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DESIGN AND EVALUATION OF AN ADAPTIVE GROUND CONTACT MODEL

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INTRODUCTION

Ground reaction forces are the driving element of human gait. They are -in the form of forceplate measures- included in virtually all inverse dynamic analyses. While it is possible to base forward dynamic analyses on such measurements, it is preferable to model the foot-floor interactions such that simulations can be performed independent of experimental data. Such a representation then facilitates the use of simulations to predict how movement would change in response to an impairment or intervention.

The interactions between the ground surface, soles of the shoes, and the foot itself are most often represented by punctiform viscoelastic units that are distributed under a one- or two-segment model of the foot [1-3]. A major problem of such an empirical formulation is the missing physical insight: How do changes in the model affect the predicted reaction forces? And, more importantly, how do subject specific properties translate into certain parameters of the model formulation? These are important questions, because the details of ground contact models are often assumed a priori or tuned on a single set of experimental data when simulating subject-specific gait dynamics. The purpose of this study was to determine whether the parameters of a published contact model [4] can be adapted to subject specifically represent measured foot-floor interactions during normal human walking. We implemented this process of parameter adaptation as an optimization problem and thereby automated it. Experimental gait data of five subjects was used to identify parameter combinations that were well suited for adaptation of the model; i.e. parameters that varied between different subjects, but remained constant for different trials of the same subject. This allowed the identification of parameters that actually reflect subject specific properties and to create a ground contact model that is capable of adapting to different subjects.

METHODS

Ground Contact Model

Our model consisted of two segments, a hindfoot and toe segment, connected by a purely passive rotational spring/damper element at the metatarsal-phalangeal joint. The toe segment was given the dynamic properties of a massless body. Hence, no knowledge of the previous state of the metatarsal-phalangeal joint was necessary when evaluating the ground contact model in dynamic simulations. The model could be described as a static function that took the current position, orientation, translational velocity and rotational velocity of the hindfoot as input and returned the corresponding external reaction forces and torques.

Eleven punctiform visco-elastic units were linearly spaced underneath the two foot segments. They were distributed roughly along the course of the center of pressure during normal gait. Additional rotational dampers along all three spatial axes ensured that the transition between contact elements was smooth and that rotations about the anterior/posterior and vertical axes were small. Arranging the elements along only one dimension and using rotational damping for the others had the advantage of reducing the number of required elements from $O(n^2)$ to $O(n)$ while the center of pressure could still move in an unrestricted and continuous manner.

Each visco-elastic unit consisted of a linear spring-damper element which created a vertical force proportional to the magnitude and speed of penetration of the unit into the ground surface. Translational dampers, perpendicular to the vertical elements created viscous friction against movements within the ground plane. A piecewise cubic function was used to scale the damping coefficients as a function of elastic deflection to ensure continuous damping forces during impact (Fig. 1).

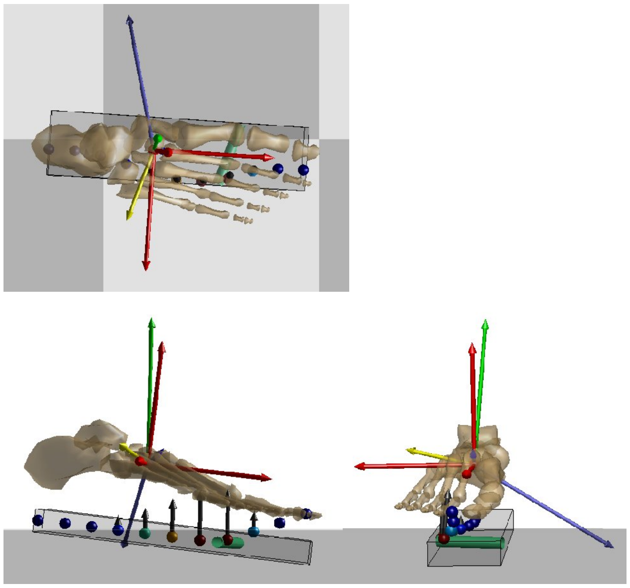

Figure 1. Top, side and front views of the ground contact model including the viscoelastic unit bounding box.

