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The Effect of Angular Coupling on the Stability of the Lumbar Spine and the Associated Risk of Injury Using Analytic Theory: A New Biomechanical Technique

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Abstract

Angular coupling is intrinsic biological property of the lumbar spine whose effect on the question of the lumbar spine's stability/instability has been very difficult to study. This work proposed and applied a new theory that is dependent on the equation of the lumbar spine in six degrees-of-freedom to study the effect of angular coupling on the stability of lumbar spine and, consequently, on low back pain. We derived the equation of the lumbar spine in six degrees-of-freedom and applied it to study the effects of $2°$, $4°$ and $8°$lateral bending, axial twist and both lateral bending and axial twist on the $10°$extension of a hypothetical lumbar spine. The results of the work show that angular coupling from lateral bending of up to $8°$ has no significant effect on the lumbar spine. The axial twist shows no significant changes at $2°$ and $4°$ but visibly affects the lumbar spine at $8°$. The combined effect of lateral bending and axial twist shows insignificant differences from the effect of axial twist alone, suggesting that the contribution of axial twist to the combined effect is greater. Additionally, the work reveals the possibility of torque transfer from the upper joints of the lumbar spine to the lower joints (L_{4-5} and L_5/S_1).We concluded that angular coupling from axial twist of up to $8°$can cause instability of the lumbar spine and increase the risk of injury to the lumbar spine. Areas for further research using this technique have been suggested.

Keywords: Lumbar spine, Angular coupling, Degree-of-freedom, Risk of injury, Torque transfer.

1.0 Introduction

The structural complexity of the lumbar spine may be the reason for the slow pace of the elucidation ofthe developmental processes of non-specific low back pain (NSLBP). Statistics from around the world reveal that low back pain is a common problem among people that exerts costs both in terms of medical and socio-economic burdens. The majority of these cases of low back pain are referred to as non-specific low back pain (NSLBP) [1-5]. Mechanical factors are often considered primarycauses.

Tounderstand the aetiology, biomechanical modelling has been extensively employed in the study of spinal loading and stability, with the results still unsatisfactory. To date, all biomechanical models can be broadly classified as anequilibrium theory or stability theory. The requirement that a biomechanical analysis is considered complete is that both an equilibrium analysis to estimate tissue loads and a stability analysis to estimate structural tolerances are carried out[6]. Finite element techniques are the dominant study techniques in the literature. However, there are areas that these techniques are still considered inappropriate. Coupling, for instance, is an intrinsic biological property contributing to the complexity of the lumbar spine and is difficult to study using the finite element techniques[7-8]. Many studies have been done on coupling[9-16], but most of these studies have focused on establishing whether or not coupling exist, the direction, and if it is an indicator of low back pain[9,17,18]. Studies that seek to know whether coupling could lead to low back pain (LBP) are scarce or not undertaken.One critical question that still demands answer is how to study coupling effects and whether it affects stability and, consequently, causes law back pain or not.

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The objective of this work was to apply a new theory to study the effect of angular coupling on the stability of the lumbar spine and its consequence on low back pain.Our theory development is based on the structural mechanics of the lumbar spine. We first developed the equation of lumbar spine in three degrees-of-freedom and used it to determine and investigate the center of mass in the sagittal plane and the reaction in the inter-vertebral disc [19-21]. In order to have a complete analysis and better understand of the dynamics of the center of mass, we moved on to develop the equation in six-degrees-of-freedom[22]. The hypothesis, therefore, include:

1. If the displacement is symmetrical over the entire lumbar spine, then the lumbar spine is less likely to sustain injury. However, if the displacement is asymmetrical, then the lumbar spine is more likely to sustain injury.
2. If angular coupling distorts the trajectory of the lumbar spine during a given task, then, the lumbar spine is considered unstable under such coupling condition[23-25].

