The lumbar spine has an intrinsic shape specific to each individual that remains a characteristic throughout flexion and extension

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Abstract

Purpose We have previously shown that the lumbar spine has an intrinsic shape specific to the individual and characteristic of sitting, standing and supine postures. The purpose of this study was to test the hypothesis that this intrinsic shape is detectable throughout a range of postures from extension to full flexion in healthy adults.

Methods Sagittal images of the lumbar spine were taken using a positional MRI with participants (n=30) adopting six postures: seated extension, neutral standing, standing with 30°, 45°, 60° and full flexion. Active shape modelling (ASM) was used to identify and quantify ‘modes’ of variation in the shape of the lumbar spine.

Results ASM showed that 89.5% of the variation in the shape of the spine could be explained by the first two modes; describing the overall curvature and the distribution of curvature of the spine. Mode scores were significantly correlated between all six postures (modes 1-9, r= 0.4 – 0.97, P<0.05), showing that an element of intrinsic shape was maintained when changing postures. The spine was most even in seated extension (P<0.001) and most uneven between 35° - 45° flexion (P<0.05).

Conclusions This study shows that an individual’s intrinsic lumbar spine shape is quantifiable and detectable throughout lumbar flexion and extension. These findings will enable the role of lumbar curvature in injury and low back pain to be assessed in the clinic and in the working and recreational environments.

Keywords Lumbar spine shape; Intrinsic shape; Posture; Shape modelling; MRI

Introduction

Statistical shape modelling has previously been used to quantify the variation in spinal shapes between individuals [1]. Commonly used methods to describe lumbar spine curvature have involved measuring the angle between the superior endplates of the first lumbar and first sacral vertebrae and the intervening intersegmental angles. These figures miss important information about the variation of curvature along the length of the lumbar spine [2]. They produce a large number of variables which are not easily compared between subjects and lack precision, especially if angles are close to zero [2, 3]. A statistical modelling approach using Active Shape Modelling (ASM) uses principal components analysis to reduce the number of variables needed to describe spinal morphology while capturing systematic variations in spinal shape. Shape modelling of the lumbar spine has been shown to be a reliable, precise [3] and accurate [2] method of characterising sagittal spinal shape. It has also been used to assess vertebral morphometry and fractures in lateral DXA images and vertebral shape on lumbar radiographs [4, 5].

Using ASM we previously quantified the large variation in spinal shapes and elicited the presence of an intrinsic spinal shape that was specific to the individual. The set of shapes could be described by two variables, which we called curviness and evenness; curviness describing the overall curvature and evenness whether the curvature was distributed along the lumbar spine or appeared primarily in one region. Correlation between the values of each variable in standing, supine and seated postures showed that the shape of the lumbar spine in one posture was related to its shape in the other postures [3]. Using the same model we have also investigated the changes that occur in spinal shape during loading [6,7] and found that axial loading of the spine results in curvier than average spines becoming more curved and straighter spines straightening further [7]. This quantitative evidence supported previous predictions that the lumbar spine would straighten under load and highlighted the importance of spinal shape to its load-bearing ability [8, 9].

Structural stability of the spine has long been recognized as being important for injury prevention [10, 11]. The stability of the spine is maintained by a compressive thrust [8, 12] or follower load [13] which is a force that follows the curve of the spine. If this force passes close to the centroid of the vertebrae, it ensures that shear and bending moments are small [14] and if it lies within the vertebrae it ensures stability. Although models for the spine have become increasingly sophisticated [15-18] only some consider posture [15, 16, 19] and many do not take into account the actual curvature of individual spines.

In order to study potential causes of injury, such as manual lifting, and understand the possible role of intrinsic spinal shape in susceptibility to and recovery from low back pain we need to know how intrinsic shape is related to movement across the whole range of flexion and extension. In this study, therefore, we have investigated the changes in lumbar spine shape throughout six postures from extension through to full flexion. The aim was to test the hypothesis that some aspects of the intrinsic spinal shape would be maintained between all postures.

Methods

Participants

Thirty healthy adult volunteers, aged 18-65 years, with no back pain for the past 12 months and no previously diagnosed spinal disorders or spinal surgery were recruited for the study. Ethical approval was granted from the local college ethics review board and participants gave their informed consent in writing prior to taking part in the study.

