	20.1(7.9)	16
	-		-		-	
Right lateral flexion	**37.1(8.7)**		**34.5(7.2)**		**22.0(7.3)**	
Forward flexion	20.8(7.3)	20	19.9(9.6)	18	13.3(5.6)	16
	-		-		-	
Rotation	-		-		-	
	-23.3(7.3)	20	-21.7(7.3)	18	-17.8(5.5)	16
Left rotation	**37.3(5.9)**		**35.3(7.5)**		**26.6(7.3)**	
Forward flexion	6.6(3.6)	18	4.9(4.8)	14	4.8(2.5)	9
	-3.6(3.4)	2	-1.2(1.1)	4	-2.3(2.0)	7
Lateral flexion	-		-		-	
	-15.3(5.7)	20	-14.4(6.8)	18	-18.6(5.6)	16
Right rotation	**37.4(6.0)**		**37.4(9.1)**		**25.3(9.0)**	
Forward flexion	5.2(4.3)	15	3.3(3.0)	13	4.6(3.1)	13
	-1.5(1.2)	5	-3.3(2.9)	5	-3.1(1.8)	3
Lateral flexion	17.2(7.2)	20	15.3(6.4)	18	18.2(6.8)	16
	-		-		-	

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

Table G.4 Means (S.D) of range of motion for primary and associated movements.

Subjects: Female

Segment: Thoracolumbar spine

Speed of motion: Fast

Primary mvt Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**73.2(11.1)**		**70.1(12.5)**		**64.9(6.6)**	
Lateral flexion	4.1(3.4)	11	3.2(2.8)	9	1.3(1.4)	6
	-3.8(3.5)	9	-3.6(2.2)	9	-4.1(2.0)	10
Rotation	2.2(1.5)	10	2.1(1.5)	14	3.9(2.5)	8
	-3.0(1.8)	10	-4.2(1.8)	4	-2.4(1.6)	8
Left lateral flexion	**33.1(5.8)**		**32.4(6.1)**		**26.6(7.9)**	
Forward flexion	18.3(7.2)	20	18.3(8.3)	17	10.2(5.8)	16
	-		-1.5	1	-	
Rotation	26.4(6.8)	20	23.3(7.3)	18	19.1(5.7)	16
	-		-		-	
Right lateral flexion	**32.7(8.3)**		**33.1(7.6)**		**20.7(6.7)**	
Forward flexion	18.6(9.3)	20	19.3(7.8)	18	12.3(6.3)	16
	-		-		-	
Rotation	-		-		20.7	1
	-20.4(7.9)	20	-21.8(5.0)	18	-16.1(4.5)	15
Left rotation	**41.5(7.2)**		**38.0(8.1)**		**26.9(8.0)**	
Forward flexion	6.6(4.3)	13	5.2(3.7)	15	5.1(3.3)	10
	-1.7(1.3)	7	-3.4(3.2)	3	-3.2(1.4)	6
Lateral flexion	-		-		-	
	-16.8(6.2)	20	-15.3(6.8)	18	-18.9(6.3)	16
Right rotation	**41.7(8.7)**		**40.4(8.3)**		**27.4(10.7)**	
Forward flexion	5.9(3.9)	14	5.6(3.7)	11	4.9(3.7)	14
	-3.5(3.0)	6	-2.8(1.8)	7	-3.1(2.3)	2
Lateral flexion	17.8(8.2)	20	17.6(5.6)	18	18.6(6.8)	16
	-		-		-	

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

Table G.5 Means (S.D) of range of motion for primary and associated movements.

