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A generic analytical foot rollover model for predicting translational ankle kinematics in gait simulation studies

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ABSTRACT

The objective of this paper is to develop an analytical framework to representing the ankle–foot kinematics by modelling the foot as a rollover rocker, which cannot only be used as a generic tool for general gait simulation but also allows for case-specific modelling if required. Previously, the rollover models used in gait simulation have often been based on specific functions that have usually been of a simple form. In contrast, the analytical model described here is in a general form that the effective foot rollover shape can be represented by any polar function $\rho = \rho(\phi)$. Furthermore, a normalized generic foot rollover model has been established based on a normative foot rollover shape dataset of 12 normal healthy subjects. To evaluate model accuracy, the predicted ankle motions and the centre of pressure (CoP) were compared with measurement data for both subject-specific and general cases. The results demonstrated that the ankle joint motions in both vertical and horizontal directions (relative RMSE $\sim$10%) and CoP (relative RMSE $\sim$15% for most of the subjects) are accurately predicted over most of the stance phase (from 10% to 90% of stance). However, we found that the foot cannot be very accurately represented by a rollover model just after heel strike (HS) and just before toe off (TO), probably due to shear deformation of foot plantar tissues (ankle motion can occur without any foot rotation). The proposed foot rollover model can be used in both inverse and forward dynamics gait simulation studies and may also find applications in rehabilitation engineering.

1. Introduction

The human foot is a complex structure comprising numerous bones, muscles, ligaments and synovial joints. Many empirical- and physics-based computational models have been developed to represent foot biomechanics (Salathe et al., 1986; Scott and Winter, 1993; Gefen et al., 2000; Carson et al., 2001; Hansen et al., 2004; Nester et al., 2007). Although very complex models are useful for gaining insight into the function of specific foot structures, simple models can represent overall foot function.

The function of the foot during walking has been modelled as a 'rocker' by many researchers. Simple models with rocker feet have been used to investigate the fundamental principles of walking (McGeer, 1990; Gard and Childress, 2001). More complex multi-segment models together with rocker (foot rollover) models have been used to simulate walking dynamics (Ju and Mansour, 1988; Koopman et al., 1995; Ren et al., 2007; Srinivasan et al., 2008). The rocker concept has also been used to analyse the behaviour of healthy and prosthetic feet (Hansen and Childress, 2004, 2005; Knox, 1996; Stein and Flowers, 1987).

For gait simulation studies, reproducing the translational ankle motion is a key requirement (Ju and Mansour, 1988; Ren et al., 2007). Previously, the rollover models used in gait simulation have often been based on specific analytical functions of a simple form. For example, Srinivasan et al. (2008) used a circular arc to represent the rollover curve, whereas Ju and Mansour (1988) used a second order polynomial. In these cases, the errors introduced by using an insufficiently complex function may be significant. Furthermore, these models are not generic in the sense that they are based on specific functions and also needs subject-specific inputs. Therefore, the first objective of this study was to create a generic rollover model based on a normative dataset, which can also utilise any analytical function, including complex spline-based representations.

Whilst the use of a rollover curve to represent the foot contact point trajectory has been demonstrated (Hansen et al., 2004), there are no published results describing the accuracy with which a rollover model can reproduce the translational motion of the ankle and centre of pressure (CoP). This is critical to the use of rollover models in gait simulation. Therefore, the second objective

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Notation

x_c, y_c	coordinates of foot contact point
x_a, y_a	coordinates of ankle joint
x_{rel}, y_{rel}	relative position of ankle joint with respect to contact point
$\rho(\phi)$	polar function of the effective rollover foot shape
$\overline{\rho}(\phi)$	normazlied polar function of the effective rollover foot shape
ρ_c, ϕ_c	polar distance and polar angle of the contact point
ϕ_{met}	polar angle of the 2nd metatarsal
ϕ_{hs}	polar angle at heel strike
ρ_{cal}	polar distance of the upper ridge of the calcaneus
x_{hs}	horizontal position of the contact point at heel strike
s	distance travelled by the contact point from heel strike
$\dot{x}_a, \dot{y}_a$	ankle joint velocities
$\ddot{x}_a, \ddot{y}_a$	ankle joint accelerations
θ	foot segment angle
ω, α	foot angular velocity and acceleration
$\dot{\rho}_c, \ddot{\rho}_c, \dddot{\rho}_c$	1st, 2nd and 3rd order differentiations of polar function $\rho(\phi)$

of this study was to establish the accuracy with which a rollover model can reproduce the ankle kinematics. Hence, the generic model was tested in both subject-specific and general modelling scenarios by validating the analytically derived ankle kinematics against measurement data.

