MODELLING THE EFFECT OF VARIATION IN SAGITTAL CURVATURE ON THE FORCE REQUIRED TO PRODUCE A FOLLOWER LOAD IN THE LUMBAR SPINE

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The aim of this study was to investigate how the forces required to stabilize the lumbar spine in the standing posture may be affected by variation in its shape. A two-dimensional model of the lumbar spine in the sagittal plane was developed that included a simplified representation of the lumbar extensor muscles. The shape of the model was varied by changing both the magnitude and distribution of the lumbar curvature. The forces required to produce a resultant load traveling along a path as close to the vertebral body centroids as possible (a follower load) were determined. In general, the forces required to produce a follower load increased as the curvature became larger and more evenly distributed. The results suggest that the requirements of the lumbar muscles to maintain spinal stability in vivo will vary between individuals. This has implications for understanding the role of spinal curvature and muscle atrophy in back pain.

Keywords: Lumbar spine; shape; model; muscle forces; stability; follower load

1. **Introduction**

In vivo, in the standing posture, the lumbar spine is subject to a combination of body weight and muscle force. Pressures measured in the intervertebral disc, and loads measured in vertebral body replacements, suggest that the resulting internal compressive force in the spine is around 500 N (Sato et al., 1999; Rohlmann et al., 2008). In vitro, however, even when motion is constrained in the frontal plane, vertical loads as small as 100 N on an isolated spine cause large deformations in the sagittal plane (Patwardhan et al., 1999). Only by constraining the load to follow the lumbar curvature can the spine carry physiological loads without buckling (Patwardhan et al., 1999).

The concept that compressive force travels along the curvature of the lumbar spine was first proposed within the framework of the arch model (Aspden 1987; Aspden 1988; Aspden 1989). The arch model treats the spine as a statically indeterminate structure, which functions by transmitting compressive force, termed ‘thrust’. The path of the thrust determines the stability of the spine. If it lies outside the spine, the spine is considered to be unstable and may be damaged by tensile stresses that develop in the tissues. If it lies within the spine then the spine is considered stable; a special case occurs when the thrust path passes normally through the vertebral body centroids so that the shear forces and bending moments are zero. This special case is similar to the concept proposed by Patwardhan et al. (1999) which they termed a ‘follower load’. The idea that spinal loads are directed along the spinal curvature has now become established and it has been demonstrated, using finite element models, that the spinal muscles are able to provide a mechanism for producing a follower load (Youn et al., 2005; Kim et al., 2007; Yoon & Kyungsoo 2007; Kim & Kim 2008; Han et al., 2011).

Studies investigating follower loads, and the ability of the muscles to achieve them, have tended to consider only one representative lumbar spine geometry. The sagittal shape of the lumbar spine when standing in a neutral posture, however, varies considerably between individuals (Keller et al., 2005; Roussouly et al. 2005; Meakin et al., 2008a; Meakin et al. 2008b; Meakin et al., 2009) both in the total curvature, which varies between 20 and 70 degrees, and in the distribution of the curvature (Meakin et al., 2008a). Han et al. (2011) have shown that in changing the curvature of the lumbar spine from 50 to 60 degrees, the muscle forces required to produce a follower load increase. Although the effects of extending the spine are unlikely to be the same as those of considering spines of naturally different shape, their results suggest that the muscle forces required to retain the path of the follower load within the spine are a function of sagittal curvature.

Determining the difference in muscle requirements for different shaped spines could be important for understanding the relationship between spinal curvature and disease and back pain. Developing a full three-dimensional lumbar spine model which includes all the associated musculature and incorporates variation in its neutral sagittal shape, however, is not a trivial exercise and so before embarking on such an enterprise we decided first to develop a simple model to explore how muscle forces might vary with shape. In this paper we report the results from a two-dimensional model that determined how variation in magnitude and distribution of curvature affect the forces required to produce a follower load in a curved structure which was representative of the lumbar spine. The model included a simplified representation of the lumbar extensor muscles and was analyzed using the graphic statics method.

2. **Methods**

2.1. ***The model***

The model (Fig. 1) consisted of six fixed points which represented the centroids of the lumbar and uppermost sacral vertebral bodies (L1 to S1). The distance between adjacent vertebral body centroids was set at 36 mm; this distance equates to the mean inter-centroid distance in the lumbar spine as determined from data described in a previous study (Meakin et al., 2008a). The shape of the model was specified by the acute angles (ϕ_2, ϕ_3, ϕ_4, ϕ_5) between adjacent segments of the line connecting the vertebral body centroids. The average shape (C0E0), shown in Fig. 1, had angles $\phi_2 = 3^o$, $\phi_3 = 8^o$, $\phi_4 = 12^o$, $\phi_5 = 30^o$; these values were based on our previous measurements of the shape of the spine in the standing posture (Meakin et al., 2008a). The orientation of the model was specified by α, the angle with respect to the vertical of the line connecting the centroids of L1 and S1; for the average shape $\alpha = 1^o$.

