Development of a Musculoskeletal Model of Lumbar Spine with 6-DOF Intervertebral Stiffness and Its Validation in Vivo

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Summary

This study developed a musculoskeletal model of the lumbar spine and validated it using surface electromyography (sEMG) of spinal and abdominal muscles. The model includes a rigid pelvis and sacrum, five discrete lumbar vertebrae, and a torso. The muscle groups around the lumbar spine were included and modeled based on Hill-type models. Six degree-of-freedom (DOF) bushing elements were applied to lumbar joints to model intervertebral stiffness. Static optimization was then used to estimate muscle activation of rectus abdominis, external obliques, internal obliques, and erector spinae. As a validation, the kinematic and sEMG data were simultaneously collected from three healthy participants during three-dimensional spinal motions. The simulated muscle activations showed a strong correlation with normalized sEMG data (R^2 = 0.81), and the predictions of vertebral compressive loading were consistent with *in vivo* measures of intradiscal pressure (R^2 = 0.83), thus confirming the model's validity.

Introduction

Musculoskeletal models of the lumbar spine are crucial for understanding the biomechanical mechanisms behind weightlifting performance, injury prevention from heavy lifting, and enhancing scoliosis rehabilitation [1]. However, its predicted load-bearing mechanism during three-dimensional motions requires quantitative *in vivo* validation.

Methods

Three healthy individuals (age: 28 ± 5 years, height: 1.7 ± 0.06 m, weight: 59 ± 8 kg) participated in the study. They were instructed to perform three-dimensional spinal motions, including full-range flexion/extension (F/E), lateral bending (LB), and axial rotation (AR) of the spine. The full-body kinematics of each participant were collected using inertial motion tracking with 17 IMUs. The sEMG signals from the rectus abdominis, external obliques, internal obliques, and erector spinae at L3 and T11 levels were simultaneously acquired bilaterally (Figure 1b).

The model (Figure 1a) was developed based on Christophy's lumbar spine model [2], which consists of a rigid pelvis and sacrum, five lumbar vertebrae, and a torso. The 6-DOF relative motions of the intervertebral disc (IVD) were taken into account. A bushing element was introduced to represent the passive forces at each joint. The stiffness parameters for each intervertebral level were derived from cadaver studies reported by previous studies [3].

Inverse dynamics simulation took the IMU-measured joint angles as the kinematics input. Lumbopelvic law [2] was applied to resolve the redundancy of lumbar kinematics. Static optimization was then used to estimate muscle activations. Given that the relative motion of each IVD is constrained by the lumbopelvic ratio, the 15 moment equilibrium equations are not independent. To ensure equation independence and maintain equilibrium at all lumbar joints, these 15 equations were combined into 3 by summing the 5 equilibrium equations corresponding to the F/E, LB, and AR DOFs, respectively.

Results and Discussion

As shown in Figure 1c, the simulated intradiscal pressure (IDP) at the L4/L5 disc showed a strong correlation with the literature reported values for various activities, including standing, F/E at different angles, LB, and AR, with a correlation coefficient of 0.83. A comparison of the estimated muscle activations and measured sEMG data for a typical participant is shown in Figure 1d. Generally, the estimated activation patterns exhibit good agreement with the normalized sEMG in both amplitude and phase, with an average correlation coefficient of 0.81 for the dominant muscles across all participants and movements.

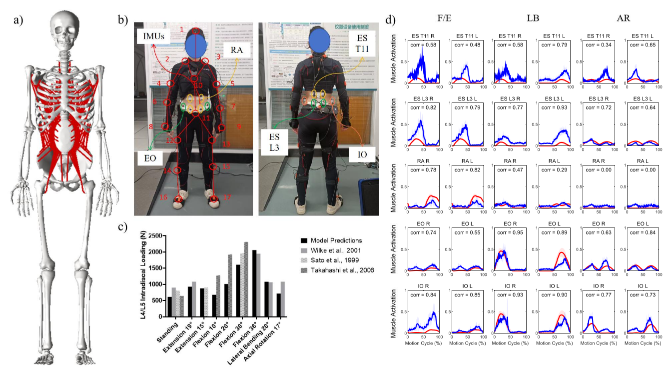

Figure 1: a) The established musculoskeletal lumbar spine model; b) Experimental setup; c) Intradiscal loading at the L4/L5 disc; d) Muscle activations during F/E, LB, and AR. Estimated muscle activations and normalized sEMG data are represented by the red and blue lines, respectively.

Conclusions

This musculoskeletal model of the lumbar spine has been validated based on measured sEMG patterns, highlighting its potential as a valuable platform for future research on human locomotion, pathological conditions, and the effects of surgical or rehabilitative interventions.

References

[1] Guo. et al. (2022). *Adv. Mech.*, **52(2)**: 253-310.
[2] Christophy. et al. (2012). *Biomech Model Mechanobiol*, **11**: 19-34.
[3] Meng. et al. (2015). *J Biomech Eng*, **137**: 101008.