Subjects: Male

Segment: Lower thoracic spine

Speed of motion: Preferred

Primary mvt Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**58.8(10.5)**		**55.6(7.4)**		**49.3(6.7)**	
Lateral flexion	3.2(1.9)	10	2.1(1.6)	6	1.4(1.1)	5
	-3.5(2.9)	5	-1.9(1.4)	9	-2.3(1.7)	11
Rotation	2.6(1.9)	9	2.3(1.7)	7	2.7(1.9)	11
	-1.1(0.6)	6	-1.9(1.8)	8	-2.5(1.8)	5
Left lateral flexion	**21.5(6.3)**		**20.2(9.8)**		**16.4(6.1)**	
Forward flexion	9.3(5.9)	13	8.4(4.7)	15	6.1(3.5)	14
	-1.5(0.6)	2	-		-1.0(1.4)	2
Rotation	17.0(6.2)	15	14.9(5.6)	15	10.8(3.8)	16
	-		-		-	
Right lateral flexion	**25.4(8.9)**		**21.7(6.8)**		**12.3(6.3)**	
Forward flexion	8.9(5.4)	15	9.9(5.9)	15	7.4(3.9)	16
	-		-		-	
Rotation	-		-		0.04	1
	-14.1(5.7)	15	-13.1(6.2)	15	-9.6(3.9)	15
Left rotation	**17.2(5.6)**		**14.7(4.5)**		**9.7(5.6)**	
Forward flexion	6.1(3.4)	14	7.5(2.4)	15	5.7(3.3)	14
	-0.5	1	-		-1.1(0.1)	2
Lateral flexion	-		0.1	1	1.7	1
	-10.3(5.2)	15	-11.8(5.6)	14	-12.7(6.2)	15
Right rotation	**18.7(6.9)**		**14.8(5.5)**		**10.8(5.7)**	
Forward flexion	6.8(3.9)	12	5.9(3.7)	15	4.7(1.9)	14
	-1.4(0.4)	3	-		-2.5(2.1)	2
Lateral flexion	11.3(7.4)	15	11.5(7.4)	15	9.9(4.8)	16
	-		-		-	

Note: Negative values of associated forward flexion refer to extension.

: Negative values of associated rotation and lateral flexion refer to movement towards the left side.

: N = number of subjects

Table G.6 Means (S.D) of range of motion for primary and associated movements.

Subjects: Male

Segment: Lower thoracic spine

Speed of motion: Fast

Primary mvt / Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**59.8(9.7)**		**57.1(6.9)**		**49.2(6.9)**	
Lateral flexion	3.5(2.5)	9	2.2(1.8)	5	1.7(1.8)	5
	-2.9(2.0)	6	-1.6(1.1)	10	-2.5(2.2)	11
Rotation	2.5(1.7)	9	1.7(1.4)	9	2.4(1.7)	12
	-1.7(0.6)	6	-3.2(1.2)	6	-3.3(1.6)	4
Left lateral flexion	**21.2(6.8)**		**19.6(8.2)**		**15.2(5.7)**	
Forward flexion	8.7(5.9)	13	8.4(4.7)	14	5.9(3.3)	15
	-1.3(1.3)	2	-0.4	1	-0.9	1
Rotation	18.1(7.8)	15	14.1(3.8)	15	11.9(4.5)	16
	-		-		-	
Right lateral flexion	**25.9(9.2)**		**20.8(6.9)**		**12.5(6.1)**	
Forward flexion	9.2(4.2)	14	10.4(6.4)	14	7.7(4.5)	16
	-0.3	1	-0.3	1	-	
Rotation	-		0.4	1	1.4	1
	-13.4(5.2)	15	-12.6(6.1)	14	-9.7(3.8)	15
Left rotation	**17.6(4.9)**		**15.6(4.9)**		**9.3(5.8)**	
Forward flexion	8.1(3.7)	14	7.9(3.8)	15	5.3(3.3)	15
	-1.31	1	-		-0.7	1
Lateral flexion	-		-		-	
	-11.2(5.1)	15	-12.0(6.2)	15	-10.3(6.2)	16
Right rotation	**19.9(6.9)**		**15.2(5.8)**		**10.9(4.8)**	
Forward flexion	7.4(4.6)	13	6.9(3.8)	15	5.5(2.0)	14
	-1.2(0.6)	2	-		-2.2(2.7)	2
Lateral flexion	11.9(6.9)	15	10.9(7.4)	15	11.7(4.9)	16
	-		-		-	

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

Table G.7 Means (S.D) of range of motion for primary and associated movements.