Imaging

A Fonar 0.6T Upright TM positional magnetic resonance imaging (pMRI) scanner (Fonar Corporation, Melville, New York) was used to take T2 weighted sagittal images of the lumbar spine. Images of 10 mm slice thickness (21 slices) and a 1 mm gap were acquired using a fast spin echo sequence [TR/TE 2023.1/140 ms]. This sequence was chosen to minimise the time participants spent holding each position thus reducing movement artefact and improving image clarity. Acquisition time was 2 minutes 51 seconds and, including set-up, each posture was held for approximately 5 minutes. All images were acquired on a 256x160 matrix with a 40 cm field of view. The mid-sagittal slice was converted in Image J (Wayne Rasband, NIH, USA) to a 256 x 256 matrix and saved in bmp format for analysis.

Protocol

Six postures were included in the protocol: sitting extension, neutral standing, standing with 30°, 45° and 60° of flexion at the back and a hanging flexion ('hang flex'). A sitting extension was chosen in preference to standing as pilot scanning demonstrated that standing produced considerably greater discomfort, increasing the possibility of movement artefact. In extension participants were instructed to sit with the buttocks against the back of the seat. A cushioned roller was placed behind the small of the back and the shoulders leaned back to encourage extension. Neutral standing involved participants standing in their natural upright posture, with the shoulders relaxed, upper arms at the sides and hands resting on a bar for balance. Once in the scanner, postures involving flexion were accomplished by aligning the fulcrum of a goniometer with the top of the femur; stationary arm positioned along the midline of the femur and moving arm aligned with the lower back. Participants were asked to bend forward and pull their stomach in towards their back, until the lumbar spine was aligned at the specific angle. The 'hang-flex' posture required participants to perform a full forward flexion of the back, within their own range of motion, while maintaining straight legs. Due to the spatial constraints and the strong magnetic field of the scanner, a goniometer was chosen as the most practical and reliable method available for measuring flexion angle.

Active Shape Modelling

Active shape modelling is a precise and reliable method of characterising the shape of the lumbar spine [1, 3]. This method has been described in detail previously [3]. Briefly, active shape modelling is a statistical model of shape that uses principal components analysis to identify ‘modes’ of variation in shape, enabling the quantification of this variation [20, 21]. The model used was created using Active Appearance Modelling software tools from the University of Manchester, UK (http://www.isbe.man.ac.uk/~bim/software/am_tools_doc/index.html), and includes a total of 168 points, with 28 points placed on specific landmarks around the edges of each vertebra from the first lumbar to the first sacral vertebrae (L1-S1) from all the mid-sagittal images. The two dimensional coordinates of these points were put into the principal components model. For each image the model produced a score for each mode of variation which quantified, in standard deviations, how much it deviated from the mean shape obtained from all the images. The output from the model was subsequently analysed using software written in MATLAB 2008a (The MathWorks Inc., Natick, Massachusetts) to calculate the intersegmental angles between lines tangential to the superior endplates of the vertebrae. These were used to aid in the interpretation of the modes.

Statistical Analysis

Statistical analysis was performed using a statistical package SPSS 20.0 (IBM SPSS Statistics, IBM Corp). Data were tested for normality using the Shapiro-Wilk test and if normally distributed presented as mean (standard deviation (SD)). One way-repeated measures analysis of variance (ANOVA) and Pairwise Comparisons were used to examine the effect of changing posture on mode scores [22]. Pearson correlation was used to assess the relationship between mode scores between postures. To assess reliability 20 randomly selected images were marked up twice (by one researcher) and a one way ANOVA (two-way random effects model with absolute agreement) carried out on the point coordinates. Intra-class correlation coefficients (ICC) were calculated as described in Bland [22]. Results were taken as significant at $P<0.05$.

Results

Thirty volunteers were included in the study (15 male, 15 female) (Table 1). Active shape modelling showed that 97.6% of the variation in spinal shape could be explained in 10 modes, with 92.5% of the variance contained within the first three modes (Fig. 1). Two main modes of variation were identified; mode 1 (M1, 85% of total variance) describing the total curvature of the spine and mode 2 (M2, 4% of total variance) describing the distribution of the curvature along the spine, confirmed by their corresponding intersegmental angles (Fig. 2). Males were found to have a more even spine in the 'hang-flex' posture than females (P=0.04), no other significant differences were seen between males and females in these two modes.

