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Original article

Investigating the contribution of the upper and lower lumbar spine, relative to hip motion, in everyday tasks

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ABSTRACT

Background: It is commonplace for clinicians to measure range of motion (ROM) in the assessment of the lumbar spine. Traditional single 'joint' models afford measuring only a limited number of regions along the spine and may, therefore, over-simplify the description of movement. It remains to be determined if additional, useful information can be gleaned by considering the traditional 'lumbar region' as two regions.
Objective: The aim of this study was to determine whether modelling the lumbar spine as two separate regions (i.e. upper and lower), yields a different understanding of spinal movement relative to hip motion, than a traditional single-joint model. This study is unique in adopting this approach to evaluate a range of everyday tasks.
Method: Lumbar spine motion was measured both by being considered as a whole region (S1 to T12), and where the lumbar spine was modelled as two regions (the upper (L3-T12) and lower (S1-L3)).
Results: A significant difference was evident between the relative contribution from the lower and upper spine across all movements, with the lower lumbar spine consistently contributing on average 63% of the total ROM. A significant difference was also evident between the whole lumbar spine-hip ratio, and the lower lumbar spine-hip ratio, for the movement of lifting only. The lower lumbar spine achieved greater velocity for all tasks, when compared to the upper lumbar spine.
Conclusion: This study has consistently demonstrated differences in the contribution of the upper and lower spinal regions across a range of everyday tasks; hence, it would appear that greater focus should be given to performing more detailed assessments to fully appreciate spinal movement.

1. Introduction

Measuring lumbar range of motion (ROM) is typically performed using 2 sensors or markers, one at each end of the lumbar spine. This includes technologies relying on electromagnetics (Shum et al., 2005, 2007), inertial sensors (Ha et al., 2013; Williams et al., 2013) and fibre-optics (Williams et al., 2010). Calculating the resultant angle between these 2 sensors provides an estimate of lumbar range of motion, with the lumbar spine modelled as a single 'joint'. The lumbar spine, however, consists of many segments or 'joints' (L1-S1) and thus this single joint model may result in lost information about more regional lumbar spine movement behaviour. Whilst previous authors have suggested that the upper and lower lumbar spines display differences in their kinematic behaviour (Williams et al., 2012; Parkinson et al., 2013; Williams et al., 2013), traditional single 'joint' models would fail to identify such subtleties and may, therefore, over simplify the description of movement. Significant scope exists to better understand and appreciate the relationship between lumbar spine and hip kinematics, given how it both underpins rehabilitation programmes (Lee and Wong, 2002) and is associated with various forms of functional disabilities, which may have a serious impact on an individual's quality of life (Cox et al., 2000).

The dominant functional tasks such as flexion, extension, lifting and transiting from stand-to-sit or sit-to-stand have long been associated with spinal disorders and spinal pain (McGill, 1997; Dempsey, 1998). Spine and hip kinematics are closely coordinated when performing many daily tasks (Mayer et al., 1984; Pearcy et al., 1985; Strand and Wie, 1999), suggesting that lumbar spine-hip

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disorders may affect functional tasks as well as the cardinal movements often employed in the clinic. Indeed, sit-to-stand and stand-to-sit activities are very regular daily tasks (Lomaglio and Eng, 2005), performed 60 times per day on average by working people (Dall and Kerr, 2010). The most important task that influences lumbar and hip kinematics is lifting objects from the floor, which is a common daily activity particularly amongst those working in jobs involving physical labour (Shum et al., 2005).

A series of studies have previously focused on quantifying the relationship between the lumbar spine relative to hip motion, during everyday tasks (Paquet et al., 1994; Lee and Wong, 2002; Wong and Lee, 2004; Shum et al., 2005; Shum et al., 2007); however, in all cases the lumbar spine was only considered as a single region. More recently, authors have adopted multi-regional lumbar spine models across clinical populations (Williams et al., 2012, 2013) and healthy subjects (Leardini et al., 2011; Parkinson et al., 2013), identifying differences in regional contribution. No study has yet, however, considered a multi-regional lumbar spine model versus hip motion, across a series of everyday tasks. Such data would significantly assist in achieving a better understanding of lumbar spine kinematics, especially when supplemented by multi-regional velocities (Shum et al., 2010), as the relative movement behaviour of the hip and its interaction with the lumbar spine has been suggested as being important (Lee and Wong, 2002; Sahrmann, 2002; O'Sullivan, 2005). Clinical studies have previously confirmed differences in this ratio between those with and without back pain (Shum et al., 2005, 2007), whilst alterations in this ratio affect the bending and compressive stresses on the lumbar spine (Dolan and Adams, 1993; Tafazzol et al., 2014).