Subjects: Female

Segment: Lower thoracic spine

Speed of motion: Preferred

Primary mvt Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**54.8(6.1)**		**53.0(9.0)**		**49.9(6.9)**	
Lateral flexion	3.4(3.5)	12	2.9(2.1)	9	0.6(0.3)	5
	-2.9(3.0)	8	-2.5(2.2)	9	-2.7(2.3)	11
Rotation	1.7(0.7)	7	2.1(1.3)	9	1.8(2.3)	8
	-2.4(2.1)	13	-1.8(1.4)	9	-1.6(0.8)	8
Left lateral flexion	**26.5(5.6)**		**23.8(8.2)**		**17.8(6.1)**	
Forward flexion	11.5(5.9)	20	10.6(6.0)	17	6.6(4.2)	14
	-		-3.8	1	-1.9(1.8)	2
Rotation	17.5(4.9)	20	13.9(5.4)	18	10.8(4.6)	16
	-		-		-	
Right lateral flexion	**29.3(8.0)**		**24.8(7.5)**		**13.4(6.5)**	
Forward flexion	10.1(5.9)	20	13.6(7.0)	16	6.7(3.1)	14
	-		-0.6(0.4)	2	-0.8(0.9)	2
Rotation	-		-		-	
	-13.2(4.9)	20	-11.9(4.9)	18	-7.8(2.8)	16
Left rotation	**18.3(4.1)**		**15.9(3.6)**		**7.9(4.7)**	
Forward flexion	7.3(4.2)	20	9.0(4.6)	15	5.3(3.9)	15
	-		-2.2(1.8)	3	-0.5	1
Lateral flexion	-		-		11.4(8.5)	3
	-13.7(6.4)	20	-14.2(6.0)	18	-10.2(5.5)	13
Right rotation	**17.6(4.9)**		**16.6(6.7)**		**8.0(5.1)**	
Forward flexion	7.0(4.3)	20	7.4(2.8)	16	6.7(3.8)	15
	-		-0.9(1.1)	2	-1.1	1
Lateral flexion	12.1(4.4)	20	12.7(4.7)	18	12.9(6.8)	13
	-		-		-12.7(9.8)	3

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

Table G.8 Means (S.D) of range of motion for primary and associated movements.

Subjects: Female

Segment: Lower thoracic spine

Speed of motion: Fast

Primary mvt Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**55.1(8.2)**		**52.9(9.6)**		**50.0(7.7)**	
Lateral flexion	3.6(3.3)	12	2.9(2.7)	10	0.9(0.9)	5
	-3.8(3.7)	8	-3.1(2.0)	8	-2.9(2.4)	11
Rotation	1.4(1.7)	9	1.9(1.6)	11	2.0(2.3)	8
	-2.5(1.9)	11	-2.0(1.9)	7	-1.8(1.5)	8
Left lateral flexion	**25.5(5.8)**		**23.4(6.7)**		**16.8(6.3)**	
Forward flexion	10.5(4.9)	20	10.6(5.5)	16	5.7(4.5)	16
	-		-1.7(0.0)	2	-	
Rotation	17.8(4.6)	20	15.3(5.9)	18	10.6(3.7)	16
	-		-		-	
Right lateral flexion	**26.6(7.9)**		**24.2(6.7)**		**14.3(8.9)**	
Forward flexion	12.3(6.0)	18	11.1(6.1)	18	6.4(3.5)	15
	-0.7(0.4)	2	-		-0.7	1
Rotation	-		-		11.9	1
	-12.7(5.9)	20	-12.2(3.5)	18	-7.5(2.3)	15
Left rotation	**19.6(5.9)**		**16.8(4.2)**		**8.5(4.1)**	
Forward flexion	7.8(3.9)	19	8.9(4.9)	16	7.1(4.6)	15
	-0.7	1	-5.6(4.4)	2	-0.1	1
Lateral flexion	-		-		9.5(8.5)	3
	-14.6(5.0)	20	-13.7(4.6)	18	-11.5(4.9)	13
Right rotation	**19.5(5.7)**		**17.0(5.8)**		**9.7(4.4)**	
Forward flexion	6.6(3.9)	20	7.0(4.1)	17	7.6(4.5)	16
	-		-0.2	1	-	
Lateral flexion	14.1(6.0)	20	14.5(5.5)	18	14.9(9.5)	14
	-		-		-9.6(11.9)	2