2.0 Material and Method

Definitions

Coupling: In order that we articulate the work and it findings in the right perspective, we categorised the coupled motion into natural and artificial coupling phenomenon. The natural coupling phenomenon is a "reflex act"- it is neither predetermined nor deliberate. This encapsulates, best, the definition of coupled motion by Paris and Loubert [26]. It is an intrinsic property, induced by the motion segments structures, does not occur in sagittal planeand the mostly studied. There is force induction. On the other hand, artificial coupling phenomenon is a "non-reflex act"-it is predetermined and deliberate. It encapsulates, best, the definition of coupled motion as described by White and Panjabi [27]. It is not intrinsic, not induced by motionsegment structures and there is no force induction rather, separate mobilization forces act simultaneously to achieve the desired motion. It is mostly experienced in athletics. For instance, a footballer that jumps to head a ball with his side head may need to flex or extend his back and side-flex or rotate to achieve his aim. It occurs in all the planes.

Perturbation: The perturbation in this work shall be the coupling angles during an extension task [6].

Equation Derivation

(I). Lumbar Spine Orientation: Using the calculus of variations, Mafuyai et al. [28] showed that the static equation of lumbar spine is

$$y = \frac{l}{\pi}\sin\left(\frac{\pi s}{l}\right) \quad (1)$$

where$y$ is the measure of lordosis, given in cm/rad;l is the length (circumference) of the lumbar spine, measured in cm; and s, also measured in cm, is the distance along the curve of the lumbar spine.

To change all measurements into linear dimensions, we multiply equation (1) by 1rad and set$\sigma = \frac{1}{3.142} = 3.183 \times 10^{-1}$, which is a dimensionless constant called the Mafuyai constant. Hence, equation (1) becomes

$$Y = l\sigma\sin\left(\frac{\pi s}{l}\right) \quad (2)$$

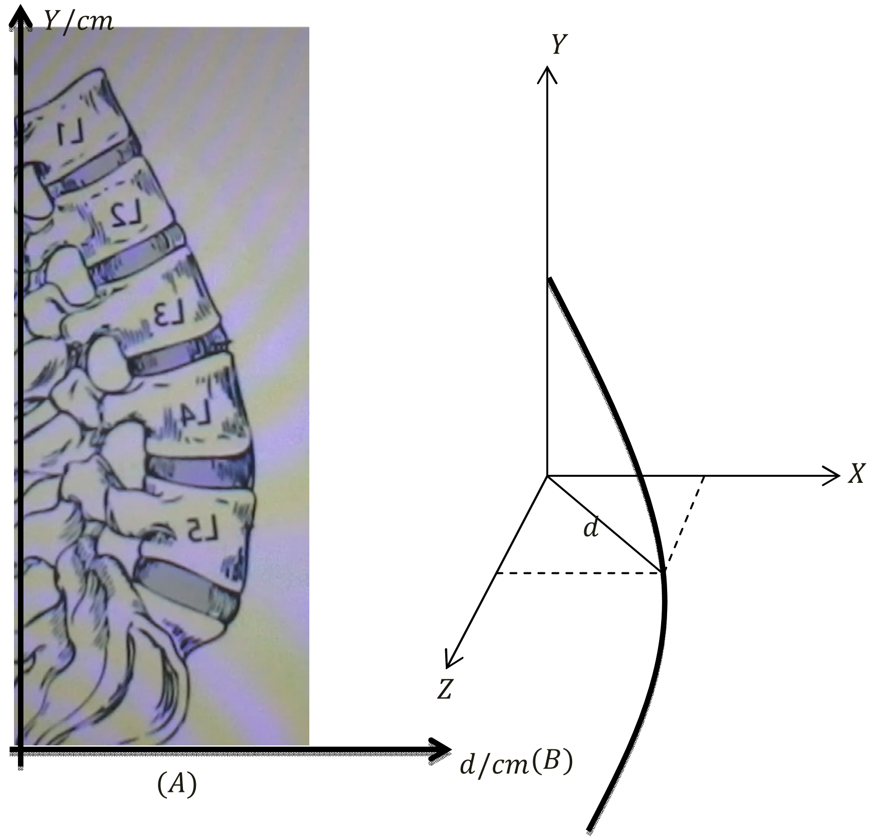

Figure 1:*Geometrical presentation of Lumbar spine in Space*

Now,consider a lumbar spine oriented in space,as shown in Figure 1A and B. If d is the distance of any rigid point on a vertebra from the Y axis of the reference frame,XYZ then, the equation will become

$d = l\sigma\sin\left(\frac{\pi s}{l}\right)$ (3)