Subsequently, this study investigated how the upper and lower lumbar regions contributed to spinal movement – relative to hip motion, when performing a range of everyday tasks. Comparison was drawn both to a traditional 'single-joint' measuring method, and to previous studies evaluating a single, everyday tasks (i.e. sit-to-stand).

2. Methods

2.1. Participants

Fifty-three male participants were recruited from Cardiff University (age = 29.4 ± 6.5 years; mass = 75.3 ± 16.4 kg; height = 1.69 ± 0.15 m). No participants had a history of lower extremity problems or spinal pain, surgery, rheumatological or neurological disorders. All participants provided written informed consent prior to data collection. The study was approved by the Cardiff School of Engineering Ethics Committee.

2.2. Instrumentation

Data describing lumbar spine and hip kinematics were collected using four tri-axial accelerometers (THETAMetrix, Waterlooville, UK), each with a 24 mm^2 footprint. Each sensor was then placed, using double-sided tape, over the spinous processes of S1, L3, T12 and the lateral aspect of the right thigh, mid-way between the lateral epicondyle and greater trochanter on the iliotibial band (ITB) (Fig. 1). Each accelerometer provided axial acceleration data pertaining to absolute orientation (tilt), with respect to gravity. Sensors were wired together in a 'daisy chain' arrangement and connected to a PC, running data collection software via USB. Data were captured at 30 Hz using the supplied 3A sensor software (THETA-Metrix, Waterlooville, UK), and stored for retrospective processing. This system has been found previously to have excellent repeated-measures reliability relating to spinal movement analysis, with the intraclass correlation coefficient ranging from 0.88 to 0.99, and a standard error of measurement ranging from 0.4° to 5.2° (Alqhtani et al., 2015).

2.3. Procedure

Participants' height and weight were determined prior to sensor attachment. Participants completed a warm up exercise, which included flexion, extension and rotation of the trunk, and then a period of sensor familiarisation for the participants. Prior to starting the actual trial, participants were asked to do one trial to familiarise themselves with the experimental procedure. Each participant stood barefoot on assigned markers and focused on a wall marker, set at a height of 2 m, with arms relaxed by their side. Participants were asked to complete forward bending, backward bending, lifting an object (wooden box with handles weighing 3 kg) from the floor and returning to a standing position, moving from stand to sit on a stool and then returning to standing. No further instructions on how to move were provided.

2.4. Data analysis

Raw data were transferred to MATLAB (MathWorks Inc, Natick, MA) and filtered at 6 Hz (low-pass, Butterworth) to remove high frequency noise (Scholz et al., 2001). Sagittal plane absolute angles for each sensor were determined, with respect to gravity and regional ROM was defined as the relative motion between adjacent distal and proximal sensors (relative angles). The whole lumbar spine was defined as the relative angle between the S1 and T12 sensors. The upper lumbar spine (ULS) was defined as the relative angle between the T12 and L3 sensors, and lower lumbar spine (Mills et al., 2007) as the relative angle between the L3 and S1 sensors. As the whole lumbar spine consists of six spinal joints and the ULS and LLS only three spinal joints, the regions were normalised per segment (i.e. the WLS kinematics divided by six and ULS and LLS kinematics divided by three). This normalisation enabled comparisons between the regions to be possible. The kinematics of ROM was determined as relative angle across time and angular velocity calculated by 5-point differentiation of the ROM-time data (Williams et al., 2013). The ratios of lumbar-to-hip motion for each region (ULS, LLS and WLS) were determined for each task. Therefore, the dependent variables for this study were ROM, peak velocity (negative and positive) and lumbar-hip ratio.