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

Table G.9 Means (S.D) of range of motion for primary and associated movements.

Subjects: Male

Segment: Lumbar spine

Speed of motion: Preferred

Primary mvt / Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**48.2(10.9)**		**46.1(10.9)**		**33.2(9.2)**	
Lateral flexion	1.9(2.9)	8	3.5(2.6)	7	1.6(1.4)	3
	-2.3(2.1)	7	-2.8(1.3)	8	-2.4(1.4)	13
Rotation	1.6(0.9)	5	3.2(2.3)	9	1.2(1.1)	10
	-1.4(1.1)	10	-3.4(3.2)	6	-1.9(1.9)	6
Left lateral flexion	**34.5(7.9)**		**32.5(7.8)**		**29.5(6.3)**	
Forward flexion	9.3(7.2)	14	8.8(6.4)	15	6.2(5.1)	15
	-7.5	1	-		-3.7	1
Rotation	5.6(2.5)	14	4.3(2.7)	12	6.2(1.6)	11
	-3.1	1	-2.7(1.9)	3	-1.8(1.1)	5
Right lateral flexion	**31.6(7.7)**		**30.0(9.3)**		**23.9(8.0)**	
Forward flexion	11.2(5.9)	13	11.5(6.2)	15	9.3(6.4)	16
	-4.3(3.3)	2	-		-	
Rotation	0.2	1	0.4	1	2.4	1
	-6.1(4.1)	14	-7.1(4.5)	14	-5.9(3.5)	15
Left rotation	**22.6(4.2)**		**22.7(5.9)**		**21.7(4.10)**	
Forward flexion	7.1(2.9)	15	9.5(3.6)	14	5.8(3.2)	16
	-		-5.5	1	-	
Lateral flexion	5.7(3.1)	10	6.4(4.3)	13	5.0(2.8)	9
	-4.7(3.9)	5	-5.5(2.3)	2	-2.8(1.9)	7
Right rotation	**21.5(4.6)**		**22.7(6.2)**		**20.1(4.2)**	
Forward flexion	7.8(3.9)	14	9.3(4.4)	13	7.6(3.9)	16
	-2.6	1	-1.1(0.8)	2	-	
Lateral flexion	4.1(4.6)	5	6.8(5.9)	4	5.7(2.1)	5
	-6.1(3.0)	10	-5.8(4.8)	11	-4.5(4.1)	11

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

Table G.10 Means (S.D) of range of motion for primary and associated movements.

