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Distinguishing between typical and atypical motion patterns amongst healthy individuals during a constrained spine flexion task

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ABSTRACT

Despite 'abnormal' motion being considered a risk factor for low back injury, the current understanding of 'normal' spine motion is limited. Identifying normal motion within an individual is complicated by the considerable variation in movement patterns amongst healthy individuals. Therefore, the purpose of this study was to characterize sources of variation in spine motion among a sample of healthy participants. The second objective of this study was to develop a multivariate model capable of predicting an expected movement pattern for an individual. The kinematic shape of the lower thoracic and lumbar spine was recorded during a constrained dynamic trunk flexion movement; as this is not a normal everyday movement task, movements are considered 'typical' and 'atypical' for this task rather than 'normal' and 'abnormal'. Variations in neutral standing posture accounted for 85% of the variation in spine motion throughout the task. Differences in total spine range of flexion and a regional re-weighting of range of motion between lower thoracic and lumbar regions explained a further 9% of the variance among individuals. The analysis also highlighted a difference in temporal sequencing of motion between lower thoracic and lumbar regions which explained 2% of the total movement variation. These identified sources of variation were used to select independent variables for a multivariate linear model capable of predicting an individuals' expected movement pattern. This was done as a proof-of-concept to demonstrate how the error between predicted and observed motion patterns could be used to differentiate between 'typical' and 'atypical' movement strategies.

1. Introduction

The spine is a highly mobile system comprised of a series of motion segments. The complexity of the system results from many degrees of freedom along the spinal column, making it difficult to fully describe the kinematic position and motion of the spine. Studies of spine kinematics have typically involved a trade-off between spatial and temporal resolution. Lateral radiographs and MR images have high spatial resolution and can describe the kinematic position of each vertebra yet are limited to a few select postures. In contrast, motion tracking devices (eg. rigid bodies, accelerometers, electromagnetic sensors, inertial measurement units) are capable of high temporal resolution throughout a dynamic movement; however, they are generally restricted to tracking motion of large segments spanning the lumbar or thoracic spine (eg. Marras et al., 1993; Cholewicki and McGill, 1996; Granata et al., 2004) and they do not directly track motion of the vertebrae. Abnormal spine motion is considered a risk factor for developing low back pain (Stokes et al., 1987); however, due to difficulties associated with recording spine kinematics, our understanding of 'normal' spine motion is limited.

Recent advances have been made towards increasing the temporal resolution of imaging modalities such as cineradiography (Takayanagi et al., 2001; Staub et al., 2015), bi-planar radiography (Dombrowski et al., 2018), and videofluoroscopy (Breen and Breen, 2017). These dynamic medical imaging modalities are the 'gold-standard' for describing spine position. Still, their utility is often restricted by their costs and accessibility. Alternatively, there have also been advances towards increasing the spatial resolution of skin surface mounted techniques for recording dynamic spine kinematics (Preuss and Popvic, 2010; Mahallati et al., 2016; Ignasiak et al., 2017; Schmidt et al., 2018; Zwambag et al., 2018). These advancements in describing spine kinematics have the

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potential to increase our understanding of what constitutes 'normal' spine motion of a larger population.

In general, substantial amounts of variation are observed within healthy and patient populations in neutral standing, flexed postures, and ranges of motion (Pearcy, 1985; Hayes et al., 1989; Miyasaka et al., 2000). Dynamic measures of lumbar spine movement have been shown to be more sensitive for differentiating between patient populations than static measures (Lehman, 2004). It would be beneficial to better understand how static postures such as neutral standing and full flexion influence dynamic motion between these endpoints and the natural variability associated with spine motion. Therefore, the objective of this study was to characterize the sources of variability within a sample of healthy individuals during a restricted dynamic trunk flexion task. It was hypothesized that a limited set of angular measures from the surface of the back could be found to describe a significant proportion of the variability between participants. The final objective of this study was to demonstrate how this set of predictor variables could be used in a multivariate linear model to predict expected movement patterns; in the future, the error between an expected and observed movement pattern for a specified task could be used to differentiate between 'typical' and 'atypical' motion.

