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

Lei Ren a,*, David Howard b, Luquan Ren c, Chris Nester b, Limei Tian c

a School of Physical Sciences and Engineering, King’s College of London, Strand, London WC2R 2LS, UK
b Centre for Rehabilitation and Human Performance Research, University of Salford, Salford M54WT, UK
c Key Lab of Terrain-Machine Bionics Engineering, Jilin University, P.R. China

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

* Corresponding author. Tel.: +44 20 7848 1170.
E-mail address: lei.ren@kcl.ac.uk (L. Ren).

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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 (see Fig. 1). The effective foot rollover shape was determined at each instance of stance phase by solving Eq. (5).

The foot angle \( \theta \) 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

\[
\begin{align*}
    x_a &= x_c + s \cos \theta \\
    y_a &= y_c + s \sin \theta
\end{align*}
\]

where \( s \) is the distance travelled by the contact point from HS, according to the non-slip assumption, which can be expressed as

\[
s = \int_{x_{hs}}^{x_c} \sqrt{\rho^2(\phi) + \rho'^2(\phi)} \, d\phi
\]

where \( \phi_{hs} \) is the polar angle of the contact point at HS and \( \rho(\phi) \) 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

\[
\frac{dy_a}{d\phi} = 0 \quad \text{when} \quad \phi = \phi_c
\]

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

\[
\phi_c + \theta - \phi_{met} - \arctan \left( \frac{\rho_{c}}{\rho_{a}} \right) = 0
\]

where \( \rho_{c} = (d\rho/d\phi) \) 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, \( \theta \), the contact point (defined by \( \phi_c \)) 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. 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 \((x_{an}, y_{an})\) 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 XDY is defined with the positive X axis being the progression direction and the positive Y axis pointing upwards.
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