As this study aimed to evaluate the contribution of ULS and LLS relative to hip motion, an ANOVA was used to test for differences between the WLS, ULS and LLS (SPSS ver. 20). Post–hoc analysis was applied using the Tukey procedure to determine the location of any differences. Statistical significance was accepted at the 5% level for all tests.

3. Results

3.1. ROM

The mean (SD) ROM (normalised per segment) are presented in Table 1.

There was a significant difference in the ROM displayed by the ULS compared with the WLS for flexion, lifting and sit-to-stand (Table 2). Significant differences were also present between the LLS and WLS for flexion and lifting (Table 2).

A significant difference was evident between the relative contribution from the LLS and ULS across all movements (Table 2), with the lower lumbar spine consistently contributing on average 63% of the total ROM (Fig. 2).

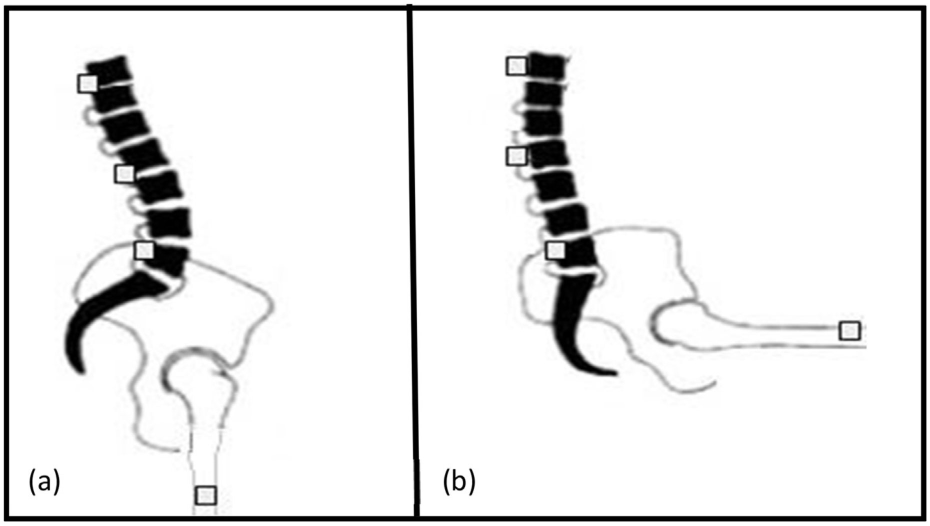

Fig. 1. Schematic representation of the three spinal sensors, over processes T12, L3 and S1. A fourth sensor was placed on the lateral aspect of the thigh, midway between the lateral epicondyle and greater trochanter on the iliotibial band (ITB). (a) Standing, (b) sitting.

Table 1
Contribution of the whole (WLS), upper (ULS) and lower (LLS) lumbar spinal regions. Range of motion data it presented as the normalised mean (degrees), with the standard deviation in parentheses.

Tasks	WLS/6	ULS/3	LLS/3
Flexion	9.8 (2.4)	7.7 (3.4)	12.0 (4.4)
Extension	−4.1 (2.6)	−2.8 (3.5)	−5.6 (4.3)
Lifting	9.3 (2.7)	7.2 (3.3)	11.8 (4.6)
Stand-to-sit	7.3 (2.8)	5.6 (3.3)	9.0 (4.9)
Sit-to-stand	7.3 (3.1)	5.4 (3.4)	8.9 (4.9)

Table 2
The p-values describing the statistical difference in range of motion data between the ULS, LLS and WLS segments (UL = 3, LL = 3 and WL = 6 segments) for each anatomical region, during a range of tasks. Statistical significance defined as $p < 0.05$, with significant data identified using an*.

Segments	Flexion	Extension	Lifting	Stand-to sit	Sit-to stand
ULS/3 vs LLS/3	<.001*	<.001*	<.001*	<.001*	<.001*
ULS/3 vs WLS/6	.006*	.191	.009*	.070	.037
LLS/3 vs WLS/6	.006*	.058	.002*	.073	.109

3.2. Ratio

The mean (SD) peak hip-lumbar ratio per segment ROM is displayed in Table 3.