Subjects: Male

Segment: Lumbar spine

Speed of motion: Fast

Primary mvt Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**48.7(9.6)**		**47.2(11.4)**		**33.1(9.8)**	
Lateral flexion	2.4(3.3)	7	3.1(2.6)	8	1.7(0.9)	4
	-1.7(1.8)	8	-2.6(1.6)	7	-2.6(1.3)	12
Rotation	1.3(0.9)	6	3.7(2.6)	7	1.7(0.9)	7
	-1.5(1.1)	9	-2.4(2.5)	8	-1.5(1.5)	9
Left lateral flexion	**32.3(8.1)**		**30.5(8.1)**		**28.5(5.9)**	
Forward flexion	9.2(5.8)	14	8.2(4.8)	14	5.9(3.4)	15
	-7.1	1	-2.6	1	-3.1	1
Rotation	4.9(3.0)	14	3.7(2.7)	10	5.2(3.1)	13
	-2.9	1	-2.9(2.8)	5	-2.5(1.1)	3
Right lateral flexion	**30.6(8.6)**		**28.5(8.2)**		**23.2(6.3)**	
Forward flexion	8.4(5.1)	14	10.5(6.5)	15	8.9(6.0)	16
	-3.2	1	-		-	
Rotation	1.8	1	1.9(1.7)	2	1.5(1.8)	2
	-6.0(3.7)	14	-6.9(3.9)	13	-6.5(4.1)	14
Left rotation	**24.9(6.0)**		**24.7(5.7)**		**22.6(4.5)**	
Forward flexion	10.5(4.4)	15	10.7(3.6)	15	6.7(3.5)	16
	-		-		-	
Lateral flexion	6.0(3.9)	11	6.3(4.6)	12	5.7(3.5)	13
	-2.1(2.9)	4	-5.8(1.5)	3	-4.8(1.3)	3
Right rotation	**25.1(6.3)**		**24.9(6.8)**		**21.4(4.4)**	
Forward flexion	11.4(5.4)	15	10.1(4.3)	15	8.9(3.9)	16
	-		-		-	
Lateral flexion	3.4(1.0)	4	3.7(3.7)	6	3.4(1.6)	6
	-6.7(3.4)	11	-7.9(4.6)	9	-3.9(3.5)	10

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

Table G.11 Means (S.D) of range of motion for primary and associated movements.

Subjects: Female

Segment: Lumbar spine

Speed of motion: Preferred

Primary mvt Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**39.2(9.2)**		**37.1(11.5)**		**32.2(6.8)**	
Lateral flexion	2.3(1.3)	11	2.3(1.9)	8	3.1(2.2)	8
	-1.2(1.2)	9	-1.4(1.0)	10	-2.9(2.1)	8
Rotation	1.6(1.5)	9	1.3(1.1)	10	2.2(1.5)	8
	-1.5(1.0)	11	-1.9(1.1)	8	-1.8(1.5)	8
Left lateral flexion	**32.6(4.2)**		**30.8(5.4)**		**25.2(6.3)**	
Forward flexion	12.2(6.6)	20	10.7(6.6)	16	7.7(4.9)	13
	-		-1.3(0.4)	2	-0.6(0.6)	3
Rotation	5.8(3.8)	18	5.7(3.8)	12	4.3(2.6)	13
	-1.8(1.4)	2	-2.1(1.4)	6	-2.2(1.9)	3
Right lateral flexion	**33.0(6.9)**		**31.3(5.9)**		**24.0(6.7)**	
Forward flexion	12.0(5.9)	19	10.6(6.8)	17	9.6(4.8)	16
	-1.54	1	-3.9	1	-	
Rotation	-		0.3	1	1.5(1.9)	2
	-5.0(3.6)	20	-4.7(3.5)	17	-5.7(3.1)	14
Left rotation	**19.3(4.4)**		**19.6(6.6)**		**18.9(5.9)**	
Forward flexion	7.6(4.5)	19	6.8(3.1)	17	5.6(1.9)	11
	-1.1	1	-5.5	1	-1.5(1.2)	5
Lateral flexion	6.1(4.6)	17	5.2(3.5)	16	6.8(2.1)	8
	-3.1(2.9)	3	-3.1(3.2)	2	-7.8(6.6)	8
Right rotation	**19.1(5.2)**		**20.1(7.1)**		**17.2(4.9)**	
Forward flexion	7.9(3.7)	18	5.3(3.2)	17	5.9(3.6)	14
	-0.6(0.1)	2	-0.5	1	-3.3(0.9)	2
Lateral flexion	1.6(1.5)	7	1.3(1.1)	3	5.9(4.6)	9
	-5.2(2.9)	13	-5.8(4.0)	15	-3.3(3.1)	7

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

Table G.12 Means (S.D) of range of motion for primary and associated movements.

