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On the Dynamics of the Human Spine: Towards Mechanical Characterizations of Back Pain and its Treatments

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Abstract: In this paper, recent research efforts by the authors and their research groups to develop and analyze a range of models for the human spine are discussed. These models range from rod-based models, to multibody and OpenSim-based models, and are motivated by a desire to improve our understanding of lower back pain and its treatments. These models are complimented by a new spine testing facility which enables validation of several aspects of the models.

1. Introduction:

The human spine is a complex system consisting of vertebrae, intervertebral discs, ligaments and actuating muscles, each element contributing in a unique manner to the kinematics and dynamics of the ensuing motion. Of particular interest is the influence of the passive and active stiffness components to the ensuing stability of the spine. This is motivated by the hypothesis that lower back pain is correlated with instability of the lumbar spine. Identifying the contribution of each element of the lumbar spine to the overall stability of the spine would permit the development of more effective treatment plans.

Efforts to quantify changes in the passive stiffness elements - consisting of the intervertebral disc, facets, and surrounding ligaments – in healthy and degenerate lumbar spines have involved various metrics. These include looking at changes in the position and orientation of the instantaneous axis of rotation [1,2] the migration of the helical axis of motion [3], and identifying differences in the stiffness matrices associated with the intervertebral joint [4,5,6]. However, we recently determined that the parameters associated with the instantaneous axis of rotation, as well as the helical axis of motion, are highly prone to error [7] thus bringing into question its utility in determining the efficacy of treatment options. The large errors associated with the instantaneous axis of rotation method has led us to concentrate on quantifying the dynamics of the intervertebral joint using various representations of a stiffness matrix [5,8,9]. Additionally, the potential energy used to derive the stiffness matrix can also be used to determine – via a work argument – the conservative forces and moments acting on the intervertebral joint (see Figure 1).

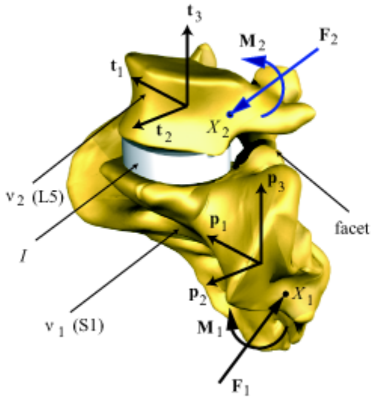

Figure 1: *Schematic of a vertebral motion segment, showing the body-fixed bases vectors* $\{\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3\}$ *and* $\{\mathbf{t}_1,\mathbf{t}_2,\mathbf{t}_3\}$ *attached to the sacrum (S1) and the fifth lumbar vertebra (L5) respectively, as well as the resultant forces and moments acting on the vertebral discs.*

Our work on the stiffness matrices of vertebral motion segments is also advantageous as it permits a simple yet relatively accurate representation of the intervertebral joint for the purpose of musculoskeletal modeling of the lumbar spine, as opposed to the more common constraint functions utilized in existing models.

In line with a comprehensive understanding of spinal kinematics, we have also conducted a significant amount of work with regards to identifying the contribution of the lumbar muscles (i.e., the active components) to spinal stability and motion. These include a musculoskeletal model of the lumbar spine built using OpenSim, an open-source musculoskeletal software program, a simpler rod-based model for the purposes of analyzing the general stability and behavior of the spine under various types of loading, and a physical spine testing machine that is able to apply physiologic boundary loading conditions. The results from our physical testing will be used to cross-validate our analytical models in the hopes of improving our current understanding of spinal kinematics and dynamics. The varying levels of complexity featured in these different models have led to valuable insights with regards to the contribution of the different muscle groups to lumbar spine motion.

2. The Stiffness Matrix of the Intervertebral Joint:

The intervertebral joint is unique compared to other joints in the human body due to its ability to control motion in all six degrees-of-freedom, and its viscoelastic properties which are load, time, and orientation dependent.