A significant difference was evident between the WLS-hip ratio and the LLS-hip ratio for the movement of lifting only. No differences were noted for the WLS-hip and ULS-hip ratio. There were significant differences between the ULS-hip and LLS-hip ratio for all movements except extension (Table 4).

3.3. Velocity

Mean (SD) peak velocity for each spinal region is presented in Table 5.

A significant difference was evident between the WLS and LLS peak velocity, but only for flexion. There were significant differences between the ULS and WLS for peak velocity for stand-to-sit and lifting. No other tasks demonstrated 'per segment' peak velocity differences. Significant differences were determined between the ULS and LLS for peak velocity during all tasks, with the exception of positive velocity during extension and negative velocity during lifting (Table 6). The LLS achieved greater velocity for all tasks when compared to the ULS with the magnitude of difference ranging from 37% to 63% greater (Fig. 2).

4. Discussion

This study used a novel methodology to investigate the ratio of normalised lumbar motion, relative to hip motion. The results demonstrate few differences between each of the WLS, ULS and LLS versus hip motion, suggesting that either model may be effective in exploring lumbar spine-hip ratios. Previous studies have explored lumbar spine-hip ratios using a WLS model, with some reporting slightly higher ratios for sit-to-stand and stand-to-sit (Shum et al., 2005). Furthermore, our data indicates a proportionally greater WLS contribution to extension (than the hip) as compared to other studies (Lee and Wong, 2002; Wong and Lee, 2004), which may be due to different patient characteristics or due to a lower mean age, resulting in greater lumbar flexibility as displayed by the differences in lumbar extension ROM (Lee and Wong, 2002; Wong and Lee, 2004).

Despite the lack of difference between the WLS, and the combined ULS–LLS models, there were differences between the ULS and LLS that suggest the relationships between the hip and these specific lumbar regions are functionally different and unique. LLS-hip ratios were consistently higher than the ULS-hip ratios, due to the greater LLS ROM. This suggests that the relationship between the separate regions of the lumbar spine and hip were not equivocal and should be explored individually to appreciate the differences in kinematic behaviour.

The calculation of ratios in this manner provides insight only to the relationship of the terminal ranges, not the through range phases. Angle–angle plots can provide a description of where the ROM of each region is plotted against one another, thereby revealing further insights into kinematic behaviour. Fig. 3 illustrates the WLS plotted against the hip and the ULS-hip and LLS-hip plots for comparison (the straight-line represents a 1:1 ratio for comparison). If a WLS model was used, the behaviour would demonstrate that the hip and WLS move at a similar time and rate throughout the movement phase i.e. broadly correlating with the