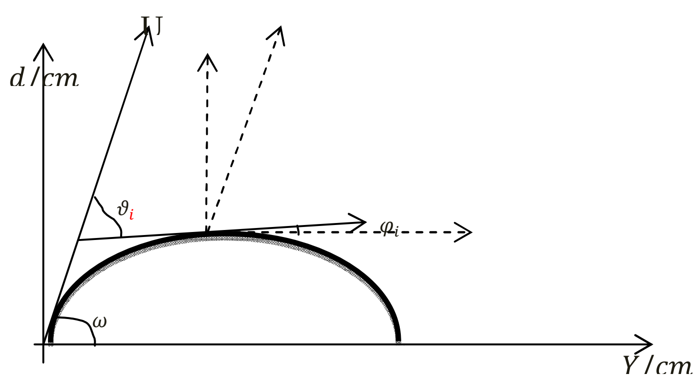

Figure 2:*Vector representation of Lumbar spine*

Now, considering Figure 2, let ωbe the angle subtended by S_1 with the vertical,φ_i the angle subtended by any rigid point on lumbar vertebra L_i with the vertical, and, ϑ_i the angle subtended by any rigid point on lumbar vertebra L_i with the vector U. Then,

$\omega = \vartheta_i + \varphi_i$(4)

Taking an element ∂s and ∂U, we have

$cos\vartheta_i = \frac{\partial U}{\partial s}$ (5)

$\therefore \partial U = \partial s cos\vartheta_i$ (6)

Integrating equation (5) we have

$U = s cos\vartheta_i$ (7)

But,

$Y = \mathrm{U}cos\omega$ (8)

Substituting equation (4) and (7) into (8) and simplifying, we have

$$Y = s\left(cos^2\omega cos\varphi_i + \frac{1}{2}sin2\omega sin\varphi_i\right) \quad (9)$$

The shortest curve joining any two points is a straight line according to calculus of variations. Mafuyai et al. [19] assumed the relationship between the distance s along the curve of the lumbar spine and the chord Y formed by it to be given by

$$s = \mu Y \quad (10)$$

where μ is a constant of proportionality for a static lumbar spine.

Comparing equation (9) and (10), we see that

$$\mu = \frac{1}{cos^2\omega cos\varphi_i + \frac{1}{2}sin2\omega sin\varphi_i} = \frac{s}{Y} \quad (11)$$

Substituting equation (10) into (3) we have

$$d = l\sigma \sin\left(\frac{\pi\mu Y}{l}\right) (12)$$

Now, from Figure 1B, we obtain

$$\sqrt{X^2 + Z^2} = l\sigma \sin\left(\frac{\pi\mu Y}{l}\right) (13)$$

(II). Motion of Rigid Body: Let $\boldsymbol{R}$ be the initial position of a point on a rigid body in space, $\boldsymbol{r}$ the final position, and $\boldsymbol{D}$ the displacement vector (Figure 3A). Then, the equation of motion of a point on a rigid body is given as:

$$\boldsymbol{r} = R_{ij}\boldsymbol{R} + \boldsymbol{D} \quad (14)$$

where R_{ij} is a rotation tensor, defined as

$$\begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} = \begin{bmatrix} \cos(\gamma) & 0 & -\sin(\gamma) \\ 0 & 1 & 0 \\ \sin(\gamma) & 0 & \cos(\gamma) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & \sin(\theta) \\ 0 & -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} \cos(\Psi) & \sin(\Psi) & 0 \\ -\sin(\Psi) & \cos(\Psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (15)$$

and γ, θ and Ψ are a set of Euler angles [29] defined as the changes in axial rotation, lateral rotation and flexion-extension rotation, respectively (Figure 3B), with a rotation convention that clockwise rotations are negative and anticlockwise rotations are positive.

