Extended Abstract

The 4th Joint International Conference on Multibody System Dynamics
May 29 – June 2, 2016, Montréal, Canada

Foot-Ground Sagittal Rolling Behaviour During Heel Contact And Its Approximation by an Exponential-Curvature Disk

Lennart Caspers[1], Urbano Lugrís[2], and Andrés Kecskeméthy[1]

[1]*Mechanics and Robotics, University of Duisburg-Essen, Andres.Kecskemethy@uni-due.de*
[1]*Mechanics and Robotics, University of Duisburg-Essen, Lennart.Caspers@uni-due.de*
[2]*Laboratory of Mechanical Engineering, University of La Coruña, ulugris@udc.es*

Modeling of the foot-ground interaction is a topic of increasing interest in biomechanics of human motion, as it is essential for forward dynamics. Currently, most approaches use an array of soft spheres attached to a hind- and forefoot rigid body, respectively, that are interconnected by a revolute joint parameterizing the metatarsal joint, e.g. [1], [2], and foot placement with respect to the ground is computed by dynamical equilibrium. This is accurate enough but (a) requires significant computation effort to find equilibrium configurations, and (b) induces superfluous high-frequency oscillations of the foot segments with respect to each other and the ground, both slowing down forward dynamics integration schemes. Recently, an alternative approach using only two surrogate disk-plane contacts per foot with virtual contact points of exponentially decaying radius as a function of tilt angle, respectively, was proposed in [3] and fitted for dynamic situations during walking and running in [4]. While in the former work the virtual contact point was computed via dynamical equilibrium, this paper extends the method by computing explicitly the progression of the physically consistent rolling point and fitting it kinematically to the measured Center of Pressure (CoP) as a function of the heel tilt angle. From this analysis, two new results arise: (a) from experimental measurements, a typical generic and more or less recurrent kinematical rolling behaviour of the ankle with respect to the ground seems to hold in healthy walkers, and (b) the measured rolling behaviour seems to confirm that the assumed exponentially-shaped curvature profile of the virtual disk approach is indeed suitable to reproduce the experimental measurements. These results seem to suggest that foot-ground contact can be approximated in a first model as a purely kinematic 3D cam-like rolling, which might be of interest not only for efficient computer models but also to derive health scores for walking patterns concerning the foot-ground interaction.

Methods: The gait of nine healthy subject was measured in a gait laboratory comprising a VICON MX 13 motion capture system with 7 cameras, 2 AMTI OR6-7-2000 force plates, and 2 high-speed cameras. Reflective markers were placed according to the Plug-In-Gait model (Fig. 1a), and the subjects were asked to walk barefooted several times at normal walking speed across the force plates. CoP displacement was measured at the force plate and re-scaled to percentage relative position with respect to the length of the CoP track on the ground when projected to the sagittal plane (0% corresponding to heel strike and 100% corresponding to toe-off), and angle α was determined from the Vicon PlugIn model. Fig. 1b) shows the average and standard deviation of experimental foot inclination α over CoP forward progression for all steps and trials.