Subjects: Female

Segment: Lumbar spine

Speed of motion: Fast

Primary mvt Associated mvts	Young	N	Middle	N	Elderly	N
Forward flexion	**38.6(9.4)**		**36.6(11.1)**		**31.4(6.4)**	
Lateral flexion	2.5(1.7)	11	2.6(1.5)	9	3.4(2.3)	6
	-1.8(1.7)	9	-2.0(1.7)	9	-2.2(1.8)	10
Rotation	1.9(1.5)	8	1.4(1.2)	11	2.1(1.7)	8
	-1.4(0.9)	12	-2.4(1.1)	7	-1.5(1.2)	8
Left lateral flexion	**29.7(3.6)**		**28.6(4.6)**		**24.1(5.3)**	
Forward flexion	9.8(4.9)	20	9.7(6.0)	16	6.2(4.5)	15
	-		-4.1(5.2)	2	-4.3	1
Rotation	5.4(3.7)	18	4.3(3.6)	13	4.1(2.6)	14
	-1.8(2.1)	2	-2.3(1.0)	5	-2.2(2.9)	2
Right lateral flexion	**29.1(6.1)**		**29.4(5.5)**		**22.2(5.6)**	
Forward flexion	10.7(5.7)	19	10.4(5.7)	17	9.2(4.7)	16
	-0.7	1	-2.0	1	-	
Rotation	0.9	1	0.6	1	2.4	1
	-5.4(3.6)	19	-5.6(3.2)	17	-5.2(2.7)	15
Left rotation	**21.3(5.0)**		**20.9(7.6)**		**19.3(6.0)**	
Forward flexion	8.2(4.4)	20	8.3(3.6)	16	6.1(3.2)	14
	-		-1.4(1.4)	2	-3.3(3.6)	2
Lateral flexion	5.5(2.9)	19	6.1(3.6)	14	4.6(4.0)	8
	-6.9	1	-1.7(1.4)	4	-6.9(5.8)	8
Right rotation	**21.1(6.3)**		**22.5(7.2)**		**18.3(6.2)**	
Forward flexion	8.1(4.5)	20	7.2(3.2)	17	7.3(3.4)	13
	-		-0.01	1	-1.7(1.0)	3
Lateral flexion	4.9(5.0)	3	1.9(1.4)	3	5.8(4.0)	9
	-5.3(3.2)	17	-6.4(4.7)	15	-5.3(2.2)	7

Note: Negative values of associated forward flexion refer to extension.
: Negative values of associated rotation and lateral flexion refer to movement towards the left side.
: N = number of subjects

APPENDIX H.

Data for Angular Velocity of the Seated Lift

Table H.1 Means (SD) of forward flexion and extension angular velocity, during phase I to IV motion, of male and female groups for the overall thoracolumbar spine and lumbar spine at the preferred and fast speeds of motion.

