THE EFFECTS OF DECLINED SURFACES ON SPINAL STABILITY: THRUSTLINE APPROACH

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Abstract: Instability of the spine is one of the important injury mechanisms. It is the failure of the transmission of the compressive forces within the physical boundaries of the spine. The possible factors affecting the stability of the spine include: spine curvature, forces due to body weight and external forces acting on the spine, the inclination of the surface on which the body stands. In the absence of any external load, the human spine is subjected to compressive loading due to the weight of the surrounding skeleton, soft tissues, internal organs and muscles of the human body. The thrustline theory is used to investigate the transmission of compressive forces and spinal stability.

Introduction

The International Association for the Study of Pain (IASP) Subcommittee on Taxonomy, defines back pain as "An unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" [1]. Troup et al [2], White and Gordon [3] define the problem of low back pain as a symptom with various pathologies, diagnoses, etiologies and medical management techniques [4]. With the complex mechanism of pain, back pain has been a matter of investigation for many researchers. Usually the direct mechanism of pain is not very obvious. While Low Back Pain (LBP) is perceived as idiopathic, its development is attributed to a combination of multi-factors like mechanical, chemical, biological, infectious, genetic, psychological, and degenerative origins [5]. The prevalence of back pain shows that there are still many unknowns to be investigated and the mechanism of back pain has not been understood very well to develop preventive methods.

There are many cases where the body is on sloped surfaces, like cycling, skiing, walking on high heel shoes and lifting. The number of studies investigating the effect of sloped surfaces on spinal stability in literature is limited. For manual material handling on inclined surfaces Zhao et al. [6] observed the potential risk factors of slipping. Shin and Mirka [7] investigated the lifting of a load with slope angles of ±10, ±20 with three different lifting styles to evaluate the effect of net moment about the L5/S1 joint and found out higher L5/S1 moment values for inclined surfaces when compared to flat surfaces.

The effect of wearing high-heeled shoes creates an effect of standing on declined surfaces. Lee et all [8] found out that women wearing high heeled shoes indicate complaints of leg and low back pain. With the empirical studies, as the heel heights increased lower back EMG increased showing high muscle activity. In addition to this, the vertical movement of the body center of mass increased significantly resulting in additional compression in the lumbar part due to change in the lumbar lordosis.

One of the most common posture problems encountered by road racing cyclists also relate to the lower back or to the upper back and neck. The style of riding focuses on maximum reduction of air resistance but if the posture length of the racing cyclist is too short , the stress on the vertebra is high and may cause lower back and cervical pain [9]. Especially on inclined surfaces it is necessary to investigate the stability of the spine with different postures to understand the injury mechanism and causes of pain for cyclists. Many of the problems might be prevented if the rider adjusts his or her posture correctly [9]. Skiers also have to change their upper body angle continuously in order to make use of aerodynamic forces on inclined surfaces [10].

One of the important functions of the spine is to support the body by transmitting the compressive forces throughout the spine, while standing cycling, lifting, or walking. Thrustline theory is used for stability analysis of human spine. The type of curvature, the direction and magnitude of the applied forces on the structure are used to calculate the force polygons. Acar and Grilli [11] considered the thrustlines for the whole spine with distributed body weight. The effect of sloped surface for different body postures with the load of body weight itself has never been investigated with thrustline approach to date.

The aim of this study is to investigate the stability of the spine under the loading of distributed body weight with respect to different ground surface angles for different body postures with the thrustline approach on a 2D model of the entire human spine.

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Methods

The construction of the model was formed by the five different parameters of the 2D sagittal view of the 24 vertebrae starting from C1 to L5. The parameters of the model are: the values for the vertebral height, vertebral width, the relative angles of orientation between adjacent vertebrae and the X and Y coordinates of the center of the inferior surface of each vertebra. The anthropometric data for the thoracic and lumbar region are obtained from Orne and Liu [12]. The origin of the vertebrae is defined as the center of the inferior end plate of the vertebral body. The X and Y coordinates of the lower surface center of the vertebrae are obtained from Acar and Grilli [11]. The center of the superior surface of the sacrum is chosen as the origin of the model. In order to investigate the effect of distributed body weight when on an inclined surface on spinal stability, the weight distribution pattern of the full spine is obtained from Acar and Grilli [11]. The weight of each trunk slice was assumed to act trough the centroid of the slice.

