Dynamic Analysis of Foot Models for Human Locomotion

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Abstract

Human locomotion dynamics has been a topic of interest since the past few decades. In many areas such as as humanoid robot design, gait rehabilitation, diagnosis of pathologies, prosthesis design, sport analysis, and motion cognition, the human locomotion is needed to be properly modelled. Dynamics of human locomotion, and the capability of implementing an accurate human gait simulation can be useful in all these areas. Modelling the foot is a key element in the human gait analysis. This is due to the complex structure of the foot as well as its contact with the ground during the gait.

Although the human locomotion is complicated mainly due to the complex musculoskeletal structure, it is reasonably acceptable to model this structure as a multibody system composed of a number of links and joints using either rigid or flexible body assumption. The foot is composed of 26 bones, 90 flexible ligaments, and 33 joints. Consequently, modelling of such an intricate structure is not straightforward. Three joints, namely, Tibiotalar, Talocalcaneal, and Talonavicular are responsible for the ankle rotations. These joints are mainly responsible for the plantar flexion/dorsiflexion, eversion/inversion, and adduction/abduction ankle rotations, respectively. The axes of rotation of the two last joints show considerable angle deviations during different modes of the ankle rotations. For instance, the Talonavicular joint axis might deviate up to 15 degrees for the plantar flexion in compare with the dorsiflexion movement [3].

Different foot models have been used for the dynamic analyses of the human gait. These models are mainly developed based on two assumptions of the number of segments and whether the model is two or three dimensional. Conclusions have been drawn using these models while not enough justifications on the appropriateness of the utilized models were usually provided. Sensitivity of predicted results by each foot model with respect to the modelling assumptions has not been completely understood. This understanding can be highly useful for any kind of human gait kinetics analysis and its related applications.

Although kinematics studies of the human gait with the multi-segment foot model are well matured these days, gait kinetics studies have not reached the same level of maturity. A model which can realistically predict the kinetics of the foot, and can be used for multiple gait cycle simulations or clinical studies has not been well established yet. Existing Tibia-foot models in the literature for kinetics analysis can be mainly categorized into four groups: two dimensional two-segment foot (Tibia and foot), two dimensional three-segment foot (Tibia, Hindfoot, Forefoot), three dimensional two-segment foot, three dimensional three-segment foot [1, 4]. In all of these models, lower kinematic pairs have been used.

In order to study the effect of each of these assumptions on the predicted results by these models, a human body model composed of trunk, thighs, shanks, and feet were developed in Simulink via exploiting its available SimMechanics functionalities for multibody dynamics analyses. These four types of foot models were incorporated in the created human model in order to compare the results. Investigations were performed for the inverse dynamics problem of the human gait in which motion of the system is known and body joint torques are calculated. To compare the results, three ankle joint torques, namely, Tibiotalar, Talocalcaneal, and Talonavicular joint torques have been picked as the comparing indicators. The aim of the study is to perform an inverse dynamics simulation of the human gait via incorporating different foot models and compare calculated ankle joint torques with each other. This can demonstrate the sensitivity of the results of the human gait simulation to the foot modelling. To know the required motion of the system for the inverse dynamics analysis, human gait have been captured via motion capture system in Universitat Politècnica de Catalunya. Markers were attached to the human body with accordance to our defined model segments and existing standard protocols. The motion was recorded by means of 12 OptiTrack FLEX:V100R2 cameras sampling at 100Hz. Two force plates AMTI AccuGait located on a walkway were used to measure the ground reaction forces. Markers trajectories on the

subject were stored and filtered for a complete gait cycle. The force plate data were synchronized with the stored trajectories. The resultant data were post-processed in order to calculate angles, angular velocities and angular accelerations of the body segments.
Three main cases are investigated. First, the effect of the foot segmentation is studied. Two-segment and three-segment foot models are incorporated in the developed human model. Ankle joint torques for each case are obtained. Second, the same process was done for the two dimensional and three dimensional foot models. Third, effects of deviation of Talocalcaneal and Talonavicular joint axes on their associated motor torques were investigated. All the geometrical and inertial properties of the human model were selected based on the anthropometric data available in [2].
In order to avoid the ambiguity of the ground reaction force distribution for the case that more than one segment is considered for the foot part, a single foot contact point with the ground has been assumed in our analyses. The analyses were performed only for two instants of gait, namely, heel contact and toe-off. In these two instants, the foot has a single point contact with the ground and the single contact point assumption is realistic. Some part of the results are summarized in Table 1.

Table 1: Ankle joints torques of the simulated human gait for the heel contact instant

Model	Tibiotalar torque [N.m]	Talocalcaneal torque [N.m]	Talonavicular torque [N.m]
2D Two-segment foot	-4.5	-	-
2D Three-segment foot	-1.7	-	-
3D Two-segment foot	-4.5	-2.4	-2.54
3D Three-segment foot	-1.7	-0.89	-1.35

Based on the results, predicted Tibiotalar joint torques for two-segment and three-segment foot models demonstrate considerable differences which can be more than 100% for the heel contact instant. Furthermore, using a two dimensional foot model does not capture the motor torques produced by the two other joints at the ankle, namely, Talocalcaneal and Talonavicular joints. Finally, when two different orientations for the axes of rotation of Talocalcaneal and Talonavicular joints are used, different torque values associated with these joints are obtained. Orientations of the axes of rotation of these joints were selected based on the reported values in the literature which are associated with neutral to plantar flexion and dorsiflexion to neutral foot movements [3]. The calculated motor torques for these two cases demonstrate up to 70% differences.
This study was performed to better understand foot modelling aspects and identify drawbacks of the existing foot models. This can be helpful for proposing a better multi-segment foot model as well as a more appropriate ankle joint model. A more realistic foot model can be further used in different open topics such as achieving multicycle gait simulation, foot-ground contact analysis, and estimation of the ankle joint torques based on the muscles electromyographic activities. Based on this study, kinetics of the foot in human gait is highly sensitive to the modelling assumptions. Using different foot models stemming from different assumptions can lead to inaccurate results and unrealistic predicted behaviour in the human gait.

References

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