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.

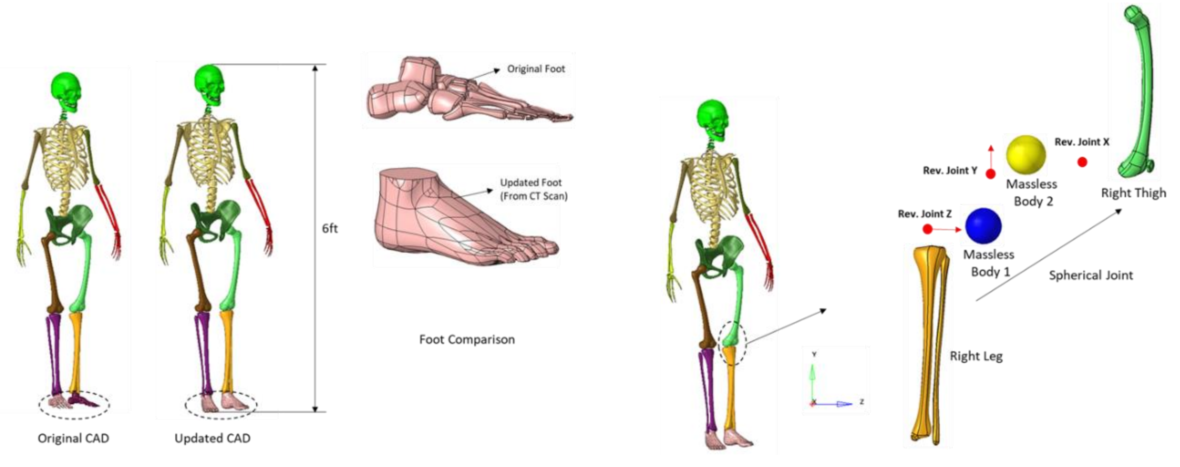

Figure 1: Human Musculoskeletal Multibody Model with Enhanced Foot-Ground Contact Modeling and Illustration of Spherical Joint Modeling Technique

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.

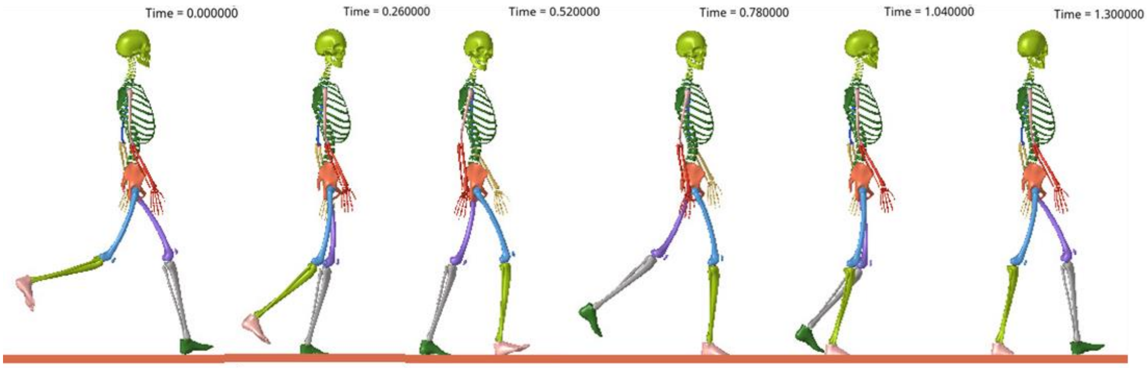

Figure 2: Kinematic Frames of Human Walking Mechanism

In this section, the interaction forces between the foot and the ground during the gait cycle of this model are examined. Understanding these forces is essential for biomechanical analysis and for developing accurate simulations of human movement. Foot-ground interaction forces were calculated for both the left and right feet. The resultant forces were recorded and processed using the SAE J211/1 filter to remove noise and provide a clearer view of the force interactions. The contact forces are shown in Figure 3.