Within each mode, strong and significant correlations between scores in all six postures revealed that an intrinsic spinal shape was present throughout the six postures, shown in Table 2 for modes 1 and 2. So, for any individual, the shape of the lumbar spine in one posture was strongly related to its shape in other postures. Similar significant correlations were present across the first nine modes and the majority of mode 10 scores, represented visually in Fig. 3. For mode 1, 34% to 57% of the variance in the flexed and extended postures is explained by the variation in standing (R^2=0.34 to 0.57, $P\leq$0.001). In mode 2, 36% to 83% of the variance in other postures is explained by the variation in standing (R^2= 0.36 to 0.83, $P\leq$0.001). When correlations were run separately for males and females a similar pattern was observed with only some minor sex differences in correlation scores (Table 2).

Box plots and Shapiro-Wilk statistics indicated that the assumption of normality was supported; $F_{max}\leq$3.72 demonstrating homogeneity of variances ; however sphericity could not be assumed and therefore the Huynh-Feldt corrected significance value was read from the repeated measures ANOVA [23]. Analysis of variance revealed that mode scores were significantly different between postures ($P\leq$0.003 in modes 1-5). For mode 1, scores were similar in extension to erect standing and most of the difference appeared on moving into flexion (Fig. 4 a). A more positive score indicated that each had a less lordotic curvature than the previous posture ($P\leq$ 0.001). Mode 2 scores were lowest in the 'extension' posture (P<0.001), corresponding to the most evenly distributed curvature (Fig. 4 b). The lumbar spine curvature became increasingly uneven though to about 30°, after which it becomes slightly more even again into full flexion. Intra-class correlation coefficients (x-coordinates ICC=0.98, y-coordinates ICC = 0.99) showed excellent marking reliability between repeated point placement.

Discussion

This study used statistical shape modelling to characterise the shape of the lumbar spine in healthy individuals and investigate the change in shape with different postures. The data presented here support the hypothesis that each individual has an intrinsic shape to their lumbar spine and that an element of that shape is maintained throughout a range of postures from extension through to full flexion in the sagittal plane. It extends our previous study in which we showed that the intrinsic shape could be identified in sitting, erect standing and lying supine [3].

This study used a 168 point template identical to that previously used by Meakin et al. [3]. Because the model was built from images of different individuals and in a wider range of postures the mean shape and the mode scores are different from those in the previous study. However, the two largest modes of variation found here, ‘curviness’ (M1) and ‘evenness’ (M2), describe a similar variation to that previously described [1, 3]. Although there is a large variation in spinal shapes between individuals [1, 3, 24-26], these two modes capture most of this variation and account for between 84% [1], 91% [3] and, in this study, 90% of the total variance. The factors that may underpin the variation in spinal shapes between individuals and possible biomechanical and clinical implications have been discussed previously [3]. For instance, spinal curvature can be influenced by factors such as vertebral disc wedging, body weight distribution, sacral slope and pelvic incidence [25, 27].

The mean lordosis angle in erect standing (calculated from intersegmental angles, L1-S1, Table 1.) was similar in this cohort to previously published figures [27, 28]. Our results show a trend for the seated extension posture to have a less lordotic curvature than in upright stranding (albeit not significantly) which is similar to previous studies that have reported the lumbar lordosis to be greater in standing than sitting [29-32]. Small differences in M1 scores at larger angles of flexion indicate that some individuals may have already reached their comfortable end-range of motion for the spine in the flex 60° posture [33] and, therefore, find it difficult to flex any further for the hang-flex posture.

Mode 2 results showed that lumbar curvature was least even (or most 'S' shaped) in the flex 30° posture. Lee et al. [33] observed that during forward flexion in asymptomatic subjects, although there was motion at all lumbar vertebral levels, the majority of relative motion occurred at the level of L1/L2 and L2/L3. Similarly Preuss and Popovic [34] and Abbott et al. [35] found that the upper lumbar segment was responsible for a greater proportion of the flexion motion than the lower lumbar segment. This might explain our findings such that the desired flexion posture was achievable largely through flexion in the upper lumbar levels with the lower lumbar spine remaining lordotic.