Subject groups	Phase I (Flexion)	Phase II (Extension)	Phase III (Flexion)	Phase IV (Extension)
Thoracolumbar spine				
Preferred speed				
Male: Young	58.3(16.7)	-59.0(19.8)	54.3(19.9)	-57.4(19.2)
Middle-aged	64.1(27.6)	-68.6(29.6)	62.5(28.9)	-66.1(29.4)
Elderly	47.3(15.9)	-49.8(16.1)	42.5(11.3)	-46.3(16.6)
Female: Young	65.4(31.2)	-66.4(19.7)	62.5(18.9)	-62.6(14.1)
Middle-aged	69.9(20.1)	-66.5(21.0)	60.9(19.3)	-64.4(16.2)
Elderly	54.9(19.4)	-55.9(20.1)	45.3(17.6)	-49.8(20.3)
Fast speed				
Male: Young	89.4(32.4)	-87.5(29.1)	77.3(30.7)	-82.8(23.5)
Middle-aged	87.9(31.9)	-95.7(43.1)	81.7(36.6)	-89.1(42.7)
Elderly	60.5(18.3)	-66.3(25.0)	59.9(24.2)	-55.0(18.2)
Female: Young	86.1(18.6)	-91.1(23.0)	82.3(27.7)	-81.7(25.3)
Middle-aged	91.5(25.8)	-91.5(34.4)	79.2(23.4)	-80.7(22.9)
Elderly	66.9(21.8)	-77.2(33.0)	49.6(20.1)	-54.6(21.9)
Lumbar spine				
Preferred speed				
Male: Young	56.5(16.1)	-58.1(16.8)	54.7(18.5)	-56.3(19.1)
Middle-aged	61.6(26.4)	-65.5(24.7)	63.0(27.6)	-61.9(25.2)
Elderly	46.9(15.6)	-49.9(14.0)	45.2(13.0)	-47.4(16.0)
Female: Young	56.0(14.6)	-61.8(18.5)	60.6(14.6)	-57.6(12.0)
Middle-aged	63.5(19.5)	-62.4(16.2)	58.8(15.5)	-59.1(12.6)
Elderly	50.2(17.1)	-50.4(17.1)	50.5(20.7)	-46.7(12.1)
Fast speed				
Male: Young	86.3(28.5)	-81.0(22.9)	78.2(26.9)	-79.2(18.7)
Middle-aged	83.3(29.7)	-83.9(27.8)	80.5(30.0)	-79.6(29.2)
Elderly	55.5(19.7)	-59.7(21.9)	62.1(20.8)	-55.2(16.4)
Female: Young	79.8(23.2)	-78.1(16.7)	75.6(19.3)	-71.1(16.2)
Middle-aged	82.8(23.7)	-81.6(21.2)	78.3(22.3)	-70.9(16.9)
Elderly	62.4(18.1)	-59.0(16.6)	58.7(19.5)	-56.9(18.9)

Table H.2 Means (SD) of left and right lateral flexion angular velocity, during phase I to IV motion, of male and female groups for the overall thoracolumbar spine and lumbar spine at the preferred and fast speeds of motion.

Subject groups	Phase I L. lat. flexion	Phase II L. lat.flexion	Phase III R. lat.flexion	Phase IV R. lat. flexion
Thoracolumbar				
Preferred speed				
Male: Young	-42.6(11.5)	34.6(8.7)	38.6(11.0)	-37.3(8.4)
Middle-aged	-47.8(15.1)	32.4(6.7)	44.8(20.2)	-36.0(10.3)
Elderly	-43.8(14.0)	30.6(7.4)	35.8(8.6)	-33.2(7.0)
Female: Young	-51.4(19.8)	36.5(16.3)	46.5(11.5)	-44.1(13.1)
Middle-aged	-49.5(9.5)	33.0(8.2)	45.6(20.1)	-35.7(13.8)
Elderly	-43.0(15.3)	32.3(13.3)	35.5(11.7)	-33.3(4.7)
Fast speed				
Male: Young	-64.6(19.3)	44.1(9.5)	59.6(16.3)	-46.4(9.1)
Middle-aged	-64.6(17.2)	40.6(12.9)	55.2(18.8)	-41.2(13.7)
Elderly	-51.3(13.1)	37.4(7.5)	47.4(10.1)	-41.4(10.2)
Female: Young	-64.7(18.8)	49.7(21.7)	66.7(22.0)	-49.6(17.9)
Middle-aged	-64.0(16.4)	43.2(14.6)	68.6(24.0)	-42.6(12.6)
Elderly	-47.8(11.3)	39.4(11.9)	39.3(12.1)	-35.3(8.0)
Lumbar spine				
Preferred speed				
Male: Young	-30.3(8.4)	24.1(7.1)	28.5(7.0)	-27.1(6.3)
Middle-aged	-31.8(12.2)	24.9(5.3)	28.1(15.8)	-26.6(9.6)
Elderly	-30.3(11.8)	22.5(5.6)	20.9(4.7)	-21.1(5.3)
Female: Young	-34.3(6.8)	23.4(7.6)	33.5(8.3)	-31.9(11.1)
Middle-aged	-32.0(8.5)	24.5(6.4)	31.9(16.5)	-25.2(10.0)
Elderly	-31.9(8.4)	22.4(5.2)	23.1(8.1)	-24.4(4.2)
Fast speed				
Male: Young	-43.0(12.5)	36.3(7.5)	36.7(11.8)	-32.9(8.2)
Middle-aged	-43.9(18.1)	29.2(8.2)	35.2(18.2)	-30.2(9.9)
Elderly	-36.9(11.4)	30.6(11.4)	30.4(6.8)	-26.6(8.2)
Female: Young	-41.8(10.9)	34.8(18.4)	48.5(14.5)	-34.3(10.4)
Middle-aged	-41.2(11.8)	31.1(9.5)	46.6(20.5)	-28.1(10.6)
Elderly	-36.9(6.0)	26.8(7.8)	28.8(10.1)	-26.4(5.7)