Three different postures have been investigated; slightly flexed (flex1), half flexed (flex2), and fully flexed (flex3) postures with only vertebral structure excluding the muscles and ligaments. The data describing the configuration of the spine in flexion are obtained from the thesis of S.L. Grilli, 1997. Visual Basic language was used to construct the model.

The spine is assumed to be in equilibrium with the body weight acting at each vertebral level. The equation of equilibrium are applied to find the end point reaction forces at the L5/S1 and C1 region of the spine. (Equations 1,2,3).

$$\sum Fx_i = 0 \qquad (1)$$

$$\sum Fy_i = 0 \qquad (2)$$

$$\sum M_i = 0 \qquad (3)$$

where Fx, Fy and M represent the x and y force components and moments respectively.

The line of thrust determines the possible pathway for the transmission of compressive forces. The state of equilibrium alone does not imply the stability. Instability occurs if the thrustline lies outside the physical boundaries of the spine. This means that the spine is incapable of transmitting compressive forces and becomes unstable. The geometric location of the thrustline determines the stability [13].

In order to apply the theory of thrustline we need to calculate the reaction forces at the end points of the spine. There are three equations of equilibrium, the number of the unknowns in this case is four:

R1: Reaction force at the bottom surface center of the L 5 perpendicular to reference line.

H1: Reaction force at the bottom surface center of the L5 parallel to reference line.

R2: Reaction force at the top surface center of the C1 perpendicular to reference line.

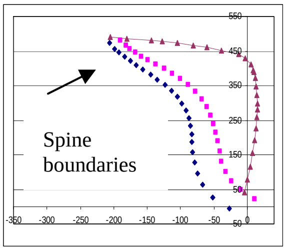
H2: Reaction force at the top surface center of the C1 perpendicular to reference line.

The weight of the head is assumed to act as force H1 thereby making the number of unknowns and the equations equal to each other. The weight of head is assumed to act 0.45 cm anterior to and 4.55 cm superior top surface center of C1. Equations 1, 2 and 3 are solved simultaneously with the distributed body weight, to find the numerical values for the reaction forces of R1, R2, and H2. The next step is the construction of the funicular polygon. It is possible to draw the thrustlines (funicular polygon) either using an analytical method or graphical method. Here, analytical method was followed by constraining the start and end coordinates of the thrustline coinciding with the start and end points of the vertebrae mainly bottom center of L5 and upper center of C1. In order to build the thrustline, x and y coordinates of the thrustline were calculated for every vertebral level. Due to the constraint of aligning the start and end points of the thrustline with the spine end points, thrustline is shifted to coincide with these points.

The location of the thrustline is inspected with respect to the physical boundaries of the spine. The more the deviation of the thrustline from the spine, the more unstable the spine becomes.

Results

With three different postures, 6 different downhill surface angles (0, 3, 6, 9, 12, and 15 degrees) are investigated. It is observed that the more the body is flexed the more unstable the spine becomes. On the other hand, for each posture as the surface inclination is increased the spine becomes more unstable. The instability is observed to increase from 0 degrees to 15 degrees (Figures 1, 2). When the body stands on a flat surface the transmission of compressive forces is easier when compared to more declined surfaces. As the model does not include the muscle forces; the only compression force provided for stability is the weight of the head. With the increase of the surface angle, however, the compressive force component of the head decreases causing more deviation of the thrustline from the spinal structure. It appears that the peak points of the thrustlines, are in the vicinity of the lumbar region, indicating that there is a need for further forces to improve stability at this region more than other regions of the spine.