The amount of curvature in the lumbar spine can affect the stresses and strains in the spine [8, 14,36] and the distribution of curvature has been linked to some spinal pathologies [37].Twin studies have reported a genetic influence on LBP occurrence [38, 39] and with suggestions of postural familial associations it begs the question of whether intrinsic spinal shape might be genetically influenced and whether certain shapes might be more prone to LBP than others. Shape modelling provides a quantitative description of the spine to investigate relationships between spinal shape and LBP, genetic associations and the biomechanics of lifting. Evidence for sex-related differences in lumbar lordosis is conflicting, some suggest that females have a greater lordosis [40, 41] while others show no significant differences [31, 42], although most of these studies make measurements externally. We did not find any differences in M1 scores between males and females. Furthermore, we did not see any identifiable trends when mode scores and postures were correlated separately by sex.

Positioning limitations should be considered. Goniometry is not as reliable at measuring flexion angles as other apparatus such as accelerometers [43] or electromagnetic motion trackers [44] but was the most feasible method of placing participants into the set flexion angles in the scanner. The choice of positioning apparatus was limited due to the strong magnetic field in the scanner and the spatial constraints making it impossible to get behind or beside the participant once they were in the scanner. The variability in spinal shapes makes positioning challenging as the internal shape can sometimes be very different to the shape at the surface of the back.

Conclusions

This study confirmed that each individual has an intrinsic shape to their lumbar spine that can be described by two variables, termed curviness and evenness. It extends our previous research by showing that elements of this intrinsic shape are maintained throughout a range of postures from extension to full flexion. Considering that the shape of the spine affects its behaviour when loaded this could have implications on movement patterns when handling loads, with the possibility of some spinal shapes being at a greater risk of injury, and on the incidence or rehabilitation of low back pain. Greater consideration should be given to an individual's intrinsic spinal shape when attempting to model lumbar spine motion and loading and within the clinical setting.

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The authors declare that there is no conflict of interest.

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Figure Legends

Fig. 1 Percentage of variance explained by the first ten modes, showing individual variance (diamonds) and the cumulative variance (squares) of modes one to ten

Fig. 2 Shape modelling produced two main modes of variation in spinal shape, representing the overall spinal curvature (M1) and the distribution of that curvature along the spine (‘evenness’) (M2). Intersegmental angles (Φ_1- Φ_5) and total lumbar spine angles (Φ_{Total}, L1-S1) demonstrate the distribution of curvature in the mean sample shape and when each mode separately is varied by two standard deviations (2 SD)

Fig. 3 Correlations between mode scores in each posture. Each square represents the Pearson correlation coefficient relating scores between each mode (n=10) and all six postures. Each block of ten by ten small squares represents the ten modes for each posture. Strong, significant correlations ($P < 0.05$) are found along the diagonals showing the same mode appearing in each posture. These are represented by the colours: white, correlation coefficient (r) = 1; yellow, $r \geq 7$; green, $7 > r > 4$

Fig. 4 Mean and 95% confidence intervals for (a) mode 1 scores and (b) Mode 2 scores for each posture

Table 1 Participant demographics and total lumbar spine angle (LS_Angle)

Participant Demographics	Male (n=15) value (SD)	Female (n=15) value (SD)	Combined (n=30) value (SD)
Age (years)	31.3 (9.8)	27.7 (9.5)	29.5 (9.6)
Age range (years)	21-52	20-50	20-52
Height (cm)	176.2 (5.3)*	166.8 (4.1)	171.5 (6.7)
Weight (kg)	78.7 (11.5)*	63.6 (7.9)	71.2 (12.4)
BMI (kg/m^2)	25.3 (3.2)*	22.8 (2.5)	24.1 (3.1)
LS_Angle (°)	63.2 (6.6)	63.7 (8.2)	63.4 (7.3)

*denotes significance *P*<0.05 from independent samples *t*-test, between males and females

BMI = body mass index; LS_Angle = total lumbar spine angle between superior endplates of the first lumbar and sacral vertebrae (L1-S1)