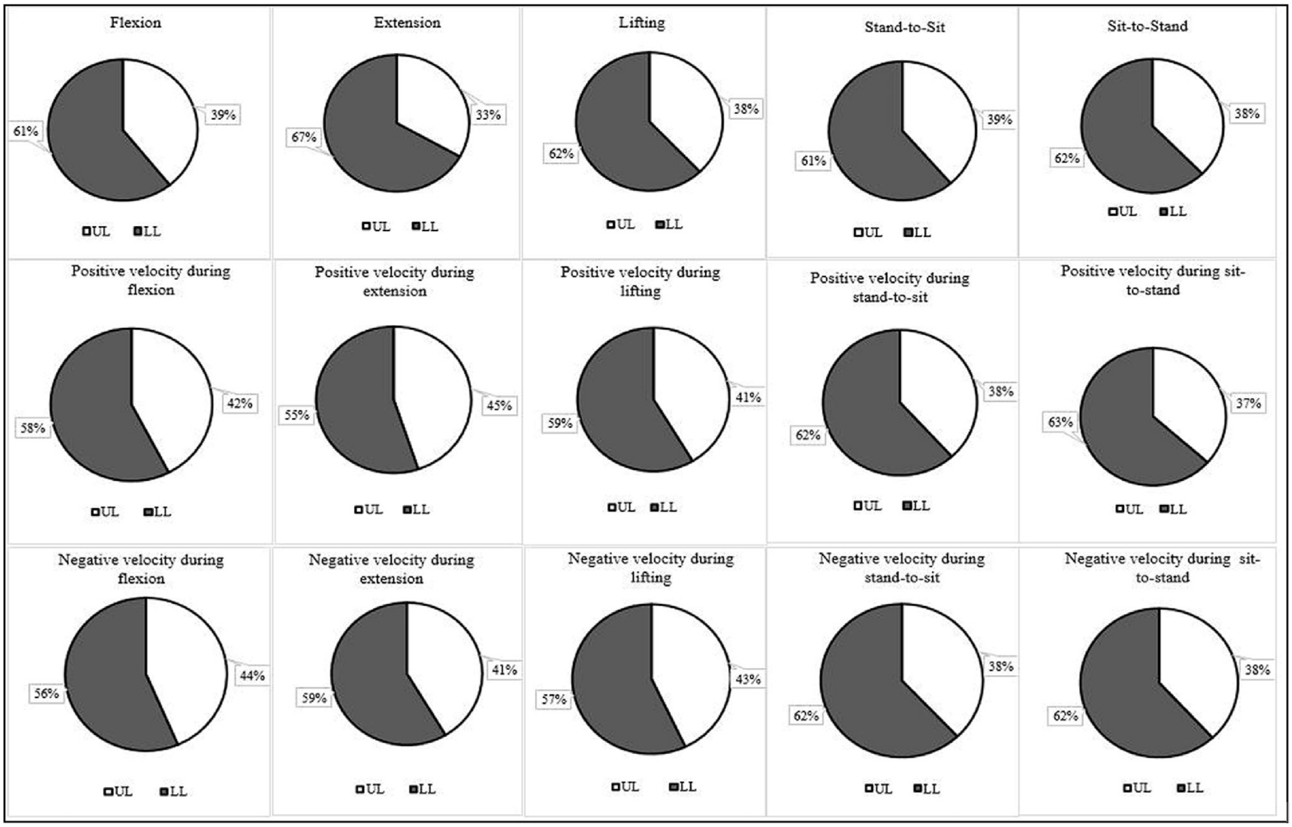

Fig. 2. Relative contributions of the upper lumbar (UL) and lower lumbar (LL) spinal regions during a series of everyday tasks.

Table 3
The ratio of normalised ROM data for ULS, LLS and WLS, versus hip ROM data (degrees). The standard deviation is presented in parentheses.

Tasks	(WLS/6)/Hip	(ULS/3)/Hip	(LLS/3)/Hip
Flexion	0.2 (0.1)	0.16 (0.1)	0.25 (0.1)
Extension	0.3 (1.5)	0.2 (1.1)	0.5 (2.3)
Lifting	0.16 (0.1)	0.1 (0.1)	0.2 (0.1)
Stand-to-sit	0.1 (0.1)	0.1 (0.1)	0.16 (0.1)
Sit-to-stand	0.1 (0.1)	0.1 (0.1)	0.16 (0.1)

Table 4
A statistical evaluation of the differences in ratio per segment for normalised ROM to hip ROM. Statistical significance defined as $p < 0.05$, with significant data identified using an*.

Segments	Flexion	Extension	Lifting	Stand-to sit	Sit-to stand
(ULS/3)/Hip vs (LLS/3)/Hip	<.001*	.556	<.001*	.004*	<.002*
(WLS/6)/Hip vs (ULS/3)/Hip	.093*	.910	.077	.234	.154
(WLS/6)/Hip vs (LLS/3)/Hip	.093*	.809	.041*	.234	.260

Table 5
Velocity per segment (degrees/s) of ULS, LLS and WLS segments during four tasks.