2. Methods

2.1. Movement task

Fifty-five healthy participants (10 F/45 M; age: 24 ± 3.3 years; height: 180 ± 10 cm; mass: 77 ± 13 kg) with no history of low back pain or injury were recruited from the university. Participants provided informed consent and all procedures were approved by the university Research Ethics Board.

Participants were instructed to flex forward from standing to full spine flexion at a self-selected pace. Movements were performed with arms held across the chest while standing with their buttocks against an adjustable support to minimize the posterior translation of the pelvis. Pelvic motion was restricted to optimize 3D marker capture volume throughout the entire flexion task and to ensure that flexion occurred in the spine rather than the hips. Movement patterns are task dependent, therefore identified movement patterns in the current study are specific to trunk flexion with a restricted pelvis. While this task is not common in daily life, restricted movements are useful for differentiating between spine motor control strategies (e.g. Granata and England, 2006; Graham and Brown, 2014). Each participant repeated the movement three times.

2.2. Data collection

Trunk motion was assessed by observing the relative change in local coordinate systems aligned with the surface of the back. A matrix [10 rows × 3 columns] of passive markers (6 mm diameter reflective discs) was applied with each row located at the level of the spinous process (T9 to S1) palpated in a neutral standing position. Markers in the center column were located over the spinous processes and the left and right columns were ~5 cm from the midline over the apex of the paraspinal muscle bellies (Fig. 1). Marker positions were recorded at 30 Hz (Optitrack, NaturalPoint Inc, Corvalis USA) and were filtered with a 4th order, zero-lag, low-pass Butterworth filter with an effective cut-off frequency of 2 Hz.

Orthonormal local coordinate systems (LCSs) were constructed for each level from T9 to S1 using a method described previously (Zwambag et al., 2018). Briefly, linear extrapolation was used to estimate three additional points at the superior and inferior end of each column of markers. The x, y, and z coordinates of each column, parameterized as a function of spine level, were fit with piecewise polynomial cubic splines (4 knots and 3 segments each); the extrapolated points were included to reduce the sensitivity to random noise at the ends of each spline. The superior/inferior (SI) vectors of each LCS were tangential to the surface of the back. The left and right splines defined a curved surface representing the local frontal plane. The anterior/posterior (AP) vectors were perpendicular to the SI vectors and normal to the local frontal plane. Finally, medial/lateral (ML) vectors were mutually perpendicular

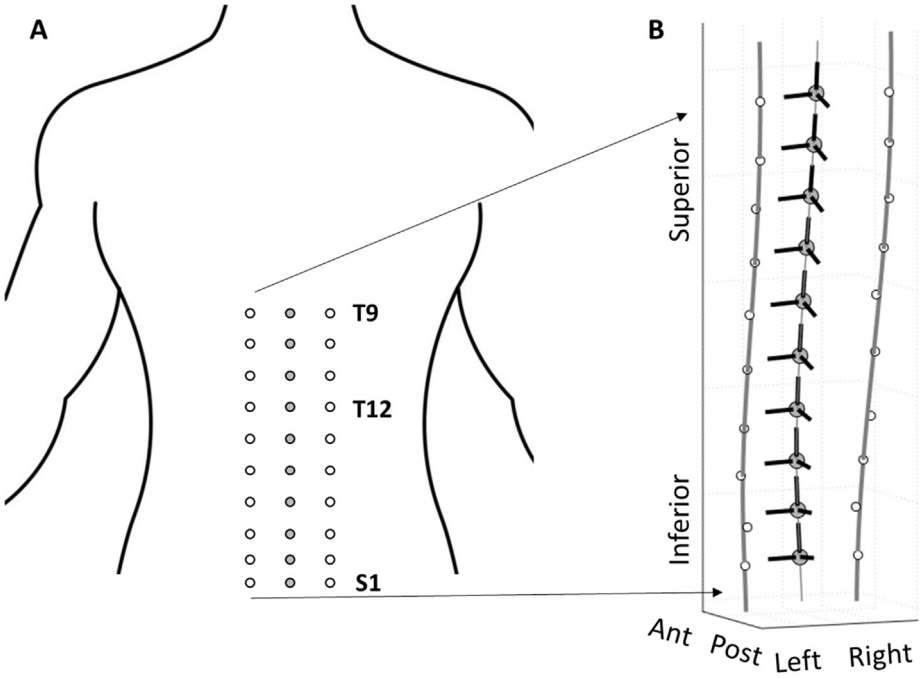

Fig. 1. (A) Schematic of marker set up for creating 3D local coordinate systems (B) Reconstruction of passive markers in MATLAB along with constructed LCS for each spine level from T9-S1.