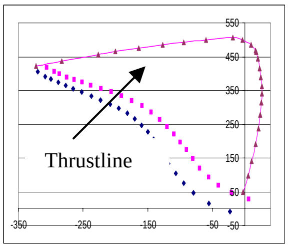


Figure 1 (left): Thrustline with 0 degree of slope for flex posture 1

Figure 2 (right): Thrustline with 3 degree of slope for flex posture 1

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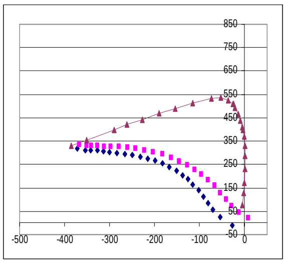
For flex posture 2, the increased slope angle causes body forces to create greater shear forces when compared to the compression forces, because of this instability is increased. The need for the muscle forces is observed to increase in the overall structure of the spine (Figures 3, 4).



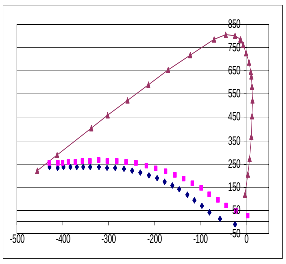
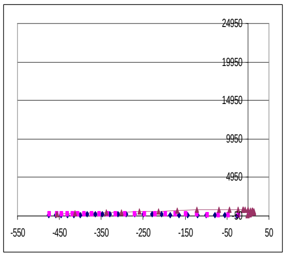


Figure 3 (left): Thrustline with 0 degree of slope for flex posture 2
Figure 4 (right): Thrustline with 15 degree of downhill slope for flex posture 2

The highest instability occurs in the fully flexed posture. All the force components acting on the spine act nearly perpendicular to the reference line leaving compression force to a minimum. The requirement for the muscle forces is highest with the fully flexed and the most declined surfaces. Fully flexed posture is observed to have the highest sensitivity to the change of angle of the surface. This indicates that as the surface inclination is increased, it might be wise to avoid fully flexed postures in order to prevent from injuries caused by loss of stability (Figures 5, 6).



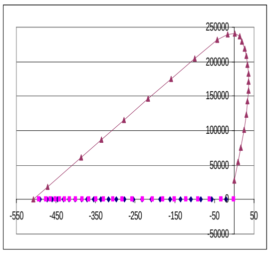


Figure 5 (left): Thrustline with 0 degree of slope for flex posture 3
Figure 6 (right): Thrustline with 15 degree of downhill slope for flex posture 3

One of the most common models in literature is the lever theory, where the spine is assumed to bend about a fixed point, namely the sacrum. The curvature of the spine is neglected in this theory unlike to thrustline theory. The flexion moments produced by the body weight acting anterior to the spine are calculated. The model determines the extension moments required to be produced by the posterior muscles. So that flexion and extension moments are in equilibrium. These moments are generally considered about the lower lumbar levels, in this case at L5/S1 region at which the moments and loads are predicted to be greatest. Equilibrium of the structure is ensured when both the forces and the moments acting on it are in equilibrium. The code was extended to apply the lever model in order to compare the two models. The lever model is applied with the distributed body forces in this research. Although in literature the whole body weight acts as point force acting on one of the specific vertebrae, here we used distributed force approach. In the figure below, moment values are shown. The moment value for each posture to be in equilibrium is observed to increase as the slope of the surface increases and the need for high muscles forces to counteract the necessary moment increases. This result shows that both the thrustline theory and the lever model produce similar interpretations.