Tasks velocities		WLS/6	ULS/3	LLS/3
Flexion	+ve vel	8.6 (2.8)	7.5 (2.9)	10.5 (4.7)
	−ve vel	8.3 (3.4)	7.4 (3.3)	9.6 (4.5)
Extension	+ve vel	5.4 (3.0)	4.9 (3.0)	6.1 (4.3)
	−ve vel	4.6 (2.8)	3.9 (2.9)	5.5 (4.1)
Lifting	+ve vel	10.0 (3.4)	8.4 (3.9)	10.5 (4.7)
	−ve vel	9.3 (3.1)	7.3 (3.3)	9.6 (4.5)
Stand-to-sit	+ve vel	9.7 (3.3)	5.5 (2.5)	9.0 (4.9)
	−ve vel	5.9 (3.4)	3.3 (1.4)	5.4 (3.2)
Sit-to-stand	+ve vel	4.3 (2.2)	3.1 (1.9)	5.5 (3.5)
	−ve vel	7.5 (3.3)	5.6 (2.8)	9.2 (5.0)

Table 6
The significant difference (p-value) considering velocity between the ULS, LLS and WLS segments for each anatomical region during four tasks. Statistical significance defined as $p < 0.05$, with significant data identified using an*.

Segments		Flexion	Extension	Lifting	Stand-to sit	Sit-to stand
+ve velocity						
ULS/3	LLS/3	<.001*	.228	.021*	<.001*	<.001*
	WLS/6	.246	.771	.110	<.001*	.082
LLS/3	WLS/6	.019*	.602	.779	.600	<.060*
−ve velocity						
ULS/3	LLS/3	.011*	.039*	.091	.001*	.001*
	WLS/6	.421	.535	.029*	<.001*	.054
LLS/3	WLS/6	.218	.346	.919	<.637	<.067

aforementioned straight grey line; however, the regional breakdown shows a significantly greater contribution from the hip, especially in the early phase of the motion for the LLS, where it is more even in the same phase of motion for the ULS. Such behaviour would not be visible with a WLS model.

The findings from the current study suggests that regional breakdown of the lumbar spine is also important regarding velocity. Differences between the WLS and regional spinal models were detected, as were differences between the LLS and ULS. This suggests that the ULS and LLS are functionally different for the higher order kinematics also. The velocities determined in this study were slightly greater than those reported in other studies for movements at natural speeds (Shum et al., 2005; Williams et al., 2013). These differences may be due to differences in characteristics of the sample, such as age (younger in the current study), sex (male in the

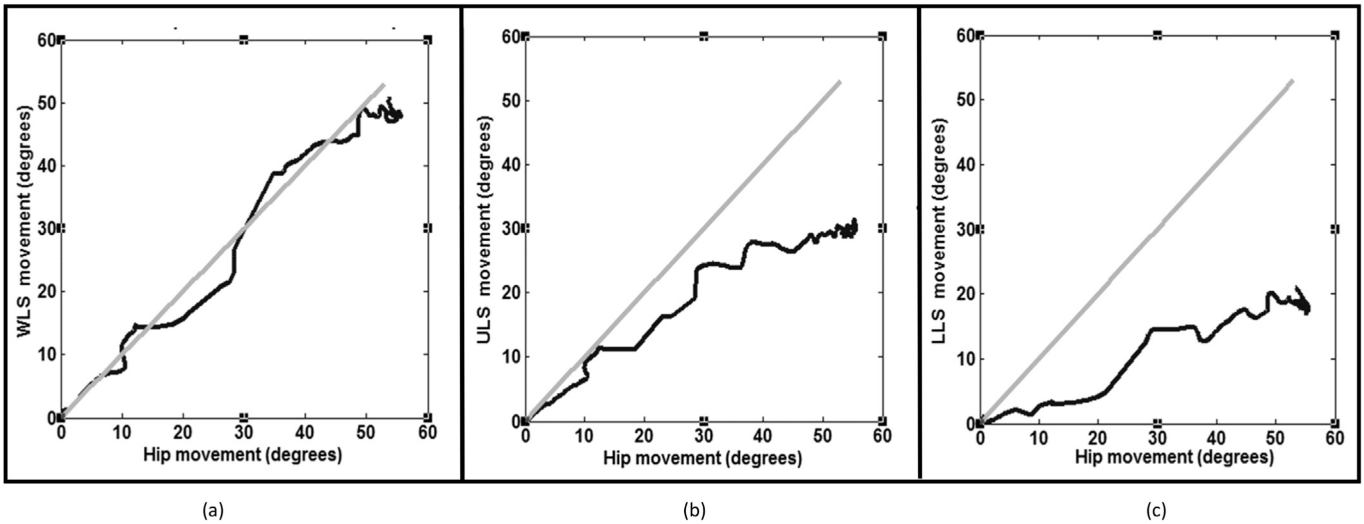

Fig. 3. The phase relationship of the lumbar spine to hip movement, with the grey line representing a sustained 1:1 relationship. These figures represent the movement phase of the WLS (a), ULS (b) and LLS (c), relative to the hip.