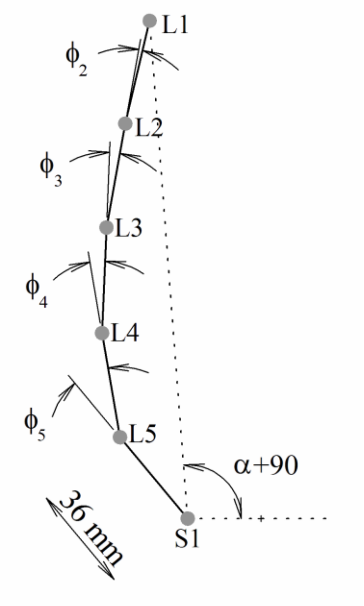

Fig. 1. Two-dimensional model developed to represent the lumbar spine in the sagittal plane. Six points, 36 mm apart, represent the centroids of the vertebral bodies from L1 to S1. The acute angles, ϕ_i, between the lines connecting the vertebral body centroids define the shape of the model and the angle, α, of the line from L1 to S1,with respect to the vertical defines the orientation.

Eight further shapes (Fig. 2) were defined to encompass variation in the magnitude, C, and the distribution, E, of the curvature. Curvature magnitude was increased (C+) by adding, or decreased (C-) by subtracting, 6^o to each ϕ_i angle. The curvature was distributed more evenly (E+) by adding, or less evenly (E-) by subtracting, the following: 4.5^o (ϕ_2), 2.5^o (ϕ_3), 0.5^o (ϕ_4), -7.5^o (ϕ_5). The variation in magnitude and distribution of curvature was based on the results of our previous study of lumbar spine shape in the standing posture (Meakin et al., 2008a). Although not reported in the previous study, the orientation of the lumbar spine (defined by the angle α in Fig. 1) was found to be highly correlated with the evenness of the curvature distribution ($R = 0.68$, $P < 0.001$). The orientation of the model was therefore co-varied with E such that $\alpha_{E+} = 11^o$, $\alpha_{E0} = 1^o$, $\alpha_{E-} = -8^o$.

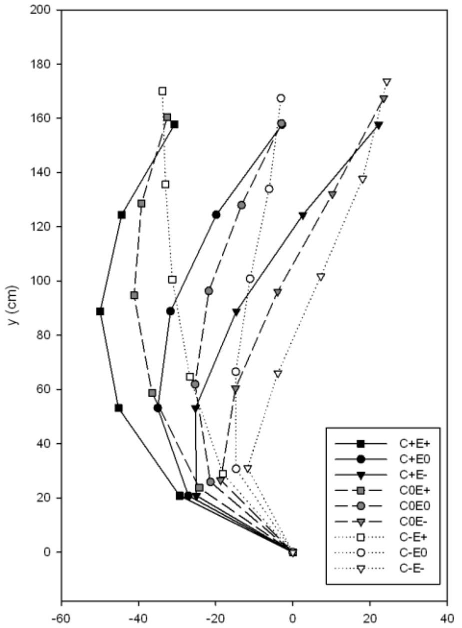

Fig. 2. The nine shapes generated for the study. The shapes encompass three different magnitudes of curvature (C+, C0, C-) and three different distributions for the curvature (E+, E0, E-). The orientation (defined by the angle of L1S1 with respect to the vertical) was co-varied with E.

Body weight and simplified muscle forces were applied to the model as shown in Fig. 3. Body weight forces, F_i, were assumed to act vertically downwards at the vertebral body centroids. These forces were calculated for a body mass of 73 kg using reported values for the percentage of body weight supported at each vertebral level (Duval-Beaupere & Robain 1987). This resulted in forces of 282 N (F_1), 17 N (F_2, F_3, F_4) and 20 N (F_5) being applied; these forces are additive such that in the analysis of the model the total force due to body weight being experienced at the level of L5 was 353 N. The muscle force, M_i, acting on each vertebral body was assumed to consist of a single force applied along a line of action connecting the vertebral body centroid to a fixed point, S0, 50 mm posterior to the centroid of S1. In reality the vertebral bodies are subjected to forces from multiple muscles with different lines of action. Combining these into a single force is a simplification but is broadly representative of the extensor muscles (iliocostalis lumborum and longissimus lumborum). The position of the point S0, which defines the line of action of the applied muscle forces, is also representative of the attachment site of these muscles (Bogduk et al., 1992) and is similar to that used in other modeling studies (El-Rich et al.,2004; Han et al., 2011).

