STABILITY OF THE SPINE MODELLED AS AN ARCH

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Abstract -The erector muscles are frequently strained through improper lifting. Stability of the spine is maintained by the muscles, ligaments and pressures inside the body cavities. Modelling of this stability has been achieved using a new arch spine model developed using optimisation techniques. The position of the thrust line in the arch spine model can be used to analyse stability of the spine, and muscle forces introduced to change the position of this thrust line. The erector muscles move the thrust line forward to the centre line of the spine in a weight lifting task in a stooped posture. A method to calculate muscle forces stabilising the spine and to calculate internal forces in the vertebrae is presented. Calculations show that L3/L4 disc loads increase with muscle and ligament forces in the lumbar region.

Key words: Stability, Spine, Muscles, Arch, Model.

INTRODUCTION

The muscles associated with the vertebral column are strong and complex because they have to provide support and movement in resistance to the effect of gravity. The vertebral column can be flexed, extended, abducted, adducted and rotated. The muscle that flexes the vertebral column, the rectus abdominis, is described as a paired, straplike muscle of the anterior abdominal wall. The extensor muscles located on the posterior side of the vertebral column is stronger than the flexors. The extensor muscles consist of a superficial group and a deep group. The erector spinae is a massive superficial muscle group that extends from the sacrum to the skull. It consists of three groups of muscles: iliocostalis longissimus and spinalis. The erector muscles are frequently strained through improper lifting. The anterolateral abdominal wall is composed of four pairs of flat, sheetlike muscles: the external oblique, internal oblique, transversus abdominis and rectus abdominis. These muscles support and protect the organs of the abdominal cavity and aid in breathing. When they contract, the pressure in the abdominal cavity increases, which can help in stabilizing the spine during heavy lifting (Kent *et al.,* 1992).

The human spine has previously been modelled as a lever, a simple beam, a cantilever beam and as an arch. The arch model was further developed in previous papers (Xiao *et al.,* 1997a; 1997b) in which a criterion for safety or stability of the spine was stated that if the best-fitting thrust line among all possible thrust lines for a specific spinal posture is found and lies within the safety core of the complete spine, then the spine is stable or safe, otherwise the spine is unstable and the risk of spinal disorders might increase. A best-fitting thrust line exists but there may be some difficulty in finding it. However, a better thrust line compared with others may be found using optimisation techniques. Objective functions to find a thrust line which is as close as possible to the centre or reference line of the spine have been generated (Xiao *et al.,* 1997b). The better thrust line obtained may not be located at the centre or reference line and may even be outside of the critical core of the spine. Considering that the human spine does not always collapse in this situation, certain muscle forces are presumably generated to maintain stability of the spinal column. In other words, some forces, e.g. muscle forces, may be generated to change the position of the thrust line and move the thrust line forward to the centre line. Contraction of erector muscles may result in pressure forces which are perpendicular to the centre line of the spine in the sagittal plane and are applied on discs and vertebrae. Prediction of these pressure forces which apply

to lumbar discs and vertebrae generated by contraction of erector muscles could be possible through relocating the thrust line on or very close to the centre or reference line using the developed arch model. Lumbar back pain and spinal disorders may be related to intervertebral disc pressure and distortion of the disc shape which may result from spinal curvature and loads applied on the spine including muscle forces. Disc pressure may be mainly balanced by this kind of pressure force. The risk of lumbar back pain and spinal disorders may increase with increasing the pressure forces on lumbar discs after the pressure forces reach certain levels. Calculation of the pressure forces on discs and against disc pressure could be meaningful for better understanding of lumbar back pain and spinal disorders.

METHODS

A brief description of our previous developed arch model may be helpful. The arch theory was employed in the arch spine model. A masonry arch is a statically indeterminate structure which can be analysed by the tool of funicular polygon. Vertical loads applied on hanging strings and arches was discussed by Heyman (1982). Loads are applied on the spine in general directions which is more realistic. A string and an arch with general direction loads in equilibrium was discussed by Timoshenko (1965). The arch is in compression while the strings are in tension. Compressive force is transmitted along the thrust line in the arch spine. The position and shape of the thrust line depends on the position of the pole O of the force polygon. To find a better thrust line is necessary to find the pole O which makes the thrust line as close as possible to the centre or reference line of the arch spine. Three assumptions for the arch and the spine are still needed. These are: loads are transmitted only by compressive forces along the arch and spine, the arch and spine have adequate compressive strengths, and shear forces are small.