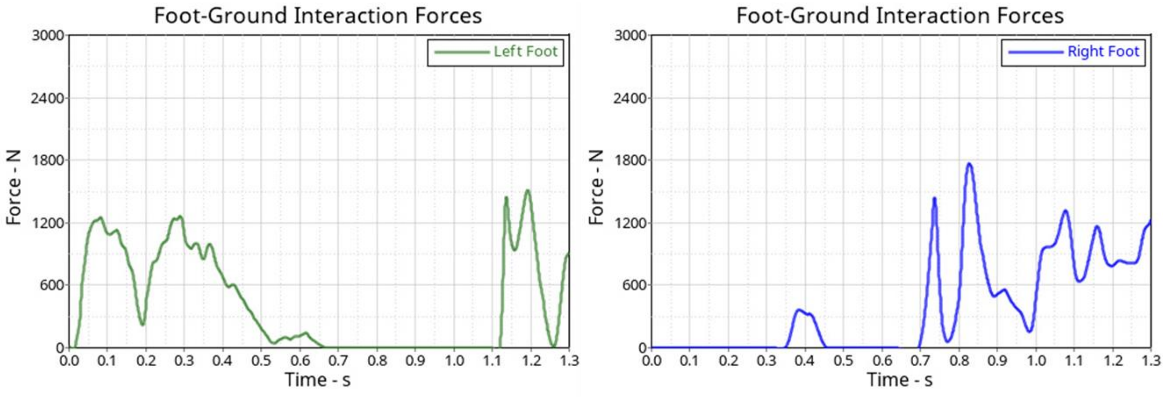

Figure 3: Foot-Ground Interaction Forces

The analysis of the foot-ground interaction forces revealed that the contact forces for both the left and right feet reached significant peaks ranging between 1500 and 1800 N. The left foot showed substantial variations in force during the stance phase of the gait cycle, with a prominent peak occurring early in the cycle. This peak force gradually decreased before increasing again towards the end of the stance phase. Similarly, the right foot exhibited noticeable fluctuations in force, corresponding to different phases of the gait. These force patterns illustrate the dynamic nature of foot-ground interactions, with distinct peaks and troughs associated with heel strike, mid-stance, and toe-off phases.

The analysis of net forces acting on the knee, as depicted in Figure 4, demonstrates the dynamic load experienced by one of the key joints in the lower extremity. This data is crucial for identifying the biomechanical demands on the knee joint and underscores the potential need for adjustments in gait patterns to alleviate excessive stress. By understanding these force patterns, targeted interventions can be developed to correct abnormal gait, reduce the risk of injury, and optimize the mechanical efficiency of the joint. Furthermore, forces at various other joints can be similarly extracted as required, providing comprehensive insights into the mechanical demands across the entire lower and upper extremities.

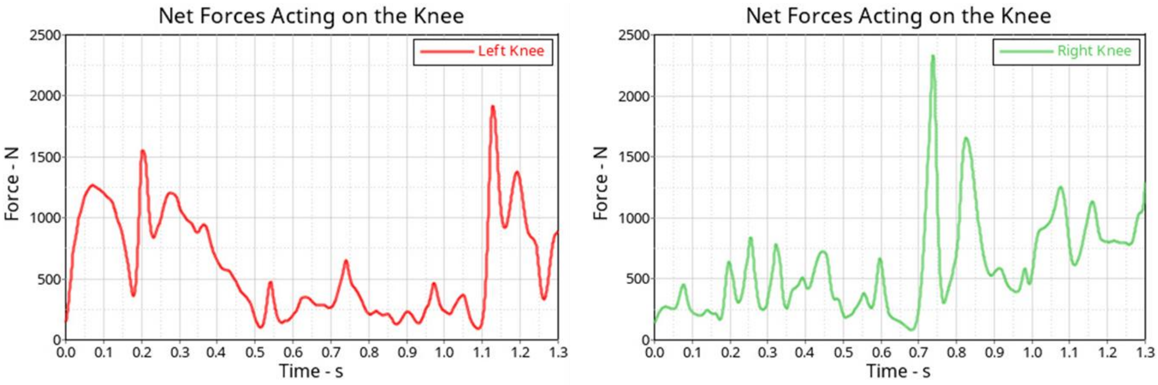

Figure 4: Net Forces Acting on the Knee

To check the model's stability and test its suitability for personalized walking patterns, the new model was tested for faster walking. To implement this change, the input joint angle vs. time duration was halved, resulting in a total duration of 0.65 seconds instead of 1.3 seconds. While the angles themselves remain unchanged, the duration has been significantly reduced. This adjustment aimed to investigate the biomechanical implications of a higher walking speed and to assess the model's robustness under these conditions.

The simulations for the faster gait were conducted using the same Motion Solve tool from Altair products. The results indicated that the model remained stable during the faster walking simulation. The kinematic frames of the faster gait cycle are shown in Figure 5, illustrating the model's performance and the joint movements throughout the cycle. This confirms that the model can be effectively used to simulate personalized walking patterns, providing valuable insights into the biomechanical effects of varying walking speeds.