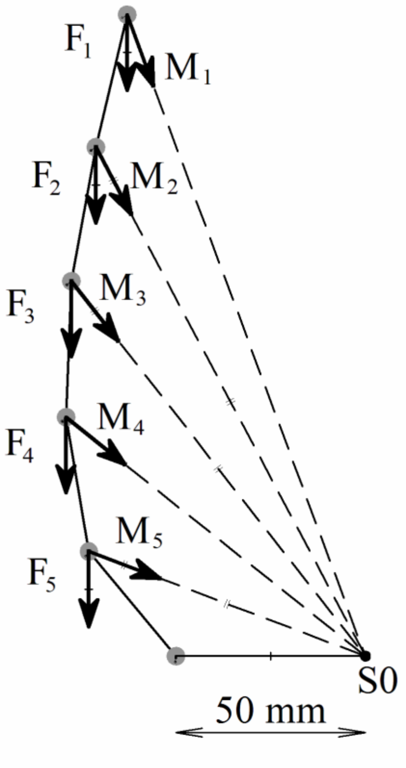

Fig. 3. The forces applied to the model. Forces due to body weight, F_i, act vertically at the vertebral body centroids. Simplified muscle forces, M_i, act along lines connecting the vertebral body centroids to a point, S0, situated 50 mm posterior to the centroid of S1.

2.2. *Follower load path calculation*

The path of the follower load was defined as being that which passed as close to the vertebral body centroids as possible and which maintained a positive curvature such that no adjacent segments of the path could be co-linear; this was to prevent artifacts in the subsequent analysis of the model. The path of the follower load was calculated using an iterative algorithm written in MATLAB® R2008a (The MathWorks, Inc., Natick, MA, USA). The end points of the path were fixed at the centroids of L1 and S1 and the intervening points were allowed to travel along lines, centered on the vertebral body centroids, which bisected the angle made by the lines connecting the adjacent centroids. The path was determined by finding the distance from the centroid, along the width line, to the nearest 0.01 mm, which gave the smallest root mean square distance.

2.3. *Analysis of the model*

The method of graphic statics, implemented using Smartsketch® software (Intergraph Corporation, Madison, AL, USA), was employed to analyze the models. This method, which is described by Heyman (1995) is commonly used in analyzing masonry arches (Block et al., 2006) but has been applied to the spine in several previous studies (Aspden 1987; 1988; 1989; Case et al., 1999). Essentially the method is used to solve static problems by constructing two reciprocal diagrams: a funicular polygon (which denotes the path of forces in the structure of interest) and a force polygon (which represents the forces in the structure). In this paper, the funicular polygon was defined by the path of the follower load.

The follower load path and force polygon created for the analysis of the average shape, C0E0, are shown in Fig. 4. The lines that extend from the pole of the force polygon, O, to the points P_i represent the follower load between vertebral body i and i+1 (i.e. OP_1 is the follower load from L1 to L2). The angle of these lines was set to that of the corresponding segment of the follower load path. The vertical arrows extending downwards from the points P_i represent body weight and were fixed at the appropriate magnitude (a 100 N scale bar is included in Fig. 4). The dashed arrows extending from the body weight arrows represent the muscle forces and were set at the appropriate angle given by the lines of action between the vertebral body centroids and the point S0. Setting the preceding aspects of the force polygon and assuming that the forces would be at a minimum, produced a unique solution for the magnitude of the muscle forces and follower load.