Parameter Optimization

The ground contact model was made adaptable by 16 parameters that described the overall position, orientation, and scaling of a bounding box enclosing the viscoelastic units, the stiffness and damping coefficients of the viscoelastic units, and the position, stiffness, and damping properties of the metatarsal axis. Numerical optimization was used to identify sets of parameters that minimized the difference between recorded and predicted ground reaction forces. The objective function used by the optimization routine expressed the weighted differences between the predicted and measured vertical force and center of pressure. The weights were chosen so that an error of 30 N in force corresponded to an error of 1 cm in the center of pressure position. The optimization problem was solved with a bounded sequential quadratic programming method.

Experimental Gait Data

The experimental data was obtained from a full body gait analysis of five young healthy adults wearing tennis shoes. Model-based inverse kinematics analysis was performed over a full cycle of gait and the position, orientation and velocities of the right foot segment were extracted. Ground reaction forces were recorded simultaneously. Each subject performed 5 repeated trials at 80%, 100% and 120% of his/her comfortable walking speed.

RESULTS

Of the parameters considered, the following three parameters could be reliably identified for individual subjects:

- The overall vertical position of the visco-elastic units.
- The overall anterior-posterior position of the visco-elastic units.
- The position of the metatarsal axis.

For these parameters, the standard deviations for different trials of the same subject were significantly smaller then the overall standard deviation, which suggests that the approach actually extracted subject-specific properties (Fig. 2). The numerical optimization of these three parameters reduced the error between predicted and measured ground reaction forces by ~55%. While adaptation of other parameters could further reduce errors, the estimated parameters varied substantially between repeated trials.

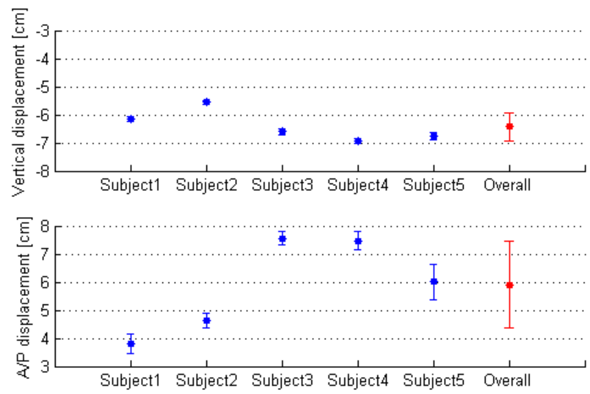

Figure 2. Optimization results for the overall vertical and anterior/posterior displacement of all units.

DISCUSSION

This study demonstrates the challenge in adapting the parameters of a simple ground contact model based on experimental measures of walking. While the global position of the spring-damper elements could be reliably identified, spring stiffnesses and damping coefficients were ill suited for optimization. This may, in part, be attributable to the high stiffness and damping of the viscoelastic units, which translates into a large sensitivity to noise in foot kinematic measures. In addition, there were problems in adapting many parameters at once due to parametric redundancies. For example, moving all units closer to the ground had a similar effect as increasing the vertical stiffness. As a result in many cases that we tried, numerical optimization of an excessive number of parameters produced results far from reasonable values. While limiting the adaptation to only three parameters restricted the potential of the model adaptation, it ensured no over fitting to noise artifacts occurred. The resulting ground contact model worked as good on unknown data as on the training set.

Our proposed adaptation method was successful in identifying subject-specific contact models that eliminated more then half of the ground force prediction errors. Further reductions in force prediction errors could be obtained by slight adaptations of measured foot kinematics. Optimized models and kinematic patterns could then conceivably be incorporated into whole body simulations of subject-specific walking dynamics, thereby obviating the need for experimental data within the simulation. Such an approach would enable perturbation-based analyses to characterize dynamic muscle function and to predict how movement would change in response to impairments and/or interventions.

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