to the SI and AP vectors. This method of constructing LCSs can be used to track the shape of the back during dynamic 3D motions with a high level of spatial resolution. It is insensitive to marker noise and yields similar angular measures compared to skin mounted electromagnetic tracking systems (Zwambag et al., 2018). As with all skin mounted motion capture techniques, skin movement artefacts are unavoidable. An advantage of the current method is that no tape or large sensors with inertia are required; therefore, any skin translation that results is naturally occurring and is not impacted by the kinematic system. Tape applied to the skin also produces tactile sensations and can alter 'natural' movement patterns (Beaudette et al., 2018). Due to relative motion between the skin and the underlying vertebrae, kinematic measures from the surface of the back are related, but not equivalent, to the position and orientation of the vertebrae.

Flexion/extension (FE), lateral bend (LB), and axial twist (AT) angles were calculated for each spine level as the rotational transformation between the superior and inferior LCSs using a flexion/extension-lateral bend-axial twist (FE-LB-AT) Cardan sequence. The total T9/S1 spine angle was also calculated between the T9 and S1 LCSs using the same sequence of rotations. All movements were assessed to ensure that motion was predominantly restricted to the sagittal plane. To compare movement strategies between individuals, calculated angles were averaged between the three trials from 0 to 100% of maximum spine flexion (T9-S1) in 5% increments. This resulted in 189 relative flexion angles (9 segments * 21 increments) for each participant. The angular kinematic measures were assessed in degrees as well as normalized to percent of each participants' segmental range of flexion.

2.3. Identification of major sources of variation

For preliminary analysis, a principal component analysis was performed on the 189 flexion angles (°) for all 55 participants to identify the number of independent factors that would be required to explain the primary sources of variation between individuals. Principal component analysis is a statistical technique that can be used to transform observations from a set of correlated variables into a reduced set of non-correlated variables, termed principal components (PC). A strength of this analysis is that it identifies a reduced set of new variables which are independent of each other. However, these transformed variables are not based on biological or mechanical concepts and consequently PCs are often difficult to interpret and compare to previous values in the literature. To overcome this limitation, the second part of the analysis involved manually identifying specific angular kinematic variables (predictor variables) which corresponded to each PC by interpreting the PC loading vectors. Loading vectors determine the spatial and temporal effect of each PC on the movement variance. A predictor variable was selected for each major PC with the requirements that each variable was (1) highly correlated to the PC and (2) weakly or non-correlated to all other predictor variables. Using this method, the large set of angular measures could be reduced to a set of relatively independent variables which are biologically or mechanically relevant.

2.4. Prediction of 'typical' motion patterns

The identified angular predictor variables were then used in a multivariate linear model of the form:

$$FE_{(LVL,\theta)} = C1_{(LVL,\theta)} * X_1 + C2_{(LVL,\theta)} * X_2 + \cdots + Cn_{(LVL,\theta)} * X_n$$

where $FE_{(LVL,\ \theta)}$ are the predicted relative flexion angles, X_1, X_2, …, X_n are the identified predictor variables, $C_{(LVL,\ \theta)}$ are the coefficients for each level (LVL: T9/T10 to L5/S1) throughout the trunk flexion movement (θ: 0–100% of total flexion angle). The sum of the absolute differences between the predicted and observed movement patterns (total error) were then used to rank individuals by how much they deviated from their expected movement pattern.

3. Results

Relative angles between adjacent LCS throughout the flexion motion are shown for all 55 individuals in Fig. 2. Minimal off axis rotations (absolute AT and LB angles) were observed throughout the movement, confirming that motions were primarily restricted to the sagittal plane; therefore, only FE angles were considered for the remainder of the analysis.