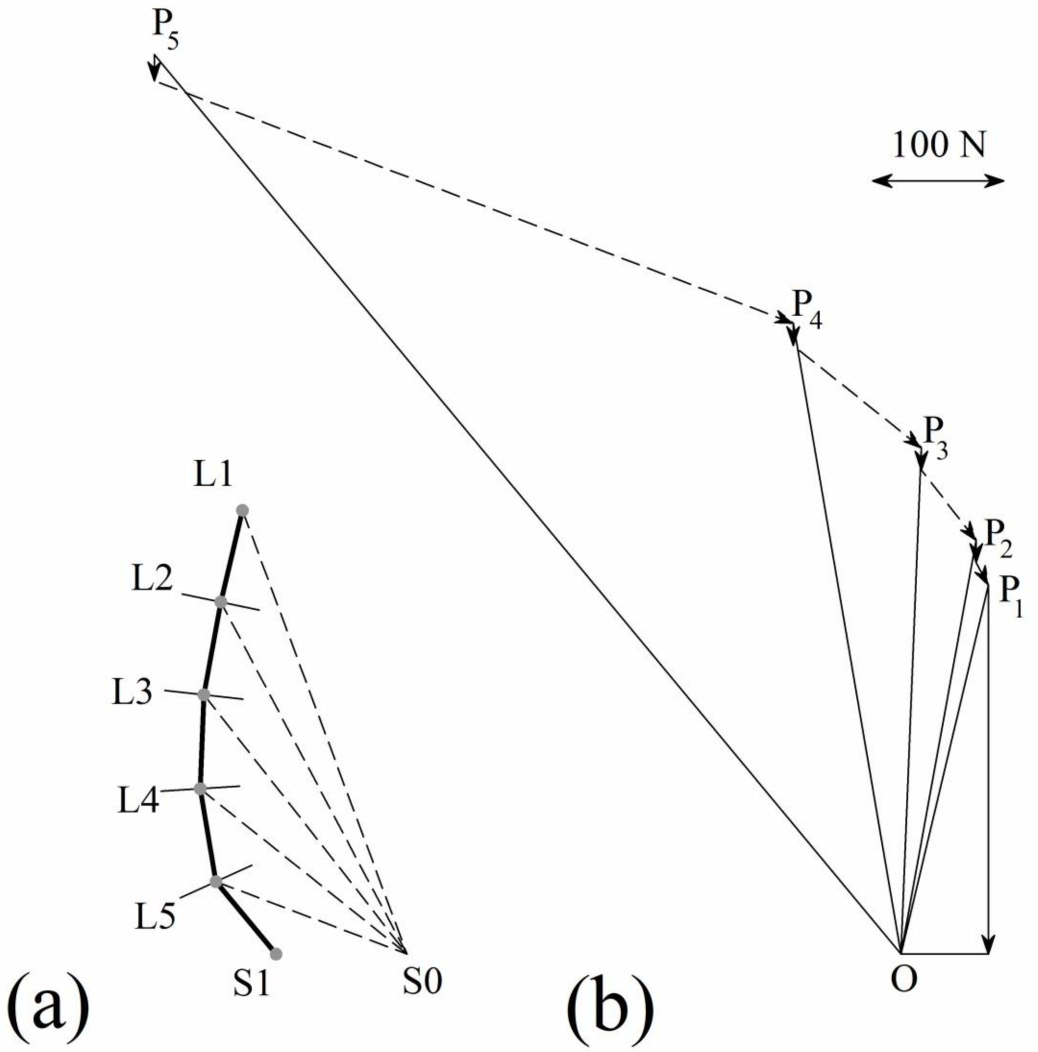

Fig. 4. Analysis of the model using graphical statics. (a) Path of the follower load passing as close as possible to the vertebral body centroids, (b) Force polygon showing the body weights (vertical arrows), muscle forces (angled arrows), and thrusts (lines connecting P_i to O).

3. **Results**

The forces predicted by the model to be required at the levels from L2 to L5 are shown in Fig. 5. For all nine shapes considered the required forces increased on passing down the vertebral levels. Shape was found to affect the magnitude of the forces such that, in general, they increased as the total curvature increase and as the curvature became more evenly distributed.