The thrust line obtained by optimisation could be located in the centre core which is called the safety core, the critical core or even outside the arch or the spinal column as shown in fig.1. Posterior extrusion of fibrocartilage from the disc, caused by hydraulic wedging pressure and the stretching of ligaments, may be a cause of back pain (Keegan, 1953). An analysis is required to determine the hydraulic wedging pressure forces and the pressure forces applied on the discs and vertebra from the corresponding muscles and ligaments acting against the hydraulic wedging pressure forces as shown in fig. 2. It might be possible to predict the level of back pain and lumbar disorders resulting from these muscle and ligament forces.
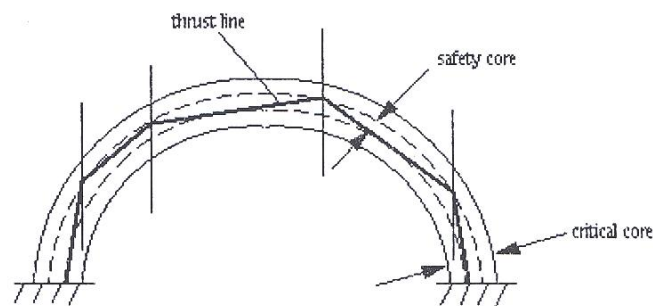

Figure 1. A thrust line lies in the safety core or critical core of an arch
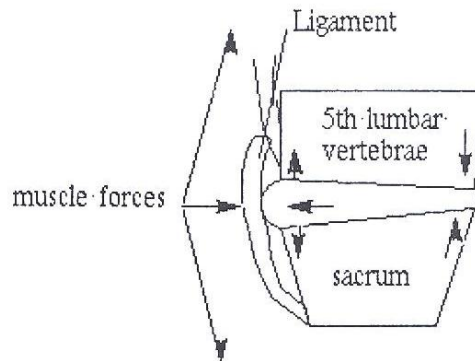
Figure 2. Muscle and ligament forces against disc pressure

Generally speaking, the closer the thrust line to the centre or reference line, the less instability of the spine except under extreme conditions. Humans have a self adjustment mechanism to ensure that the spine does not collapse and this mechanism could result in the thrust line lying at or close to the centre or reference line by selecting alternative muscle groups or adjusting the posture to maintain the stability of the spine. The corresponding muscle forces could then be predicted through placing the thrust line at or close to the centre line of the spine. The thrust line may be located outside the safety core, or critical core or even far away from the spinal column for some loading conditions. If some muscle forces act on the spine, the position of the thrust line will be changed. It is supposed that if the thrust line moves at or very close to the centre or reference line of the spine, then the muscle forces can be calculated through the new position of the thrust line.

RESULTS

Earlier work (Xiao *et al.,* 1997a) used a different loading system for analysing the muscle and ligament forces in the lumbar region to maintain the stability of the spine. In extension to that work, a 755N male in a stooped, forward bending posture with straight knees holds a 900N weight with both hands (assumed to act on T6). The head and shoulders weight of 130N acts on T2, the trunk weight of 230N acts on Tl2, and intra-abdominal pressure of 70N acts perpendicularly to each of the vertebrae L1 to L5 as in the earlier work. The difference between the earlier and current work is that ligament and muscle forces are introduced which are applied to the discs and vertebra in the lumbar region and act perpendicularly to each of the vertebrae L1 to L5. A solution is required for this new loading situation.

All forces act in the sagittal plane as shown in fig. 3. The body weight, intra-abdominal pressure forces and additional loads held in the hands are treated as the external forces. The ligament and muscle forces applied on the discs and vertebrae in the lumbar region are treated as the additional external forces in the new situation. The other unknown ligament and muscle forces are treated as reaction forces acting on both ends of the spine (sacrum and head/neck). In this way, the ligament and muscle forces to be applied to the discs and vertebrae in the lumbar region to change the position of the thrust line and force the thrust line to move at or close to the centre or reference line can be predicted. These are the forces required to balance the other loads, e.g. body weight, additional loads and intra-abdominal pressure forces, and to keep the spine stable. Without considering the Ligament and Muscle Forces (LMF) which are applied on the discs and vertebrae in the lumbar region, but considering Intra-abdominal Pressure Forces (IaPF), the thrust line lies outside the surface of the spinal column. The