current study) and the presence of pain (Williams et al., 2013). The additional information gained from the regional breakdown of the lumbar spine identified that the LLS consistently moved at greater velocities. The authors are not aware of this having previously reported in the literature, though this is important since it suggests a non-even split of velocity throughout the ULS and LLS, a finding masked by a traditional single segment model.

This study also investigated the contribution of the ULS and LLS regions, relative to hip motion, when performing a range of everyday tasks. Modelling the lumbar spine as two distinct regions identified differences in the normalised (i.e. per-segment) ROM, with the LLS contribution greater than ULS by at least 2.4°, and WLS by 1.5°, over all tasks. ROM percentages per LLS segment were greater than ULS over all five tasks (Fig. 2). Hence, it was evident that modelling the WLS underestimated the LLS motion by as much as 37%, and over-estimated the ULS motion by as much as 45%. Whilst this finding is in agreement with previous studies (Williams et al., 2010; Leardini et al., 2011; Williams et al., 2012; Parkinson et al., 2013; Williams et al., 2014), the current study was the first to adopt a method of normalisation to enable a quantitative comparison. The findings are consistent with studies adopting stereoradiography (Pearcy et al., 1985) and cadaveric testing (Yamamoto et al., 1989), contributing to the increasing body of evidence that suggests a non-uniform breakdown of ROM contribution for the lumbar segments. Subsequently, this indicates that simply modelling the lumbar spine as a whole region may omit some important kinematic information, and under-estimate the LLS contribution.

The findings of the current study have important clinical ramifications. Clinicians are beginning to advocate the assessment of two separate functional regions within the lumbar spine (O'Sullivan, 2005; Dankaerts et al., 2006), with the belief that these are functionally individual. This study confirms that indeed there are functional differences in the ROM of lumbar spine models, and velocity of motion during a range of functional tasks and provides support for the use of a more detailed spinal kinematic model. Greater contributions to motion from the lower lumbar spine, as well as greater movement velocities, may help to explain increased prevalence of low back pain or pathological change in this spinal region more than the upper lumbar (Biering-Sørensen, 1983; Beattie et al., 2000). Usually, greater degeneration takes place in the lower lumbar spinal segments (Twomey and Taylor, 1987; Quack et al., 2007) and it is assumed that this is due to greater mechanical stress upon this region (Adams and Hutton, 1983). Assessment of the lumbo-pelvic rhythm has also been suggested during clinical assessment of the back (O'Sullivan, 2005), as the hip motion effects the resultant bending stresses (Dolan and Adams, 1993) and muscle activities, as well as the forces acting on the lumbar spine (McGill et al., 2000; O'Sullivan et al., 2002; Kamińska et al., 2010). Insights into lumbo-pelvic rhythm can be afforded through the determination of ratios and angle–angle plots, and this study provides novel detail regarding the regional spinal ratios.

This study provides further evidence for the separation of the whole lumbar spine into smaller regional sections, as suggested previously (Parkinson et al., 2013), to truly determine detailed kinematic information for the lumbar spine.

Limitations of the current study include a single sex population preventing the extrapolation of the findings to females. The sample was representative of a young non-impaired population and findings relating to more elderly, or those in pain or impaired, may differ from the current findings. Analysis was limited to the sagittal plane and more detailed 3-dimensional kinematics would provide detail regarding out of plane motions.

5. Conclusion

The findings of the current study suggest modelling the lumbar spine as two distinct regions demonstrates normalised kinematic differences compared to treating the lumbar spine as a whole. It is evident that modelling the lumbar spine as a whole entity underestimates the contribution from the LLS and over-estimates the contribution from the ULS. This suggests that to model the lumbar spine as a whole may omit some important kinematic information. Clinicians should be aware of the differences between the regions to better inform their clinical assessment of the lumbar spine.

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