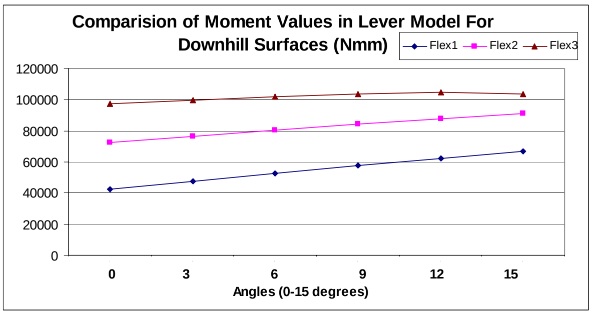


Figure 7: Comparison of moment values

Discussion

The results above show that the stability of the spine is related to the slope of the surface. The effects are important for the postures with prolonged conditions. Especially race cyclists' back, particularly the lower back and the neck may adopt an unnatural posture for hours. When the slope of a road changes, even a comfortable posture may turn into a painful posture. De Vey Mastdagh emphases that the posture length is an important parameter and too short postures are harmful as they ask for too much contribution of the lumbar region muscles causing cramps and too much load on vertebrae [9]. This idea is compatible with the interpretation of the location of the thrustlines. In our studies, the posture length, which is the length of line connecting the superior surface of C1 and inferior surface of L5, decreases from 523 cm to 490 cm from the most erect posture to most flex posture. As the spine is flexed, the length of the posture becomes shorter. In the thrustlines shown above, the peak points coincide with the lumbar region and the deviation of the thrustlines becomes larger as the slope angle increases. This indicates that there is a need for the contribution of the internal forces to contain the thrustlines within the physical boundaries of the spine. Moreover, the need for back muscles increases at most with the highly flexed postures, agreeing with the ideas of De Vay Mastdagh related to shorter span of body postures.

The results by Shin and Mirka show that L5/S1 moment vary as a function of lift technique and ground slope angle [7]. The results found in this paper also indicate that the L5/S1 moment is sensitive to slope angle. However, the change of lifting technique or the body posture has not been inspected in this study. The same postures have been used for all surface angles (0 to 15 degrees).

The conventional biomechanical approach for addressing low back injury risk is evaluating the magnitude of the forces and moments acting on/about the spine. The stability approach adds another dimension to the solution of the problem. Even if the forces acting on the spine are too small, there is always a likelihood of injury because of the failure of transmission of compressive forces within the spine. The thrustline model looks at the transmissibility of the forces within the spine. In this paper, the distributed loading pattern of the body weights is used for applying the lever theory different from the general approach where point forces are assumed to act on the spine. In lever model, in order to calculate the muscle forces necessary to produce the counteracting moment for flexed postures, single muscle force estimation method is used. Although there are many muscles acting on the spine, in order to reduce the system to static determinacy by a single –equivalent trunk extensor muscle is assumed to act on the spine [15], [16], [17] . The construction of a single-equivalent model (SEM) involves assumptions on the anatomy of the muscles contributing to the net moment and on load sharing between these muscles. These assumptions determine the line of action and lever arm of the SEM. In addition, most SEMs assume constant values for lever arm and orientation of the muscle with respect to the joint force applications [18]. However, it has been shown that the erector spinae lever arm and orientation depend on trunk posture [19]. With the thrustline method, it is easier to include the change of orientation of muscle forces with respect to the trunk postures including the change of lever arm of the muscles.

Conclusions

Lower back injury risk is mainly attributed to the magnitude of the forces exceeding the structural tolerance limits of the spinal units. The stability of the spine which is its ability to conduct the forces within its structure is one of the concerns in back pain related research. Supporting the upper body by transmitting compressive forces to the lower body during daily activities is one of the important mechanical functions of the spine. The stability of the spine might also be affected by the change of slope surface the body stands. In this paper, six different slope angles were simulated with three different body postures by applying thrustline theory. The model is formed with the sagittal view of the vertebrae including the body weight forces and excluding any other external forces. The thrustline approach has been used to study the effect of change of slope on spinal stability. The lever theory is also applied to see the change in the moment acting on the L5/S1 region of the spine.

The model will be developed to include all the muscle and ligament forces to investigate the significance of other internal forces in stability. The effect of postural changes with wider range of surface decline and incline angles of the spine will be included.

In order to gain a more general view about the effect of sloped surfaces on spinal stability, uphill surfaces should also be investigated as a future work.

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