thrust line of 5x70 N (IaPF) is shown in Figure 3. If the thrust line moves close to the centre or reference line, then the corresponding LMF of 5x170 N and 5x 220 N has to apply. The thrust Line of 5x170 N (LMF) and the thrust Line of 5x220 N (LMF) are shown in fig. 3. Calculations show that a range of LMF between 5x120 N and 5x270 N results in corresponding thrust lines close to the centre line of the spine. The internal forces between the vertebrae under different LMF are shown in fig. 4. Calculations further show that LMF varies from 0 N (Xiao *et al.,* 1997a) to 2216 N, the corresponding L3/L4 disc loads change from 1469 N (Xiao *eta/.,* 1997a) to 2216 N which increases with increasing LMF as shown in fig. 5.
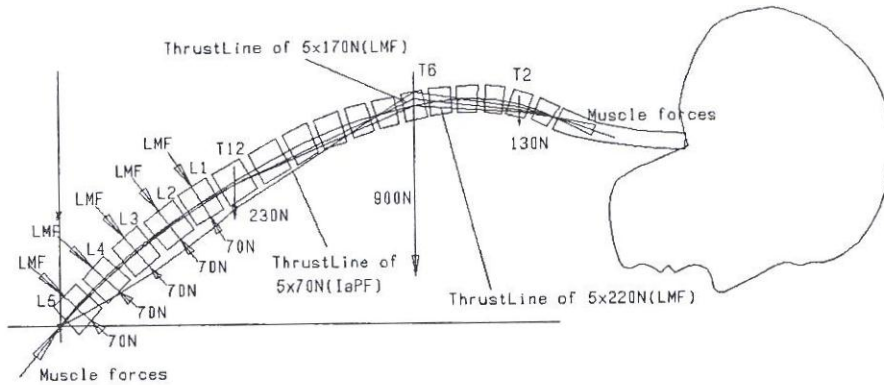

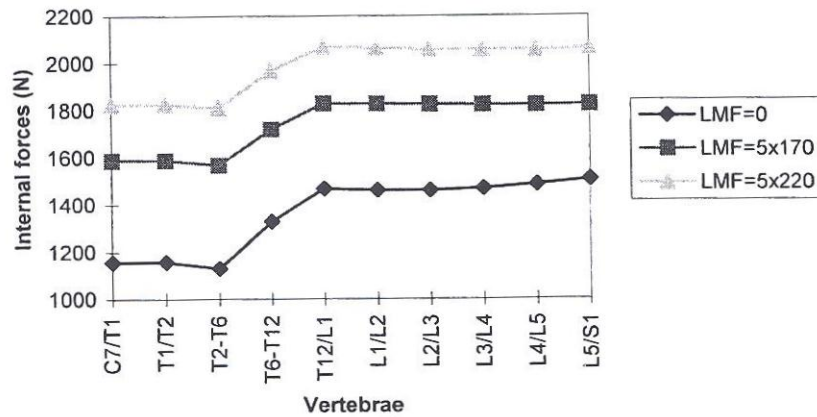Figure 3. Stability of the spine under intra-abdominal pressure forces and muscle forces

Figure 4. Internal loads between vertebrae under different muscle and ligament forces

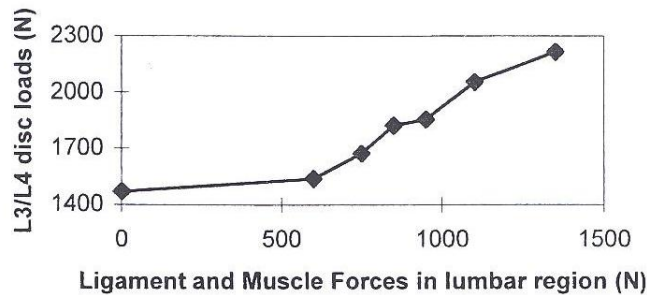## Stooped posture, hold 900 N, Intra-abdominal pressure forces = 5x70 N

Figure 5. L3/L4 disc loads increase with increasing LMF

DISCUSSION

The developed arch spine model provides a way to analyse spine stability, calculate muscle forces and determine internal loads in the vertebrae as an arch. If any additional forces are introduced into the arch spine, the position and shape of the corresponding thrust line will be changed. In weight lifting in a stooped posture with Intra-abdominal Pressure, the thrust line will move forward to the centre or reference line of the spine as erector muscle forces and ligament forces in the lumbar region are introduced. In the above case studies, under body weight, additional load of 900 N and Intra-abdominal Pressure forces of 5x70 N, forces ranging between 5x120 N and 5 x 270 N are needed to move the thrust line very close to the centre or reference line of the spine and to keep the spine stable. The muscle and ligament forces increase from 0 N to 5x120 N to 5x270 N to keep the spine stable which results in L3/L4 disc loads increasing from 1469 N to1540 N to 2216 N. It should be noted that the L3/L4 disc load is 1469 N before the muscle and ligament forces are introduced (LMF=0) in which the spine is unstable, the L3/L4 disc loads increase up to 2216 N after the muscle and ligament forces are introduced to keep the spine stable. This result of 2216 N of L3/L4 disc loads is smaller than the experimental result of 3330 N in a similar weight lifting task of 20 Kg in the literature (Nachemson, 1985) and other muscle forces may need to be introduced into the arch spine model. The analysis of the stability of the spine in this paper may provide a way to assess the level of back pain and spinal disorders from the values of the erector muscle forces and ligament forces. It shows the function of muscles in the stabilisation of the spine.

ACKNOWLEDGEMENTS

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