APPENDIX I.

Terms and Definitions

Kinematics

Kinematics is that phase of mechanics concerned with the study of motion of rigid bodies, with no consideration of the forces involved (White and Panjabi, 1990). While the vertebrae are not in fact rigid bodies, in the usual motions of the spine they can be considered to behave as rigid bodies (White, 1971).

Coordinate system

The right-handed orthogonal (90 degree or Cartesian) coordinate system has been recommended for precise orientation of the human body (White and Panjabi, 1978). In the present study, the positive x axis is the anterior direction, the positive y axis the left lateral direction and the negative z axis the cephalo-caudal direction.

Motion segment

The motion segment is the traditional unit of study in spinal kinematics. A motion segment consists of two adjacent vertebrae and all intervening soft tissues. The motion segment is considered to be the functional unit of the spine, representing the smallest mechanical unit of the spine involving kinetics as well as kinematics (White and Panjabi, 1990; Hall, 1991).

Translation

A body (any piece of matter) is said to be in translation when movement is such that all particles in the body at a given time have the same velocity relevant to some reference and moves in the same direction and to the same extent (White and Panjabi, 1978; Bogduk and Twomey, 1991).

Rotation

A body is said to be in rotation when movement is such that all particles along some straight line in the body or a hypothetical extension of it have zero velocity relative to a fixed point. The body moves in a similar direction but to different extents depending on their radial distance from the fixed point. Rotation is an angular displacement of a body about some axis. The axis may be located outside the rotating body or inside it.

Degrees of freedom

One degree of freedom is motion in which a rigid body may translate along a straight line or may rotate about a particular axis. Vertebrae are traditionally described as having six degrees of freedom. They may instantaneously translate along any of the three orthogonal axes or rotate about any of the three axes.

Range of motion (ROM)

An indication of the two points at the extremes of the physiologic range of translation and rotation of a vertebra for each of the six degrees of freedom. Translation is expressed in millimeters or inches, and rotation in degrees. Only the ranges of rotation about the three axes are presented in this study.

Coupling

Coupling is applied to motion in which rotation or translation about one axis is consistently associated with rotation or translation about another two axes. In this study the coupling is concerned with the rotational components. For example, rotation about the vertical axis is associated with rotations about the anteroposterior and lateral axes.

Pattern of motion

Pattern of motion is defined by the Euler angle time series of the relative attitude of the segments. Changes in the normal coupling or the instantaneous axes of rotation are considered abnormal patterns of motion.

Angular velocity

Angular velocity is the time rate of change of angular displacement and is calculated as the change in angular displacement that occurs during a given period of time. If the angular displacement of an object is known as a function of time, its angular velocity can be determined by taking its first derivative with respect to time. In this study, the peak and average angular velocities are reported.