In 1976, Panjabi et al. [6] introduced the idea of quantifying the kinematics of this joint using a stiffness matrix. This was later followed by a number of related works [4,10,11,12]. Motivated by these studies, we investigated the effect of varying the placement of a total disc replacement device on the stiffness matrix of the lumbar spine [5]. We found that the stiffness matrix obtained is asymmetric. This can be attributed to both the non-conservative muscle forces, contact forces, and ligaments as well as the change in the basis vectors used to parameterize the motion.

Additional aspects of the asymmetry present in the stiffness matrix are illuminated by the analysis presented in [9]. There, we describe how to derive the Cartesian stiffness matrix for a single rigid body using the Euler angle parameterization of rotation commonly employed in the biomechanics community. In addition, we also show how the conservative forces and moments acting on the rigid body are related, via a work-energy argument, to the potential energy function. These concepts are then extrapolated to the case of multibody systems in [8] with an emphasis on the Cartesian stiffness matrix of the lumbar spinal column. In both of these studies, we elaborate upon the asymmetry behind the stiffness matrix, and show how it can be related to the conservative forces and moments acting on the joint.

2. Multibody Models of the Spine:

Several models of the human lumbar spine have been presented in the literature [13-19]. Chronologically, these models typically show increased complexity and realism.

In [20,21], we develop a musculoskeletal model of the lumbar spine using the OpenSim open-source musculoskeletal software platform [22] (see Figure 2).

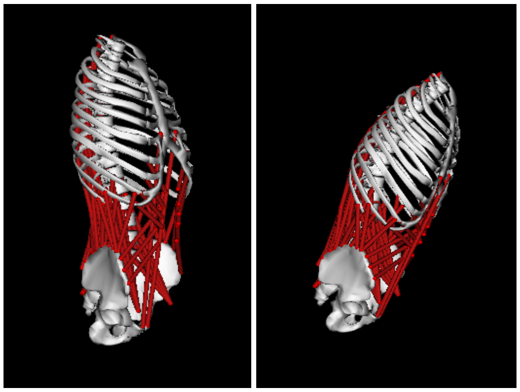

Figure 2: *The musculoskeletal model of the lumbar spine, featuring the 210 muscle fascicles of the 7 main muscle groups of the lumbar spine, the pelvis, sacrum, 5 individual lumbar vertebrae, and the torso. The spine is shown here in the neutral posture and a flexed (by 30˚) posture.*

Our model extends the bodies of work previously cited in two manners. First, detailed lumbar musculature featuring the 210 muscle fascicles of the lumbar spine is combined with the musculotendon parameters (defined by [23]) to produce more physiologically accurate muscle actuation. Second, as the model is based on the open-source platform, OpenSim, it can be incorporated into existing musculoskeletal models for the human that have been developed using this platform. These models include representations of the cervical spine [24] and the lower limb [25]. In addition to this, we are in the process of integrating the Cartesian stiffness matrix described in [5,8] and [9] into the model. This will permit a more realistic representation of intervertebral motion.

3. Rod-Based Models for the Spine:

A separate rod-based model of the spine that models the spine as a single continuous elastic rod has been constructed. This rod-based model captures the overall behavior of the spine, and serves to complement the more kinematical and anatomically detailed musculoskeletal model described previously. In contrast to most spine models in the literature, our model focuses on movements in the sagittal plane.

Buckling of this model – defined as the existence of two or more distinct configurations for a given set of applied forces – was analyzed, and the stability of these different configurations studied using a method we developed. This method is based on Legendre's treatment of the second variation of the energy function. This treatment is not typically used in rod-based models and has several advantages compared to the traditional Jacobi treatment where the existence of conjugate points leads to the conclusion of instability.

If θ is the angle that the tangent vector to the rod's centerline makes with the vertical, and β is the dimensionless terminal load parameter, then for Legendre's treatment we show that if the solution of the Riccati differential equation,

$$w' = w^2 + \beta \cos(\theta),$$

is bounded, then the rod configuration is stable (see Figure 3); if a bounded solution to the Riccati equation cannot be obtained, it strongly suggests that the rod configuration is unstable.

