Foot-ground contact modelling for computational prediction of human walking motion

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Prediction of human motion is a field of great interest in clinical and sport applications, such as for anticipating the result of surgery, for assisting the design of prosthetic and orthotic devices, or for understanding how an exercise can be performed in an optimal way. The validity of motion prediction results relies on a realistic biomechanical model, which includes body segments, joints, actuators (at joint or muscle level) and contact models to characterize body-ground interaction.

Regarding the modelling of foot-ground contact interaction during walking, there are mainly two options: using kinematic constraints (hard contact) or a constitutive contact model (compliant contact). The first method defines the interaction between the foot and the ground using ideal kinematic constraints, which change at each phase of the gait cycle [1]. In such case, the foot can be modelled as a single point, as a rigid body with two contact points, or as a curved plantar surface rolling over the ground without sliding. Usually it is assumed that the heel strike is fully inelastic without sliding. Conversely, the second method establishes a physical relationship between the developed contact forces (normal and tangential) and the relative foot-ground displacements and velocities. As for the normal force, different approaches have been used in the literature: series of spring-damper units [2], two or more spheres with a compliant Hunt-Crossley model [3], or a nonlinear volumetric contact model [4]. Regarding the tangential force, some authors use also spring-damper elements and others use a friction model, based on either the Coulomb friction model or the bristle model [3,4].

The most challenging issue when modelling foot-ground contact interaction is the identification of the tangential force model [3,5]. In this study, we propose a method to compute the tangential force, based on the hypothesis that during healthy walking at a self-selected speed such force can be computed directly from the normal force. Based on experimental measurements, we propose the following relationship between the tangential force in the anterior-posterior direction T_{ap} and the normal force N:

$$T_{ap} = [a\ \tanh(c\,x) + b\,(\tanh(c\,x) + 1)]\,N \tag{1}$$

where $x \in [-1,1]$ is a dimensionless time variable (corresponding $x = -1$ to the heel strike and $x = 1$ to the toe off); and a, b, c are the force model parameters.

Experimental data for three young and healthy subjects (aged 22, 25 and 27) walking at self-selected speed were collected to validate the model. The subjects walked over the ground enclosing two force plates (AMTI, AccuGait sampling at 100 Hz). Six gait cycles per subject were measured, thus obtaining twelve sets of normal and tangential forces (six for right foot and six for left foot). Four of them were used to calibrate the contact model parameter values per subject, and the eight remaining were used for validating the model (see Figs. 1a and 1b).

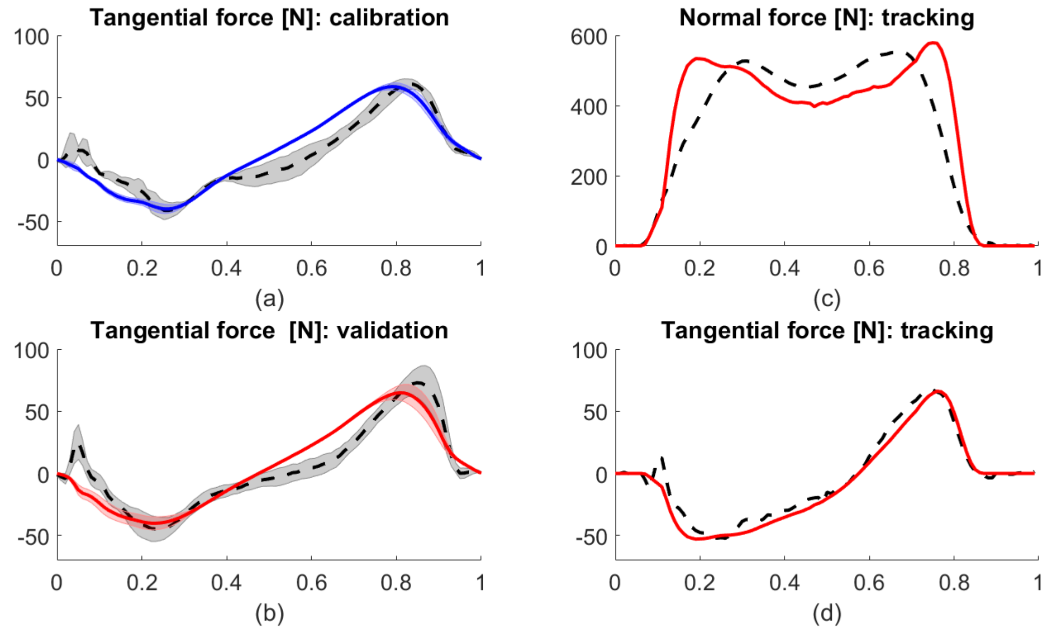

Figure 1: Left: Calibration results (a) and validation results (b) of the tangential contact model for Subject 1: mean and standard deviation of experimental data (dashed black), calibration results (blue), and validation results (red). Right: Results of normal (c) and tangential (d) ground reaction forces obtained when tracking walking motion for Subject 3, using the calibrated contact model parameter values: experimental force measurements (dashed black) and predicted force values (red). Results are shown for normalized stance time.

The presented foot-ground contact model was used in an optimal control tracking framework for simulating two-dimensional walking motion in the sagittal plane. In this formulation, both motion and forces were design variables that minimized the pelvis residual wrench for obtaining a dynamically consistent walking motion [6]. The foot-ground normal force was obtained based on the model presented in [3], which uses sphere-plane contact elements. First, two separate optimizations were done to identify the contact model parameter values per subject, which were used in the tracking optimization. The model was developed in OpenSim and the optimal control problem was solved using GPOPS-II. The normal and tangential contact forces obtained when tracking walking motion for Subject 3 are shown in Figs. 1c and 1d.

Future work includes the comparison between the proposed tangential contact model and other existing models such as [2,4], and also developing a three-dimensional foot-ground contact model.

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