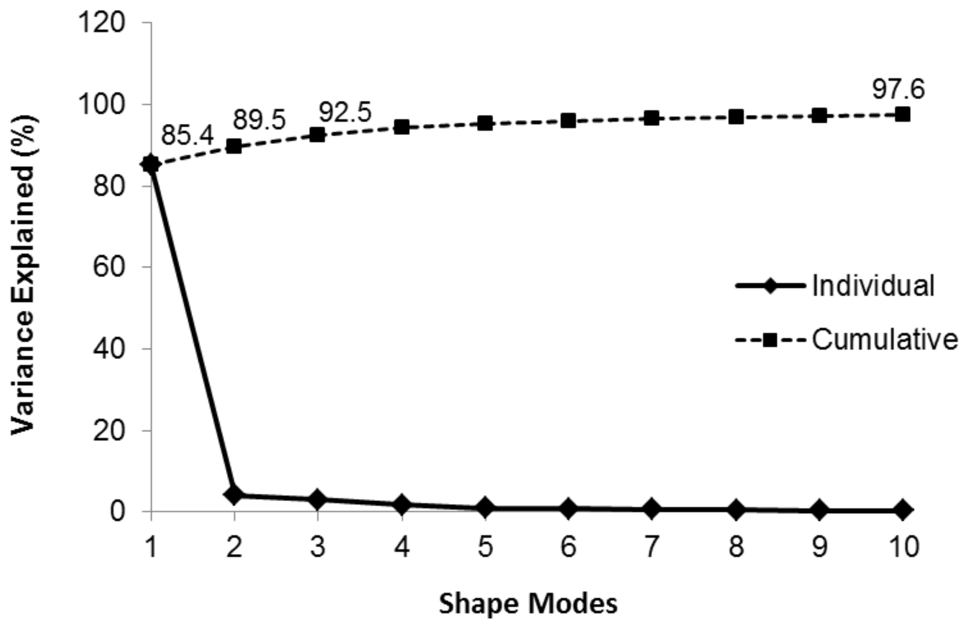
Table 2 Pearson correlation values (*r*) for mode scores between postures

Pearson Correlations	Male (n=15) *r* (*P* value)	Female (n=15) *r* (*P* value)	Combined (n=30) *r* (*P* value)
Mode 1 in Erect with:			
Extension	0.54 (0.038)	0.87 (< 0.001)	0.75 (< 0.001)
Flex 30°	0.67 (0.006)	0.71 (0.003)	0.67 (< 0.001)
Flex 45°	0.45 (0.097) NS	0.73 (0.002)	0.61 (< 0.001)
Flex 60°	0.72 (0.003)	0.66 (0.008)	0.64 (< 0.001)
Hang Flex	0.27 (0.35) NS	0.82 (< 0.001)	0.58 (0.001)
Mode 2 in Erect with:			
Extension	0.93 (< 0.001)	0.90 (< 0.001)	0.91 (< 0.001)
Flex 30°	0.63 (0.011)	0.58 (0.024)	0.60 (0.001)
Flex 45°	0.73 (0.002)	0.66 (0.007)	0.68 (< 0.001)
Flex 60°	0.74 (0.002)	0.61 (0.017)	0.67 (< 0.001)
Hang Flex	0.69 (0.005)	0.63 (0.016)	0.62 (< 0.001)