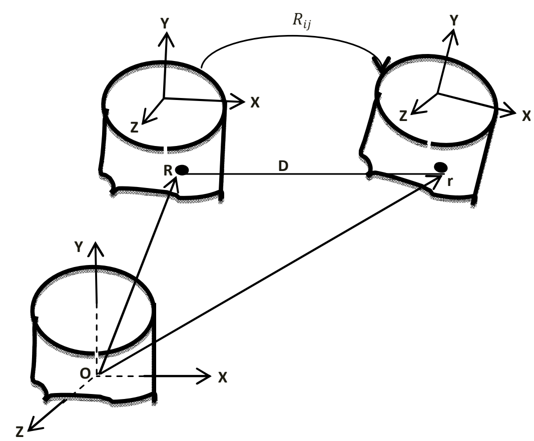

Figure 3A: Rotation of a Vertebra relative to another showing the displacement of a point on a rigid body

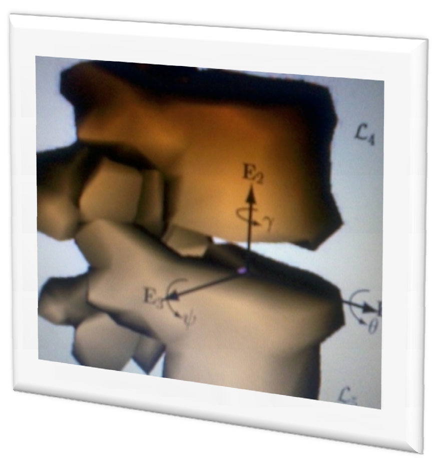

Figure 3B: The coordinate system for relative motion at the L4/L5 Joint

Writing equation (14) in components, substituting it into equation (13) and choosing a point on the rigid body that coincides with the origin of the coordinates for simplicity, equation (13) simplifies into

$$\sqrt{(x_0 - D_{x_0})^2 + (z_0 - D_{z_0})^2} = l\sigma cos(\theta) \sin\left(\frac{\pi\mu\beta\left(y - D_y\right)}{l}\right) \quad (16)$$

where

$$x_0 - D_{x_0} = \frac{x - D_x}{\cos(\Psi)} \quad (17)$$

$$z_0 - D_{z_0} = \frac{z - D_z}{\cos(\gamma)} \quad (18)$$

$$\beta = \frac{1}{\cos(\Psi)\, co\, s(\gamma) - \sin(\Psi)\sin(\gamma)\sin(\theta)} \quad (19)$$

Letting $x_0 - D_{x_0} = (d_0 - D_{d_0})sin\alpha$, $z_0 - D_{z_0} = (d_0 - D_{d_0})cos\alpha$ and $\alpha = \tan^{-1}(\frac{\cos(\gamma)}{\cos(\Psi)})$, we can write equation (16) as

$$d_0 = l\sigma cos(\theta) \sin\left(\frac{\pi\mu\beta\left(y - D_y\right)}{l}\right) + D_{d_0} \quad (20)$$

Where d_0 is a measure of lordosis in terms of linear displacement at neutral posture, l is the length of the lumbar spine, σ is Mafuyai's dimensionless constant given as $\sigma = 3.183 \times 10^{-1}$ and μ is Mafuyai's ratio, defined as the ratio ofa distance along the curve of the lumbar spine to the chord formed by it.

μ, for a dynamic lumbar spine, is given by

$$\mu = \frac{l}{Y + D_y} \quad (21)$$

$$D_y = Y - \frac{Y}{\beta} \quad (22)$$

Convention: in extension, D_y is negative and it is positive in flexion.

3.0 Application

We considereda hypothetical lumbar spine of length $l = 20cm$, with the chord Y formed by the lumbar spine as $18cm$. We determined, for $y = 0,5,10,15$ and $20cm$, the values of $d_0 - D_{d_0}$ using equations (19)-(22) for neutral posture (i.e., $\Psi = \gamma = \theta = 0°$) and $10°$-extension (i.e., $\Psi = 10°$) with $2°, 4°$ and $8°$ coupling in lateral bending and axial twist for various combinations. The graphs were plotted and analysed.