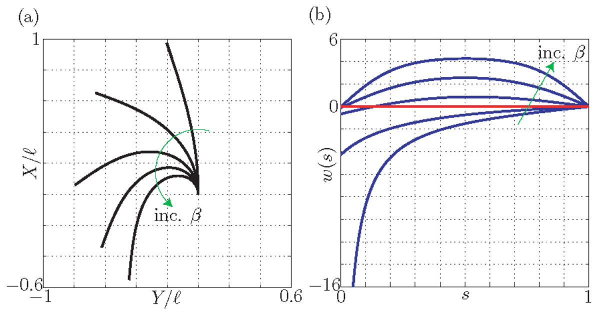

Figure 3: *(a) Stable rod configurations and (b) bounded Riccati solutions for a range of applied loads (β). The rod here is initially straight and has a clamped boundary condition at the bottom and a free condition at the tip [26].*

4. The Spine Testing Facility:

In addition to the musculoskeletal and analytical models mentioned in Sections 2 and 3, we developed a spine testing facility to quantify the effects of imposing physiological boundary conditions on in-vitro lumbar columns. The results of our studies would be used to determine which core muscles are essential to routine activities. For starters, we have focused on the erector spinae, rectus abdominis and deep multifidus muscle groups. The erector spinae and rectus abdominis were selected as they comprise the two main muscle groups of the lumbar spine while motivation for incorporating the deep multifidus stem from studies linking atrophy of this muscle group to chronic lower back pain [27]. Additionally, the activation of the deep multifidus could be specified without requiring the simultaneous activation of the other core muscles.

The three muscle groups previously mentioned were used to load a cadaveric spine under the following four loading conditions: (a) unloaded spine; (b) unloaded with only the deep multifidus activated; (c) torso weight (245N) with the deep multifidus, erector spinae and rectus abdominis fully activated; and (d) torso weight, erector spinae and rectus abdominis fully activated with a 75% reduction in the deep multifidus activation. The experimental set-up is shown in Figure 4. Our results showed that a 100% reduction in the multifidus activation (a) produced a 1.08° (L3/L4) and 1.53° (L4/L5) lordosis change for the unloaded cases while a 75% reduction in the deep multifidus activity (d) resulted in a 2.12° (L3/L4) and 1.49° (L4/L5) change for the loaded cases. We also found that, there was a 28% increase in the spine compression forces when the spine was loaded (c) and (d). This increase was necessary to maintain the neutral posture of the lumbar column tested and is consistent with other studies found in literature [28]. Our findings substantiate the important role the multifidus plays in maintaining lumbar lordosis. Future experiments will involve analysis of axial rotation and lateral bending, as well as the incorporation of the transverse abdominals, psoas, and internal and external oblique muscle groups for the purpose of further understanding lumbar spine kinematics.

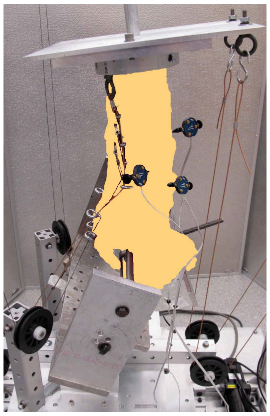

Figure 4: *Spine Testing Facility showing the spine in a neutral position together with the pelvic attachment frame, muscle cables and torque motors.*

5. Closing Remarks:

A summary of the research to date by the PIs has been presented. For the remainder of the grant, the research will focus on the continued development of the musculoskeletal model and the incorporation of the appropriate stiffness matrix for the vertebral joint. In this manner, we hope to be able to quantify the response of the lower back to physiological loadings and how back pain treatments effect its response. We also plan to continue the development of the rod-based models and complete the stability analysis of these models.

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