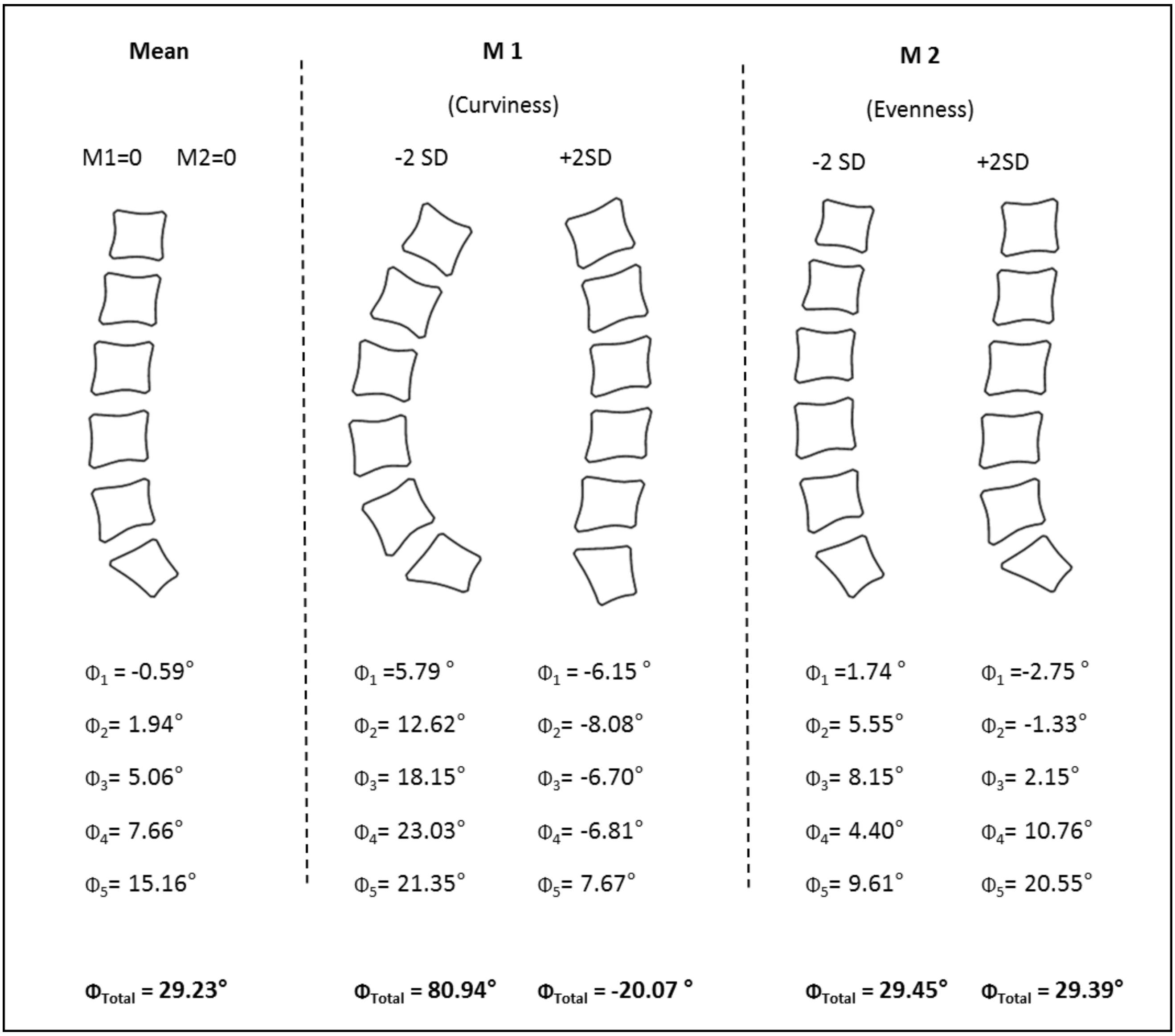
NS= not significant.

Figures

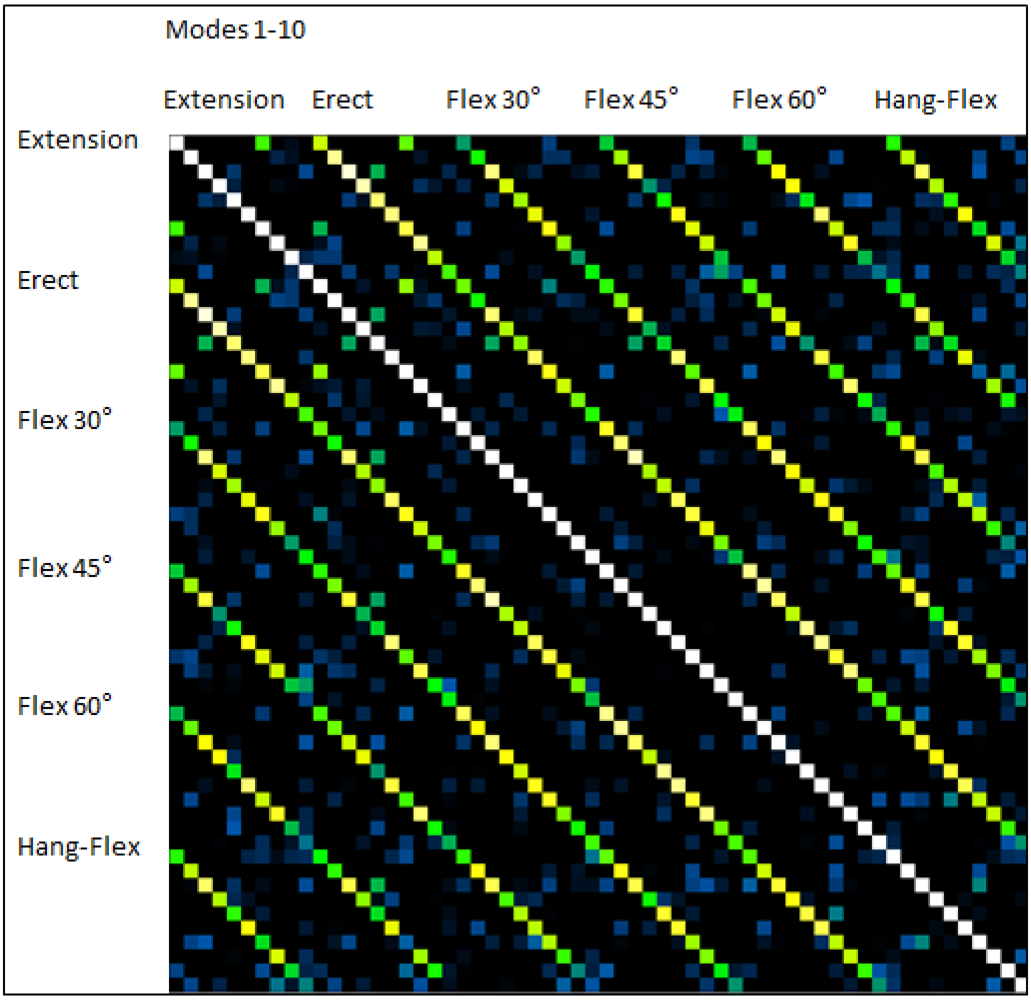
1.