The principal component analysis identified five PCs which described 96.6% of the total variation in flexion angles observed across participants throughout the restricted-pelvis dynamic flexion task (Table 1).

The first two PCs corresponded to kinematic measures in neutral standing. Specifically, PC1 and PC2 were strongly correlated to the relative flexion angles between the L3/L4 LCSs ($r = -0.89$; $p < 0.0001$) and T10/T11 LCSs ($r = -0.84$, $p < 0.0001$), respectively (Fig. 3). The relative angles between LCSs at L3/L4 and T10/T11 in neutral standing were also strongly correlated with relative angles between adjacent LCSs in the lumbar (L2-S1) and lower thoracic (T9-L1) regions, respectively in neutral standing (Table 2). Further, the L3/L4 and T10/T11 angles in neutral standing are independent of each other (Table 2).

The third and fourth principal components were related to the range of flexion calculated as the difference between the maximum and minimum angles. PC3 was strongly correlated with the range of flexion of the entire T9/S1 spine ($r = -0.90$, $p < 0.0001$; Fig. 3). The T9/S1 range of flexion was also moderately to strongly correlated with the ranges of flexion calculated for each set of adjacent LCSs ($0.67 \leq |r| \leq 0.82$). PC4 accounted for regional differences in the range of flexion amongst lumbar and lower thoracic levels. Analysis of the loading vector revealed that a positive PC4 score increased the range of flexion for all segments below L2 and decreased the range of flexion for all segments above L1. Based on these observations the kinematic predictor variable that was strongly correlated with PC4 ($r = -0.74$, $p < 0.0001$; Fig. 3) was the ratio between the ranges of flexion of L4/L5 and T11/T12.

While the first four PCs were largely determined by the neutral standing posture or flexibility PC5 characterized a temporal difference in movement strategy. Analysis of the loading vector revealed that a positive PC5 score was associated with a greater proportion of flexion occurring in the lower lumbar levels during the first half of the movement and greater thoracic motion in the later half of movement. The kinematic measure that best correlated with PC5 was the relative angle between the T12 and L1 LCSs at 50% of trunk flexion ($r = -0.73$; $p < 0.0001$; Fig. 3). Participants who initiated trunk flexion in a 'top-down' manner had greater T12/L1 angles at the midpoint of the movement than individuals who used a 'bottom-up' movement strategy.

A multivariate linear model was created using the five identified predictor variables: L3/L4 and T11/T12 angles in neutral posture, T9/S1 range of flexion, the ratio between L4/L5 and T11/T12 range of flexion, and the T12/L1 angle at 50% of the movement cycle. The R^2 of the model was 0.96, and the average absolute error across participants between the observed and predicted angles between adjacent LCSs was $\leq 0.9°$ throughout the entire movement. Predicted motion patterns represent the 'typical' motion pattern accounting for an individual's neutral standing posture, their total and regional flexibility, and their temporal movement strategy. All individuals were ranked from most 'typical' to most 'atypical' by the total error between the predicted and observed movements. The participant who used the most 'typical' and two