4.0 Results

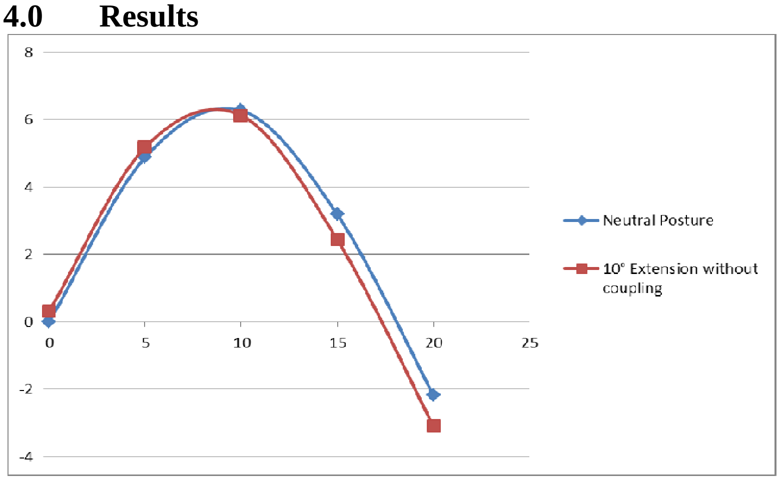

Figure 4A: *Comparison of the plots of Neutral posture and* $10°$ *of extension without coupling*

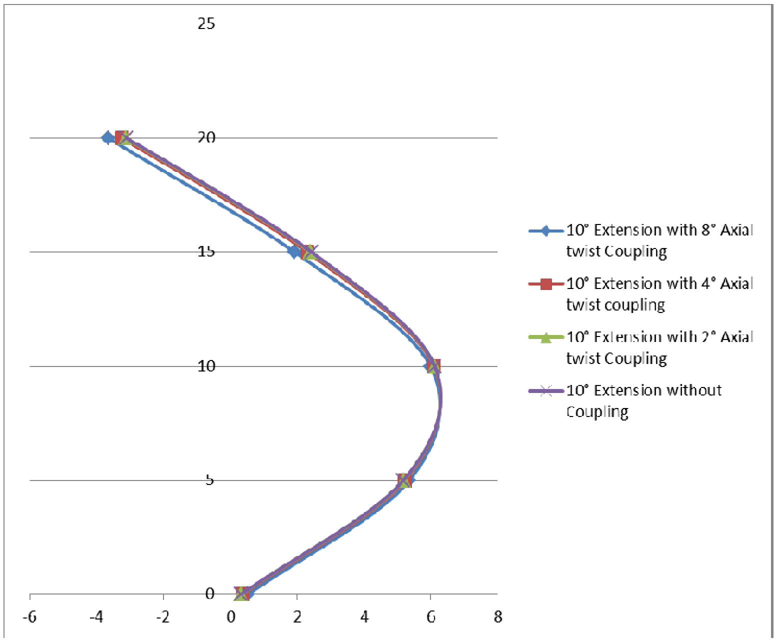

Figure 4B: *Comparison of the plots of* 10°*of extension without coupling and* 10° *of extension with axial twistcoupling of*2° , 4°*and*8°

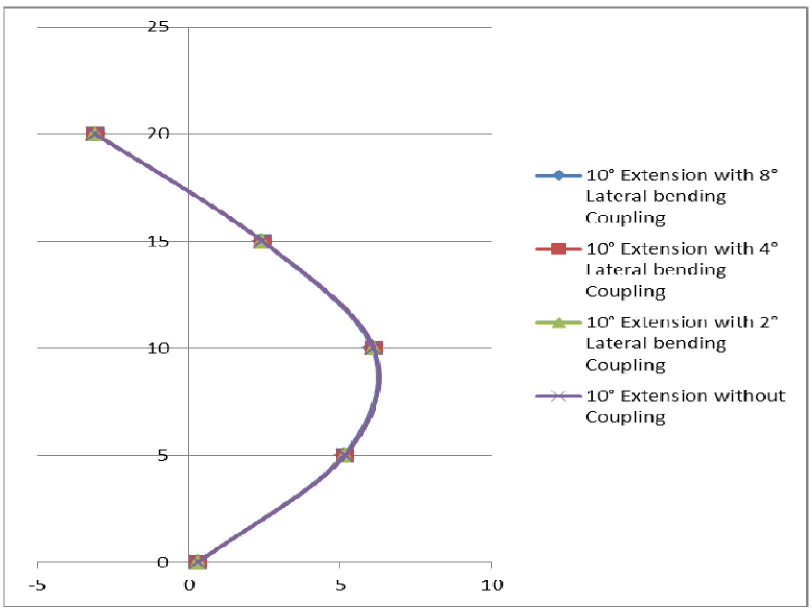

Figure 4C: *Comparison of the plots of* 10°*of extension without coupling and* 10°*of extension with lateral bendingcoupling of*2° , 4°*and*8°*.*