120
100
80
60
40
20
0
Variance Explained (%)
85.4
89.5
92.5
97.6
Individual
Cumulative
1
2
3
4
5
6
7
8
9
10
Shape Modes

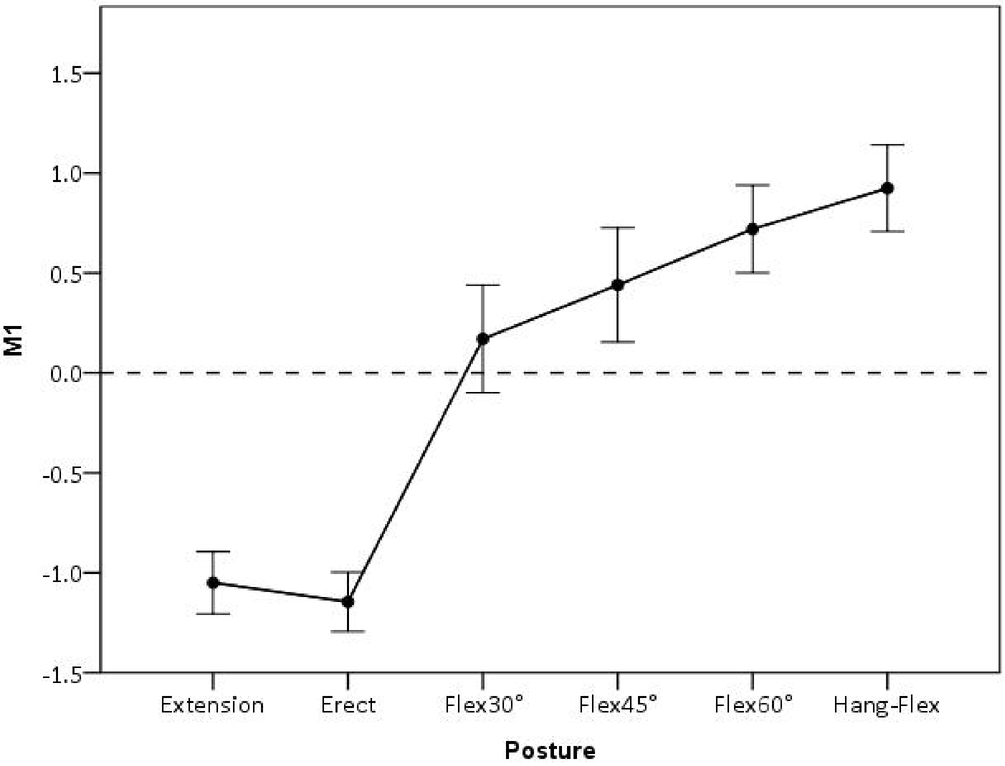
2.