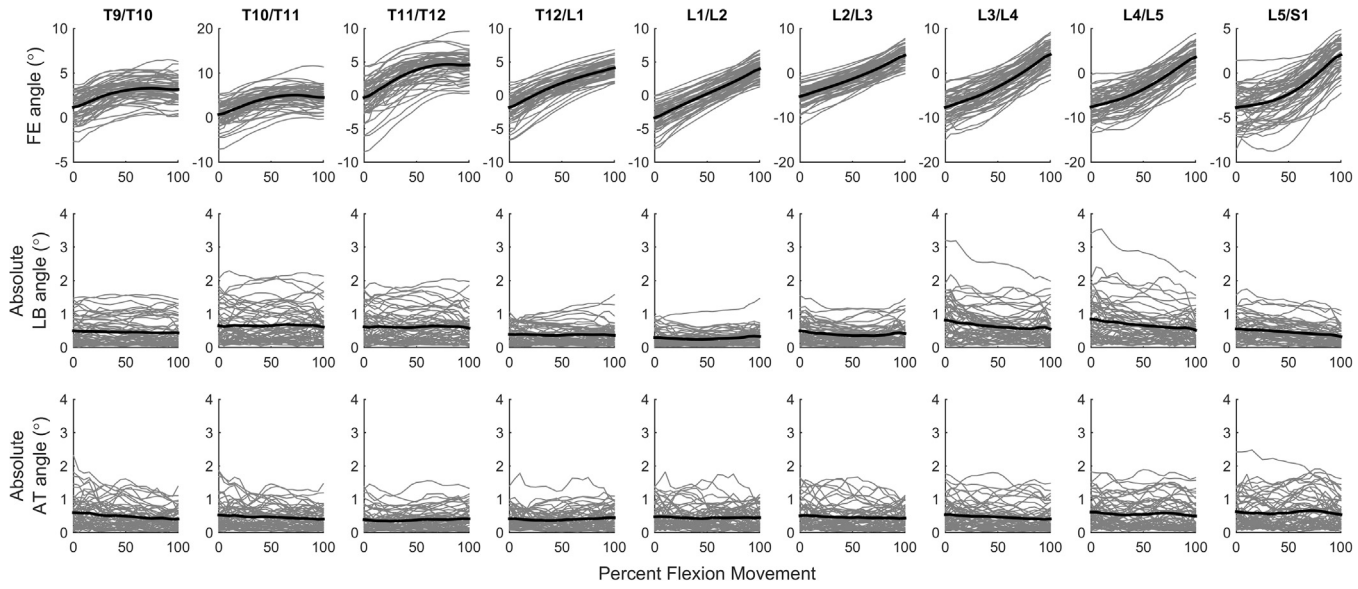

Fig. 2. Relative angles between adjacent local coordinate systems aligned with the surface of the back throughout the flexion movement for all individuals (grey lines) and the average of the sample population (black line); negative FE values are lordotic and positive FE values are kyphotic. The absolute LB and AT angles are shown because only the magnitude of off-axis motion, rather than the direction, was considered important for this study.

Table 1
Variance and cumulative variance amongst 55 healthy individuals explained by the first five principal components for 189 (9 levels * 21 instances) relative angles between adjacent LCS aligned with the surface of the back.

Principal component	Explained variance	Cumulative explained variance
PC1	53.5	53.5
PC2	31.5	85.0
PC3	5.2	90.2
PC4	4.0	94.2
PC5	2.4	96.6

participants with the most 'atypical' movement patterns are shown in Fig. 4.

4. Discussion

Individuals with abnormal standing postures or movement patterns are believed to have an increased risk of developing a low back injury (Stokes et al., 1987). However, the large amount of variation in neutral postures, ranges of motion, and movement strategies among healthy individuals makes it difficult to distinguish between abnormal and normal spine motion. The aim of this study

