3D Biomechanical Simulation of Human Walking: Empirical Data and Inverse Dynamics Integration

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Abstract

In the rapidly evolving field of biomechanics, 3D human modeling and gait analysis have emerged as pivotal tools for understanding complex locomotor dynamics. This study leverages multibody dynamics techniques to intricately model the human musculoskeletal system, aiming to provide a more comprehensive and accurate analysis of human gait patterns. By integrating computational methods with detailed biomechanical models, this research endeavors to overcome the limitations of traditional gait analysis, offering insights into the intricate mechanisms that govern human locomotion. This approach not only enhances the fidelity of human movement simulation but also holds significant potential for clinical applications in diagnosing and treating gait-related disorders.

In this study, a three-dimensional multibody model of a representative adult 50th percentile human was first constructed by segmenting the human body into 13 distinct rigid bodies, each representing a critical component of the human musculoskeletal structure. These components include two feet, two legs, two thighs, a pelvis, a torso, two upper arms, two lower arms, and a combined segment for the head and neck (which can be expanded to include detailed head and neck complex for application other than gait analysis). This segmentation was meticulously designed to reflect the biomechanical composition of the human body, ensuring a realistic representation of human anatomy in the model.

To simulate the complex motions of the human body, 12 spherical joints were strategically implemented between each of these rigid bodies. This was accomplished by modeling three orthogonal revolute joints at each connection point, corresponding to the local *x'*, *y'*, and *z'* axes, thereby replicating the multidirectional movement capabilities of a spherical joint. This approach allowed for a high degree of movement fidelity within the model. Another pivotal aspect of the research involved the meticulous simulation of the contact dynamics between the foot and the ground, a critical component in the study of gait biomechanics. Accurate modeling of this interaction is essential, as it is at this juncture where the ground exerts reactionary forces on the body, significantly influencing gait mechanics and the overall stability of human motion. A 3D rigid-to-rigid surface contact model was employed, utilizing a Hertzian-based normal contact force model with dissipated damping as well as a modified Coulomb-based friction model [1]. To achieve enhanced accuracy, the foot in our skeletal model was substituted with a CT scan of a complete foot. The entire developed musculoskeletal multibody model, as well as the foot contact modification, are depicted in Figure 1, which also illustrates the 3 orthogonal revolute joints representation of a spherical joint.

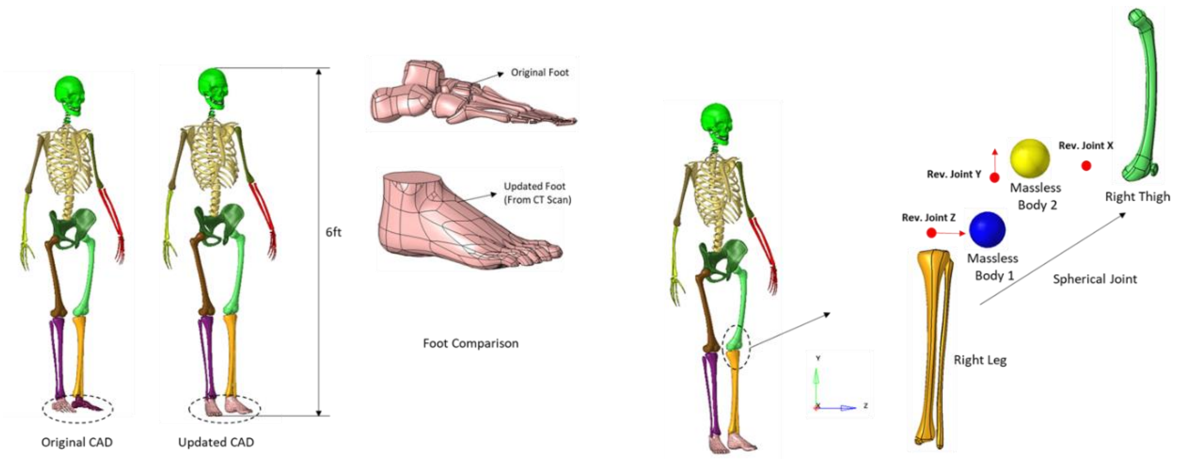

Figure 1: Human Musculoskeletal Multibody Model with Enhanced Foot-Ground Contact Modeling and Illustration of Spherical Joint Modeling Technique

To infuse the model with lifelike motion, joint angles obtained from empirical gait analysis experiments were utilized [2]. The geometric sizes and inertial properties of the model as well as angles were adjusted to compensate for differences between the skeleton model and the physical characteristics of the experimental specific subject. These measurements were key in accurately articulating each revolute joint, enabling a dynamic and authentic simulation of human gait. This approach not only amplifies the model's realism but also anchors the simulations in true-to-life human movement patterns, as typically observed in everyday scenarios. The kinematic framework demonstrating a human walking pattern is shown in Figure 2.

Figure 2: Kinematic Frames of Human Walking Mechanism

This study focuses on human gait simulation through the application of inverse dynamics [3], providing a comprehensive biomechanical analysis of human motion. By employing measured joint angles, this approach not only achieves precise replication of kinematic movements but also enables the calculation of forces and torques on each body segment. This is crucial for understanding musculoskeletal loading conditions and the mechanical stresses in various gait patterns, offering valuable insights for applications ranging from athletic training to orthopedic care. More than just replicating motion, the model's detailed analysis of force and stress distribution across joints and limbs is instrumental in identifying abnormal gait mechanics, crucial in clinical diagnostics and treatment of musculoskeletal disorders. Additionally, the model's capacity to simulate various motion scenarios of diverse population allows for safe and effective testing of medical hypotheses and treatment plans in a virtual setting, contributing to personalized care and heralding new possibilities in biomechanical research and healthcare innovation.

References

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