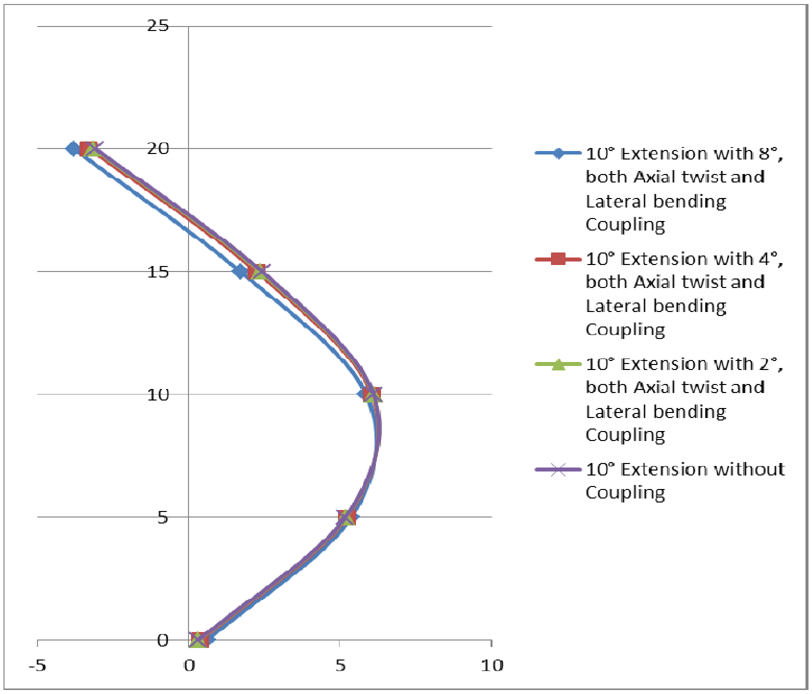

Figure 4D: *Comparison of the plots of* 10°*of extension without coupling and* 10° *of extension with both axial twist and lateral bendingcoupling of*2° , 4°*and*8°

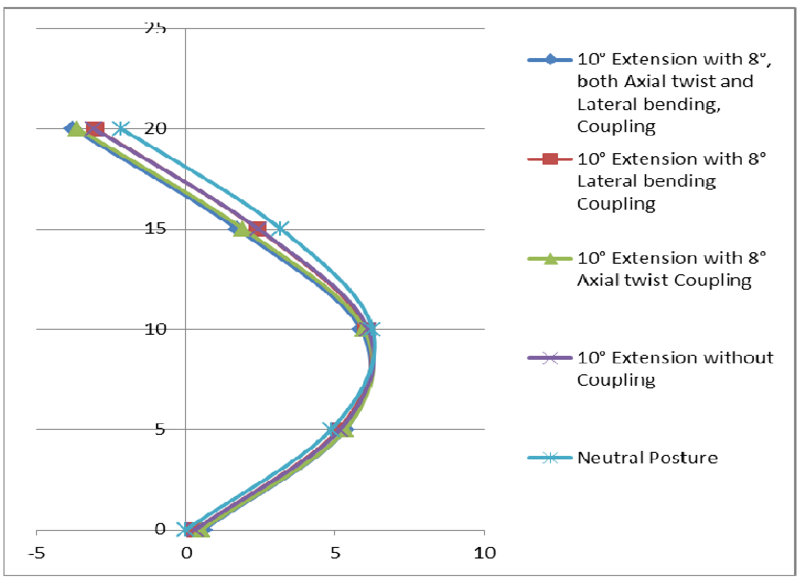

Figure 4E: *Comparison of the plots of Neutral posture,* 10° *of extension without coupling and* 10°*of extension with axial twist, lateral bending and axial twist and lateral bending coupling of*8°

The equation of the lumbar spine in six degrees-of-freedom (Equation 20)contains the three translational coordinates $x, y and z$ and the three rotational coordinatesγ,θandΨ. With the addition of equation (12) to (19), vertebral displacement can be determined.
The comparison of the graph of the lumbar spine at neutral posture to the graph of the lumbar spine at 10^o extension (Figure 4A) shows that there is asymmetric displacement of points on the lumbar spine from their neutral position. This asymmetric displacement is more pronounced with 8^o axial twist coupling during the10°extension (Figure 4B) than 8^o lateral bending coupling during the 10^o extension (Figure 4C).The combined effects of the coupling of both axial twist and lateral bending during 10^o extension is not significantly different from the effects of the axial twist alone (Figure 4D and E)suggesting that

the changes are largely the contribution of axial twist. The effects of coupling at lower angles of 2^o and 4^o for both axial twist and lateral bending during a 10^o-extension do not show significant differences from 10^o extension without coupling (Figure 4B and C).