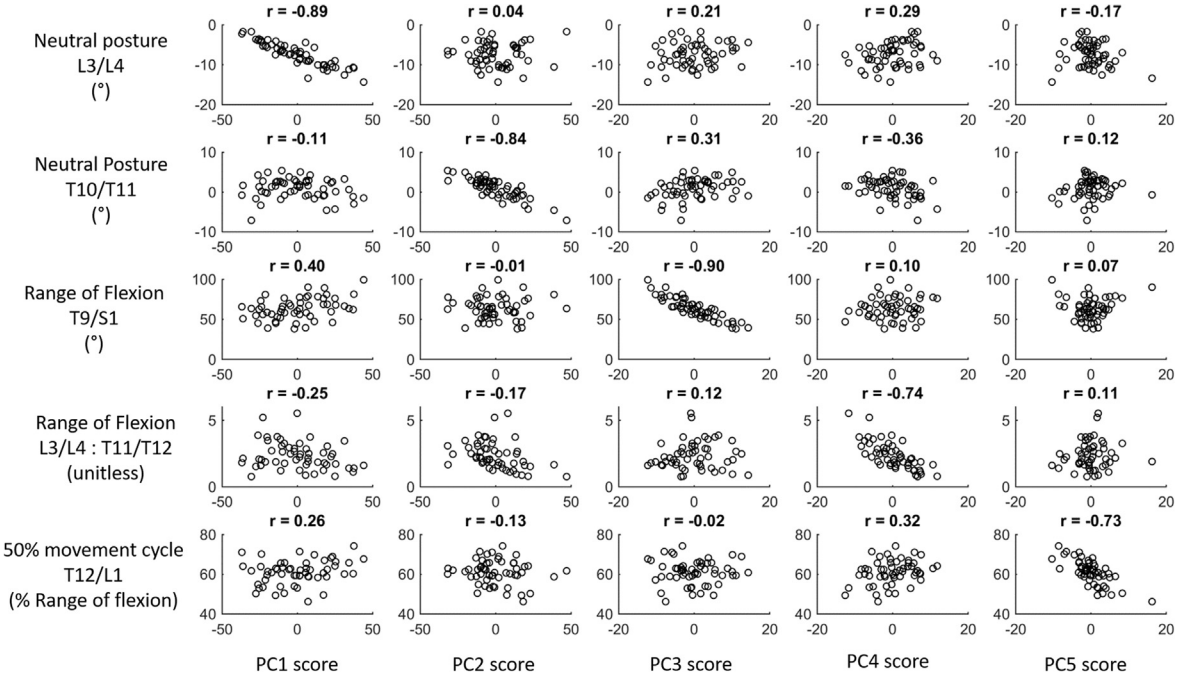

Fig. 3. Scatterplots along the main diagonal highlight the strong correlations ($|r| > 0.7$) between PC scores and selected predictor variables. Scatterplots not located on the main diagonal demonstrate that predictor variables are not correlated or are weakly correlated ($|r| \leq 0.4$) with other PCs.

Table 2
Relative angles (°) between adjacent LCSs in neutral posture and ranges of flexion from neutral to full trunk flexion. Correlation coefficients are between the relative angles and the identified predictor variables for the first three PCs.

	Neutral posture (°)		Correlation coefficient (r)		Range of flexion (°)		Correlation coefficient (r)
	Mean	SD	T10/T11	L3/L4	Mean	SD	T9/S1 range of flexion
T9/T10	1.2	1.5	**0.93**	−0.13	2.7	1.1	**0.67**
T10/T11	0.9	2.5	–	−0.01	5.3	2.3	**0.72**
T11/T12	−0.1	2.6	**0.99**	0.10	5.7	2.3	**0.71**
T12/L1	−1.6	2.0	**0.91**	**0.38**	6.2	1.6	**0.79**
L1/L2	−3.1	1.8	**0.64**	**0.72**	7.5	1.5	**0.82**
L2/L3	−5.0	2.2	**0.28**	**0.94**	9.5	1.8	**0.79**
L3/L4	−7.4	3.0	−0.01	–	12.4	2.6	**0.79**
L4/L5	−7.4	3.0	−0.14	**0.95**	11.9	2.8	**0.77**
L5/S1	−3.8	2.0	−0.15	**0.75**	6.6	2.0	**0.70**
T9/S1	−26.4	15.0	**0.62**	**0.77**	63.6	13.5	–
T9[†]	13.2	6.2	**−0.63**	**−0.46**	–	–	–
S1[†]	−13.2	11.0	**0.48**	**0.78**	–	–	–

Bold values indicate variables are linearly correlated ($p < 0.05$). Positive and negative angles in neutral standing indicate a kyphotic and lordotic curve, respectively.
[†] Orientation of the AP vector normal to the surface of the back in neutral standing relative to horizontal.