Mean
M 1
(Curviness)
M 2
(Evenness)
M1=0 M2=0
-2 SD
+2SD
-2 SD
+2SD
Φ_1 = -0.59°
Φ_2= 1.94°
Φ_3= 5.06°
Φ_4= 7.66°
Φ_5= 15.16°
Φ_{Total} = 29.23°
Φ_1 =5.79 °
Φ_2= 12.62°
Φ_3= 18.15°
Φ_4= 23.03°
Φ_5= 21.35°
Φ_{Total} = 80.94°
Φ_1 = -6.15 °
Φ_2= -8.08°
Φ_3= -6.70°
Φ_4= -6.81°
Φ_5= 7.67°
Φ_{Total} = -20.07 °
Φ_1 =1.74 °
Φ_2= 5.55°
Φ_3= 8.15°
Φ_4= 4.40°
Φ_5= 9.61°
Φ_{Total} = 29.45°
Φ_1 =-2.75 °
Φ_2= -1.33°
Φ_3= 2.15°
Φ_4= 10.76°
Φ_5= 20.55°
Φ_{Total} = 29.39°

3.

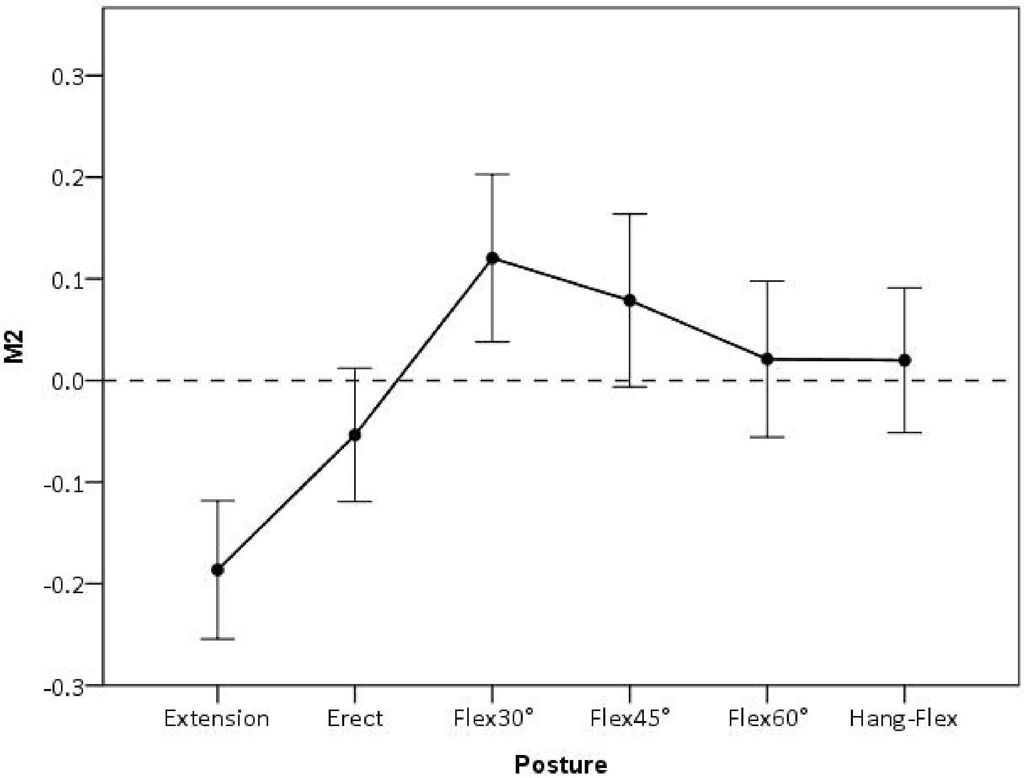

Modes 1-10
Extension
Erect
Flex 30°
Flex 45°
Flex 60°
Hang-Flex
Extension
Erect
Flex 30°
Flex 45°
Flex 60°
Hang-Flex

4. A



1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
M1
Extension
Erect
Flex30°
Flex45°
Flex60°
Hang-Flex
Posture

4 B.



0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
M2
Extension
Erect
Flex30°
Flex45°
Flex60°
Hang-Flex
Posture