5.0 Discussion

Accounting for subject variability is one of the liabilities of optimization approach but an asset of the biological approach [30]. The beauty of the analytic theory is that it can account for subject variability as well as other biological intrinsic properties such as angular coupling that other approaches could not account for. Equation (20) contains such variables as the length$l$ of the lumbar spine and μ (Mafuyai ratio), which is defined as the ratio of length of the lumbar spine to the chord formed by it. Additionally, for the same task, the variablesx, y, z,γ,θ and Ψ in equation (20) can differ between individuals due to physiological differences, anatomical differences and differences in the style of performing a task. For instance, the task of bending and picking up a pen from the floor by a tall and short person will require variations in their angular parameters. This can definitely lead to differences in loading of their spinal segments and account for the variability in the risk of injury by different individuals for a given task. Estimation of this variability experimentally, is a difficult task. Equation (20) promises to be a useful tool for this estimation, since the kinematics of each of the segments of the lumbar spine with respect to the six coordinates can be derived and consequently, the loading information realized. Furthermore, the analytic theory can be a more convenient means to study the role played by the lumbar spine posture in the developmental processes of low back pain [31]. For instance, changing the angular variables γ,θ and Ψ in equation (20) will lead to different posture of the lumbar spine and the factors that affect the capacity of the erector spanae, for example, to resist moments and exert forces[32,33] could be inferred.

Considering the origin of the coordinate system (Figure 1A), and with respect to Figure 4A, the vertebrae at the upper end (L_1, L_2 ,etc.) of the lumbar spine are displaced more from their original position than the vertebrae at the lower end (L_5 and L_4). This can be so in real lumbar spine since the range of motion of the lumbar vertebrae increases from L_1 to L_5[34,35]. Applied torque can easily result in translational motion as well when the range of motion is exceeded. This situation could lead to transfer of torque to the lower part of the lumbar spine since this is where there is more rotational "freedom". This transfer of torque explains why this part of the lumbar spine is more susceptible to injury. This finding corroborated the findings of Joanna et al., [36]which shows that stress distribution in the lumbar spine increases downward from L_1 to L_5.This concept of torque transfer further explains why low magnitude external load could still result in back injury[37].The 8^o degrees axial twist coupling further increases the chances of injury from both translational displacements at the upper part of the lumbar spine, once the range of motion is exceeded, and compressional and disc creeping at the lower part of the lumbar spine as a result of the increasing torque at that point. The translational displacement that may result from axial twist coupling at the end range of motion will result in the increase of neutral zone which implies segmental instability [24].

The unequal distribution of torque and forces resulting from "unpreserved" shape of the lumbar spine when undertaking a task (extension) implies the instability of the lumbar spine during the task according to our hypothesis.The idea of taking the advantage of coupled motion in manual therapy (rehabilitation) should be given a second though if axial twist at large angle is involved. Because this can aggravate situation once the vertebrae have reached the neutral zone due rotation at the primary axis.

6.0 Conclusion

This work proposes a new theory for lumbar spine analysis, and the results show that with simply measurable data such as angular displacement, other parameters of the lumbar spine can be analysed. The work shows that at high angles, axial twist results in instability of the lumbar spine when considering coupling as a perturbation and increases the risk of injury. We conclude that coupling from axial twist can easily deform the lumbar spine, and this may be the reason why the minor act of bending to pick up a pen from the floor can result in low back injuries[37].

Further Research

Using this technique and results, further work can be done to study the effect of the variability of movements of the lumbar spine within and between subjects[8] and its link to low back pain. This may explain why some vertebrae and subjects are more prone to injuries under the same task than others[37]. Additionally, the unresolved questions of the instantaneous axial center of rotation[38] and center of mass of the lumbar spine can be looked into analytically using the equation of the lumbar spine.

7.0 References

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