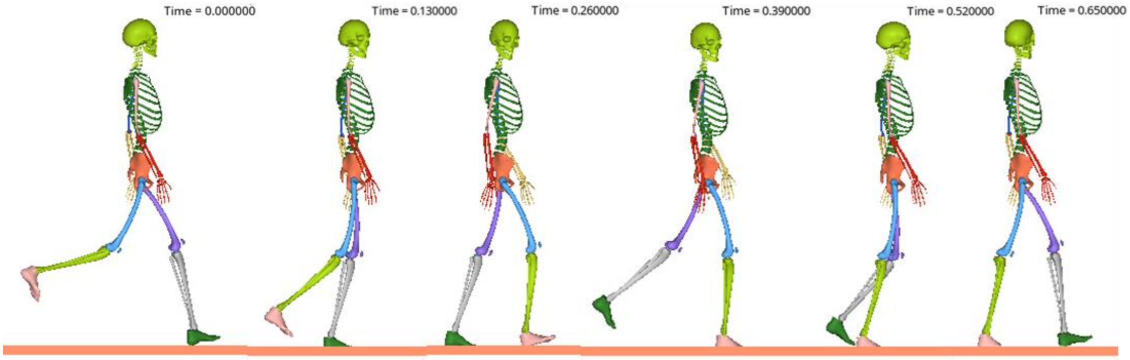

Figure 5: Kinematic Frames of Human Walking Mechanism – Faster Gait

The interaction forces between the foot and the ground during the faster gait cycle were also analyzed to assess the biomechanical effects of increased walking speed. The resultant forces for both the left and right feet were calculated and processed using the SAE J211/1 filter to ensure clear and accurate representation as shown in Figure 6, the contact forces for the left and right feet peaked at significantly higher values within the shortened cycle duration, exhibiting rapid fluctuations indicative of a more dynamic interaction. In the new model, the right and left feet reached peak forces between 1850 N and 2250 N, illustrating the increased mechanical demands and dynamic nature of the faster gait. These results confirm the model's capability to handle these heightened mechanical demands. The rapid changes in contact forces reflect the increased biomechanical challenges posed by faster gait, underscoring the importance of robust model stability for accurate simulation of various walking speeds.

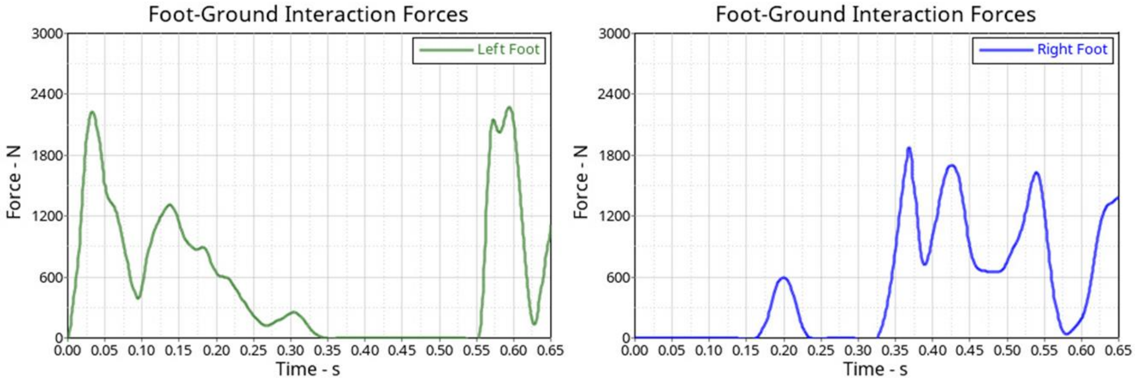

Figure 6: Foot-Ground Interaction Forces (Faster Gait)

The comparison of foot-ground interaction forces between slower and faster gaits reveals significant differences in both magnitude and timing. The faster gait cycle, completed in 0.65 seconds, exhibits more rapid and frequent force fluctuations, indicating a more dynamic and impactful interaction with the ground, as shown in Figure 7. In contrast, the slower gait, extending over 1.3 seconds, displays smoother and less intense force variations, reflecting a more gradual loading and unloading process.

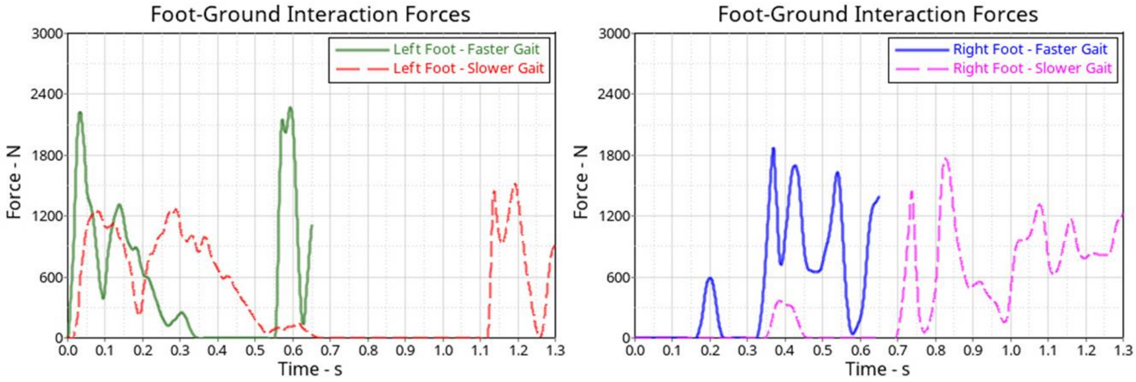

Figure 7: Foot-Ground Interaction Forces – Comparison

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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