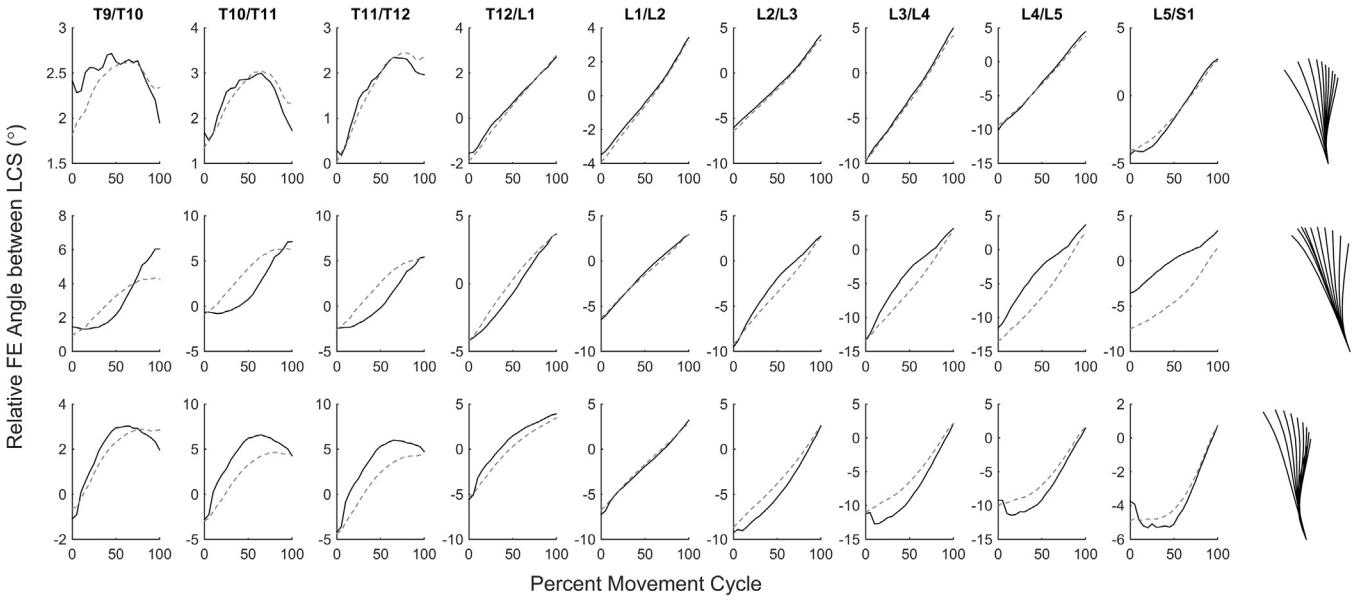

Fig. 4. The observed (solid black) and predicted (dashed grey) motion patterns for three individuals. Selected individuals are the participant with the most 'typical' (top row) and two participants with the most 'atypical' (middle and bottom rows) movement patterns in this sample of young healthy individuals. The lateral view of the shape of the T9-S1 spine throughout trunk flexion is shown on the right.

was to identify variations in spine movement patterns within a sample of healthy individuals. Five angular kinematic measures, related to neutral posture, flexion range of motion, and temporal sequencing of motion, were identified which accounted for greater than 95% of the total variation in movement patterns during restricted spine motion.

4.1. Neutral standing posture

Neutral standing posture largely determined how the spine moved throughout flexion. Eighty-five percent of the variation amongst healthy individuals could be explained by two independent angular measures associated with the neutral spine posture. This is a positive finding for spine research considering the large number of studies that have investigated the neutral spine posture. Lateral standing radiographs are the 'gold-standard' for examining vertebral orientation and have been used extensively for diagnostic purposes, surgical planning, and rehabilitation outcome measures (eg. Chaleat-Valayer et al., 2011; Le Huec et al., 2014). Sacral slope, pelvic tilt, lordosis angle, and sagittal balance of the spine are common outcome measures which are often believed to be associated with the risk of developing an injury or spine disorder (Legaye et al., 1988; Roussouly et al., 2005). However, the relationship between these static measures and spine dynamics, which are strongly linked to risk of injury (Marras et al., 2010), has largely been unexplored. The current study indicates that sagittal standing posture has a large influence on the shape of the spine throughout a restricted spine flexion movement. Further work is needed to determine how standard radiographic measures, such as sacral slope, sagittal alignment, and pelvic tilt are related to the shape of the back in neutral standing.

The results of this study also highlight the large amount of variation in neutral standing postures amongst healthy individuals. The implication of this variability is that it is unlikely that neutral spine posture alone will be capable of distinguishing between normal and abnormal postures. Another important observation was that at least two measures of neutral spine posture were required to characterize the shape of the T9-S1 spine, since lumbar angles

and lower thoracic angles were found to be independent of each other in a young healthy population.

