Chapter 17
Efficient Simulation of Soft Tissue for Human, Robotics, and Exoskeleton Applications

Stefan Holzinger, Andreas Zwölfer, and Daniel Rixen

Abstract This paper explores the simulation of human lower limb dynamics using the floating frame of reference formulation to model bones and soft tissues as flexible bodies discretized with 3D volume finite elements. The study compares joint forces during landing on one leg using different modeling approaches: a purely rigid body model, a rigid body model with lumped rigid wobbling masses, and the aforementioned floating frame of reference formulation-based model. Results demonstrate that wobbling masses reduce joint forces compared to purely rigid body models. Although more computationally demanding than the rigid body models, the floating frame of reference formulation approach offers insight into soft tissue behavior, making it a promising tool for human body dynamics and related applications.

Keywords Multibody · FEM · Human · Robotics · Exoskeletons

Introduction

Human pain and injuries are often caused by loads imposed during movements of the human body especially when high accelerations are present [1]. Loads within the human body are difficult to measure directly, but can be calculated using multibody and finite element simulations [2]. Multibody dynamics refers to the computational methods employed for the dynamic analysis of systems that consist of interconnected rigid and deformable components. Multibody human models conventionally represent human segments as rigid bodies actuated by lumped muscle (e.g. Hill type) force elements [3]. However, bones are covered with muscles and other soft tissues. This so-called wobbling mass represents more than 80% of the total mass of a segment [4], and it has been shown that it cannot be neglected due to its essential contribution to human body dynamics [4]. Modellers interested in the behaviour of wobbling mass often employ the aforementioned rigid/lumped musculoskeletal multibody models to calculate skeletal motion and muscle activation, in order to use this information as an input for computationally expensive non-linear finite element analyses, see e.g., [5]. This one-way coupled simulation approach is tedious from a modelling perspective, computationally intricate, and physically inaccurate when the effects of wobbling masses (inertia and damping) has a significant impact on the overall human motion. The floating frame of reference formulation is a standard method in multibody dynamics and used to model bodies with complex shapes that can undergo large rigid body motions but exhibit only small deformations [6]. An advantage of the floating frame of reference formulation is that it accounts for the nonlinear coupling of small deformations superimposed to arbitrarily large rigid body motion [7] and modal reduction techniques can be applied, reducing the system size to just the included modes [8]. A promising approach, both from the computational and the modelers perspective is the so-called nodal-based floating floating frame of reference formulation, as it eliminates inertia shape integrals entirely, simplifying both the derivation and implementation without needing lumped mass approximations [6, 8]. Although the floating frame of reference formulation is conventionally employed for small deformation problems and linear elastic materials, it still can be used to analyze the dynamics of a human lower limb. This is because bone and muscle make up about 70% of the total weight of a human lower limb [9] and it has been shown that a linear material law is often sufficient to model their mechanical behavior [10]. While the floating frame of reference formulation has already been used to model the human skeletal system [11], to the best of the authors knowledge, it has not been applied for the dynamic analysis of a human lower limb with wobbling masses. In this paper, we demonstrate

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Matthew Allen et al. (eds.), *Special Topics in Structural Dynamics & Experimental Techniques, Vol. 5*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.13052/97887-438-0150-4_17

how the floating frame of reference formulation can be used to analyze the combined dynamics of skeleton and wobbling masses during human movement, and examine how wobbling masses affect body motion and joint forces.

Simplified Model Of A Human Lower Limb

As a representative example, we investigate the loads arising in the human knee and hip joint during landing on one leg and compare the results to ones obtained from conventional modeling approaches. The drop height is 0.2 m. For simplicity, we consider in this work a simplified model of a human lower limb, which is illustrated in 1. The considered model consists of six bodies: foot, upper and lower leg bones, hip, one body replacing the entire thigh muscles and one body replacing the entire lower leg muscles. Anthropomorphic data for each body segment is taken from [12, 13]. The thigh bone connects to

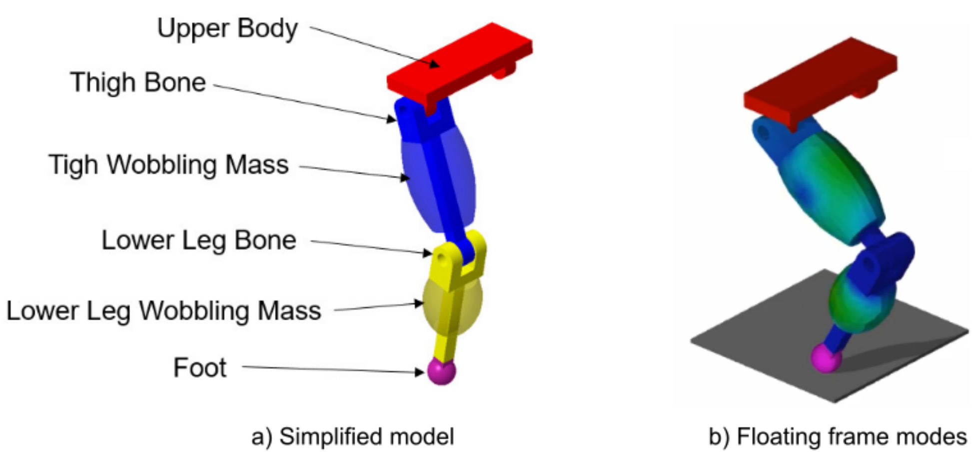

Fig. 1 Simplified model of a human lower limb

the hip and the lower leg bone at the knee, both using springs and dampers forming compliant revolute joints. A torsional spring-damper connects the lower leg and thigh representing the muscle forces acting on both body segments during landing. When using the nodal-based floating frame of reference formulation for modeling, both the lower leg and thigh bone as well as both muscle bodies are considered to be deformable. Component mode synthesis is used for modal reduction.