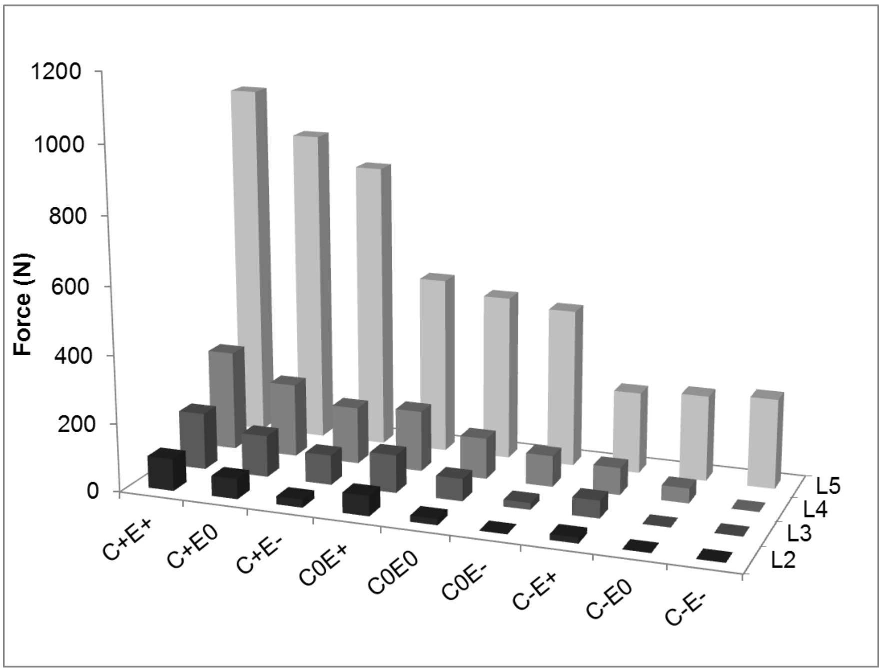

Fig. 5. Required force predicted at each vertebral level for all nine shapes analyzed.

4. **Discussion**

The results from the model show that the applied forces required to produce a follower load in a curved structure vary with the magnitude and distribution of the curvature. Despite the assumptions and simplifications in the model, which are discussed below, the results lead us to hypothesize that the natural sagittal shape of an individual’s lumbar spine will influence the effort required by their lumbar musculature to maintain stability, via a follower load, when in the standing posture.

In the current study, the method of graphic statics was used to determine the forces (due to muscles) required to make a follower load travel along a path of given shape (defined by the sagittal curvature of the lumbar spine) under the assumption that the vertically applied forces (due to body weight) did not change. This differs from the analysis of the arch model (Aspden, 1989), and our previous experimental work (Meakin et al., 2008b), where the path of the follower load, or the shape of the lumbar spine, changed due to additional vertical load being applied The difference between the two analyses is demonstrated by considering a horizontal string from which are hanging two weights. The deformed shape of the string can be changed to an alternative conformation by changing either the tensile forces at the ends of the string or the magnitude of the supported weights.

One of the simplifications in the model was the representation of muscle forces as a single force applied at each vertebral level and directed towards a fixed point behind the sacrum. In reality, there are a number of muscles associated with the lumbar spine (Bogduk et al., 1992) which may apply forces, either actively or passively (Ward et al., 2009), to maintain stability. Of these muscles, the ones that are most closely represented by the model are the iliocostalis lumborum and longissiums lumborum extensor muscles which have insertion points at the individual vertebral bodies and the sacrum. The study by Han et al. (2011) suggests that it is these extensor muscles, with the assistance of the smaller intersegmental muscles (interspinales and rotatores), that are mainly responsible for producing a follower load; suggesting that our simplification is not unreasonable.

The path of the follower load in the model was set to be as close to the vertebral body centroids as possible. This represents the ‘ideal’ situation where shear and bending forces are minimized. In reality the follower load may take a path which is closer to the posterior boundary of the vertebral bodies. This would still maintain the stability of the spine (Aspden, 1987), but would require lower muscle forces at the expense of developing some shear and bending force.

Our hypothesis that muscular effort will vary with the sagittal shape, is supported by some experimental evidence in the literature. The pattern of muscle activity along the lumbar spine in subjects standing upright, for example, has been reported to exhibit inter-subject variation (Joseph and McColl, 1961). In addition to this, further analysis of data presented by Dolan et al. (1988) for 10 subjects shows that the ratio of the electromyographic signal from the muscles at the level of L5 to that at L1 increases with lumbar lordosis.

Variation in muscle requirements could have important implications for understanding the role of spinal shape and muscle function in back pain. Several studies have shown that the lumbar muscles, particularly at the lower vertebral levels, are smaller in low back pain patients than in control subjects (Kamaz et al., 2007; Hides et al., 2008; Wallwork et al., 2009). Although size is not a unique predictor of muscle strength, it does place limits on the maximum force that a muscle can generate and it is generally thought that a smaller muscle will be weaker and less able to stabilize the spine. Differing muscle requirements for different shaped spines, however, may make this apparent muscle atrophy more, or less, important for certain individuals.

In conclusion, the results of this study suggest that differences in the shape of the lumbar spine, both its curvature and the evenness of the distribution of curvature, have an effect on the forces required to ensure stability in standing. Further modeling work will show how shape affects the force required from individual muscles of the lumbar spine and allow us to predict how muscle atrophy affects spinal stability.

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