4.2. Range of motion

After accounting for differences in neutral standing posture, it is unsurprising that the next greatest source of variation amongst individuals was the total spine (T9-S1) flexion range of motion. This is consistent with previous radiographic studies which identified large variations in ranges of flexion within healthy and patient populations (Pearcy, 1985; Adams and Hutton, 1986; Dvorak et al., 1991, Staub et al., 2015). Because the variation in range of flexion *within* healthy and patient populations is often larger than the variation *between* populations, it is unlikely that flexion range of motion, as an isolated variable, will be able to differentiate between healthy individuals and patients.

An interesting finding from this study is that flexion range of motion of the T9-S1 spine is largely independent of neutral standing posture since range of motion was only moderately correlated with the neutral L3/L4 angle ($r = -0.54$) and was weakly correlated with the neutral T10/T11 angle ($r = -0.34$). This finding may seem contradictory to the previous section that concluded neutral posture had the greatest influence on spine motion. However, together these results imply that there is greater variability in neutral posture than there is in range of flexion motion and that an individual's spine flexibility is weakly influenced by their neutral posture. The negative correlation with L3/L4 indicates that individuals who start with a more lordotic posture are more likely able to flex farther than individuals who start with a 'flatter' lumbar spine; this moderate association is consistent with the results of Zander et al. (2018) who found that lumbar lordosis in neutral standing was correlated ($r = 0.67$) with the range of flexion of the lordotic spine. The fourth greatest source of variation amongst healthy individuals was also related to flexion range of motion, however this parameter re-weighted range of flexion between lower thoracic and lumbar regions. When lumbar and lower thoracic neutral postures and ranges of motion were considered, ~90% of the variation in dynamic movement patterns amongst individuals could be accounted for during this task. Therefore, the combination of these four variables may be able to distinguish between 'normal' and 'abnormal' spine movement patterns.

4.3. Movement strategy

The final source of variability that was uncovered in this study was associated with how an individual transitioned between neutral and fully flexed positions. The fifth PC score separated individuals who initiated movement in a top-down versus bottom-up manner. These movement strategies have also been previously observed in the literature (Kanayama et al., 1996; Okawa et al., 1998; Harada et al., 2000; Ignasiak et al., 2017); however, the link between them and the risk of developing injury is unknown. A simple rigid-linked segment model predicts that the external demand placed on the spine is greater in the mid-range of spine motion when using a bottom-up movement strategy due to greater moment arms between with the spine and the upper body center of mass. However, the muscular activation patterns associated with top-down and bottom-up movements have not been investigated. Therefore, the difference in spine loading patterns between these two movement strategies is unknown. Differences in bottom-up and top-down motions were observed between young and aged populations (Ignasiak et al., 2017); however, it is unknown whether this was linked to changes in muscle strength, spine degeneration, or altered neuromuscular control associated with ageing.

4.4. Predicted movement patterns

The multivariate model was able to predict motion patterns with a high level of accuracy based on the five predictor variables. It should be noted that the main goal of this part of the analysis was not to develop a model for predicting flexion patterns during constrained spine flexion, but rather to demonstrate how identified predictor variables could be used to detect 'abnormal' or 'atypical' movement patterns in the future. In the current data set, all participants were young healthy individuals with no history of low back pain. The pelvic constraint also would have affected movement patterns compared to unrestricted or 'natural' spine motion. Therefore, no conclusions are drawn regarding whether observed movement patterns are 'normal', instead average movement patterns are considered 'typical' for this population and task and the extremes of movement are considered 'atypical '. Further research is required to determine the sources of movement variation during unrestricted, functional spine movements, as well as those associated with age, sex, BMI, and history of low back pain.

Spine motion is highly variable amongst healthy individuals. Characterising the types and amounts of variation observed in healthy populations will aid future studies in identifying when 'abnormal' motion occurs. The shape of the back from T9 to S1 in a neutral position can be characterized by two independent measures associated with the curvature of the spine in the lumbar and lower thoracic regions. These measures, along with the range of flexion of the T9 to S1 spine, were able to explain ~90% of the variation in spine motion amongst healthy individuals. Finally, a method of predicting a 'typical' motion pattern for an individual is proposed as a method which could be applied to functional spine movement tasks to distinguish between 'normal' and 'abnormal' movement patterns.

Conflict of interest

None.

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