In the first conventional modeling approach, all system bodies are modeled as rigid bodies. The lower leg (bone and muscle) is modeled as a single rigid body, and similarly, the thigh (bone and muscle) is modeled as another rigid body. In the second conventional approach, all system bodies are considered to be rigid bodies, but in contrast to the first conventional approach, the bodies representing lower leg and thigh muscles are connected to the respective bones using three translational and three rotational springs allowing the muscle rigid bodies to move relative to the bones. All herein considered multibody simulations are performed using the open source C++-based multibody dynamics simulation software exudyn [14]. In all considered modeling approaches, the foot is modeled as a rigid body and is connected to the lower leg using a compliant joint that mimics a rigid joint. Explicit time integration is used to allow efficient contact computation in exudyn. As time integration scheme, we use the explicit Lie group Euler method, cf. [15].

Results

In 2, the joint forces in the knee and hip joint during landing are shown for all three considered modeling approaches. As can be seen in 2, the joint forces obtained from the first conventional modeling approach, denoted with RB, are approximately 28% higher than the joint forces obtained from the second conventional modeling approach (RWM) and the floating frame model (FWM).

In contrast, the peak joint forces obtained from the RWM-model are close to those of the floating frame model. As expected, it turns out that the first conventional modeling approach is computationally the most efficient one, requiring 12 seconds for computing 240000 time steps using a time step size of 1.25×10^{-6} s. The second conventional modeling approach

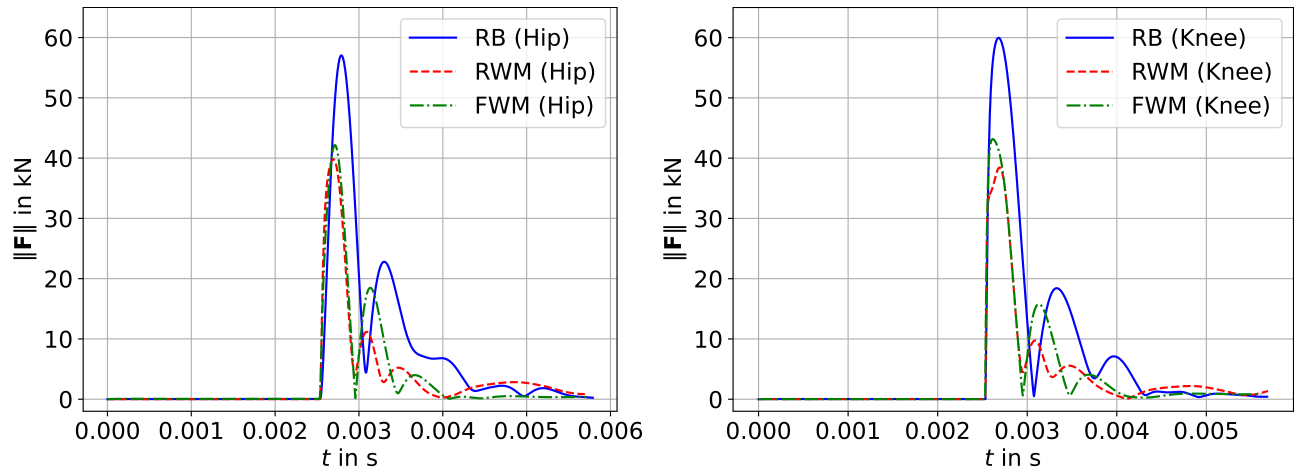

Fig. 2 Joint forces in the knee and hip joint during landing on one leg

required 14.3 seconds of CPU-time for simulation and the floating frame model with 10 modes required approximately 1307 seconds.

Conclusion

Wobbling masses significantly affect joint forces and rigid body motions, potentially reducing joint forces. While being computationally more demanding than the rigid body models, using the floating frame of reference formulation with modal reduction yields a substantial boost in computational efficiency as compared to nonlinear transient finite element simulations. For computing joint forces, a rigid wobbling mass approach may serve as an alternative to the floating frame of reference approach. However, using the floating frame of reference formulation for modeling wobbling masses in multibody dynamics offers substantial advantages, such as eliminating the need to compute inertia tensors from CAD models and enabling direct coupling with bones through finite element methods (FE) without the need for estimating spring stiffness and damping parameters for compliant joints. Additionally, the FFRF approach provides access to stresses and strains, which are not accessible in rigid body models.

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