2. Methods

2.1. Foot rollover model

In the stance phase of walking, the foot was modelled as a rocker, rolling over the ground surface from heel strike (HS) to toe off (TO) without slipping (see Fig. 1). The effective foot rollover shape, which accounts for joint motions, deformations of the foot arch and of the soft tissues, was defined to be the trajectory of the foot contact point with the ground (x_c, y_c) in the foot's local coordinate system (Hansen et al., 2004). In this study, the rollover shape was described by a polar function $\rho(\phi)$, where ρ is the distance between the ankle joint and a point on the rollover curve and ϕ is the polar angle of that point measured with respect to the reference line connecting the ankle joint and the upper ridge of the calcaneus.

The foot angle θ relative to the progression direction was defined by the line connecting the ankle joint and the 2nd metatarsal head (see Fig. 1). The ankle joint position (x_a, y_a) was described as

$$\begin{cases} x_a = x_c + x_{rel} \\ y_a = y_c + y_{rel} \end{cases} \tag{1}$$

where x_{rel} and y_{rel} are the relative position of the ankle with respect to the contact point. Eq. (1) can be written as

$$\begin{cases} x_a = x_{hs} + s + \rho_c \cdot \cos(\theta - \phi_{met} + \phi_c) \\ y_a = \rho_c \cdot \sin(\theta - \phi_{met} + \phi_c) \end{cases} \tag{2}$$

where $\rho_c = \rho(\phi_c)$, ϕ_c is the polar angle of the contact point, ϕ_{met} the polar angle of the 2nd metatarsal, i.e. the angle from the reference line to the line connecting the ankle joint and the 2nd metatarsal, x_{hs} the horizontal position of the contact point at HS and s the distance travelled by the contact point from HS, according to the non-slip assumption, which can be expressed as

$$s = \int_{\phi_{hs}}^{\phi_c} \sqrt{\rho^2(\phi) + \dot{\rho}^2(\phi)} \cdot d\phi \tag{3}$$

where ϕ_{hs} is the polar angle of the contact point at HS and $\dot{\rho}(\phi)$ is defined as $d\rho/d\phi$.

At the contact point, the ground forms a tangent to the rollover curve and, hence, the slope of the rollover curve should be zero. In other words, the contact point's vertical position relative to the ankle should satisfy the condition

$$\frac{dy_a}{d\phi} = 0 \quad \text{when} \quad \phi = \phi_c \tag{4}$$

Substituting the second term in Eq. (2) into (4), leads to

$$\phi_c + \theta - \phi_{met} - \arctan\frac{\dot{\rho}_c}{\rho_c} - \frac{\pi}{2} = 0 \tag{5}$$

where $\dot{\rho}_c = (d\rho)/(d\phi)$ when $\phi = \phi_c$. This equation defines the relationship between the polar angle of the contact point and the foot angle. Given the effective rollover shape $\rho(\phi)$ and the foot angle trajectory θ, the contact point (defined by ϕ_c) can be determined at each instance of stance phase by solving Eq. (5).

2.2. Ankle kinematics

The ankle kinematics (position, velocity and acceleration) is important for simulating the body dynamics during gait (Ren et al., 2007). In this study, the translational kinematics of the ankle in stance phase can be derived analytically from the rotational motion of the foot based on the rollover model. The ankle positions (x_a, y_a) can be determined by Eq. (2) based on the contact point position

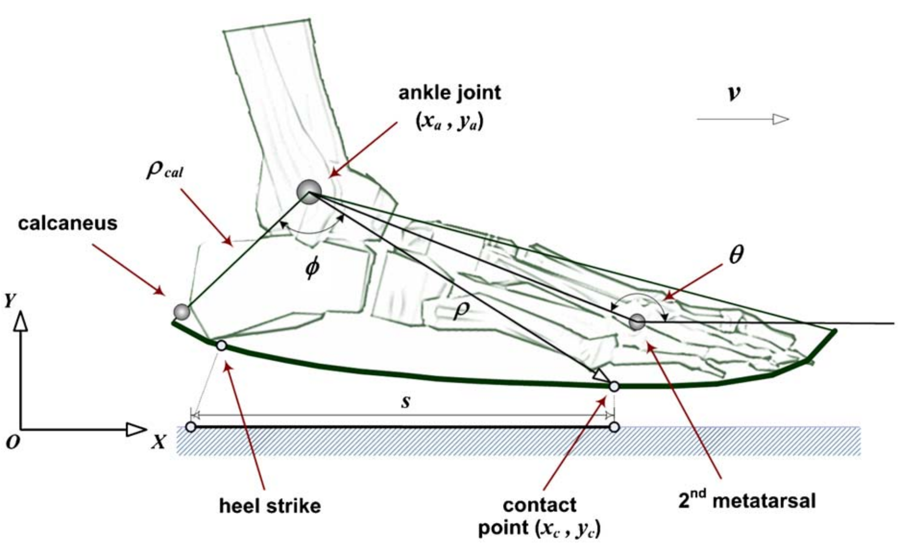

Fig. 1. The rollover model of foot–ankle kinematics during stance phase. The effective rollover shape from heel strike to toe off was defined by a polar function $\rho(\phi)$. To describe ankle and foot motions, a fixed coordinate system XOY is defined with the positive X axis being the progression direction and the positive Y axis pointing upwards.