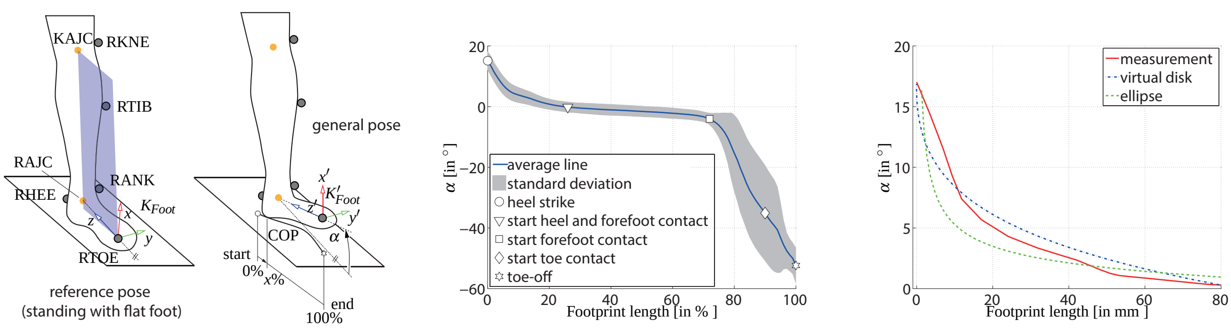

Figure 1: Foot rolling behaviour measures and fitting: (a) Definition of foot inclination angle α and CoP progression x as percentage of total footprint length, (b) average and standard deviation of foot inclination angle α over CoP progession for barefoot walking trial of nine healthy subjects, (c) fitting results for ellipsoid and exponential surface during heel contact

Results: From the measurements, one can recognize four typical foot contact phases during normal walking: (1) a heel-contact phase in which there is a pronounced, almost purely kinematic rolling behaviour with decaying curvature over CoP forward motion, (2) a double hind-/forefoot contact phase in which there is again a clear rolling behaviour with practically constant and very small curvature, (3) a forefoot contact phase in which curvature strongly varies, probably due to metatarsal joint actuation, and (4) a forefoot/toe contact phase with very large and varying curvatures, probably due to metatarsal joint and toe actuation, respectively. To the knowledge of the authors, the identification of these phases and their characteristic behaviour are new in the literature.

The experimentally observed rolling behaviour can be sought to be reproducible by an appropriate surrogate purely rolling surface. Here, the virtual disk model presented in [3] is revisited for this purpose, but now explicitly deriving its physical rolling surface shape and the kinematical behaviour of the progression of the physical rolling point in terms of the ankle inclination angle α, both discussed here only for the heel contact phase in the sagittal plane as the generalization to 3D still requires additional research. As proposed in [3] and further analyzed in [4], a virtual planar contact disk with exponentially decaying radius $r(\alpha) = \rho(1 - e^{-C\alpha})$ can be introduced for foot-ground modeling such that its rim touches the ground without slip at the immaterial contact point P (Fig. 2a), ρ, C being shaping parameters. From this the physical rolling point can be determined as follows. Let $r^\star$ be the distance of the immaterial contact point P from the footprint center $C^\star$ corresponding to P for $\alpha = 0$. For an infinitesimal increase $\mathrm{d}\alpha$, point P progresses by $\mathrm{d}r^\star = r' \cos\alpha\, \mathrm{d}\alpha$ outwards, where $(\cdot)' = \partial/\partial\alpha$ and $\mathrm{d}r^\star$ is the projection of $\mathrm{d}r$ on the ground. The material rolling point Ω currently having velocity zero of the yet unknown material rolling surface must be at a distance $\widehat{r}^\star$ from the point $C^\star$ such that the vertical velocity component $\dot{z}_a = \mathrm{d}\{r(\alpha)\sin\alpha\}/\mathrm{d}t$ of the virtual disk center is equal to its vertical roll velocity component $[\widehat{r}^\star - (r^\star - r\cos\alpha)]\dot{\alpha}$. Thus, one obtains

$$\widehat{r}^\star = r^\star + r' \sin\alpha \quad , \quad \text{with} \quad r^\star(\alpha) = \int_0^\alpha r'(\bar{\alpha}) \cos\bar{\alpha}\, \mathrm{d}\bar{\alpha} \; = \; \frac{\rho C}{1+C^2}\left[\sin\alpha\, e^{-C\alpha} + C\,(1 - \cos\alpha\, e^{-C\alpha})\right] \quad . \qquad (1)$$

A typical resulting 3D axis-symmetric rolling surface is shown in Fig. 2b). Fig. 1c) shows a best-fit of the shaping parameters ρ and C for a measured α/CoP curve, together with a best-fit of an ellipsoid profile. One can see that the exponential radius surface follows better the measured curve than a best-fit ellipsoidal surface. Moreover, the exponential radius approach leads to an explicit formula for roll arc over roll angle, which is not the case for the ellipsoid contact surfaces. Thus, the exponential profile disk contact seems to be well-suited suited for reproducing foot-ground roll motion. The extension of this to 3D kinematic foot roll modeling is subject of future research.

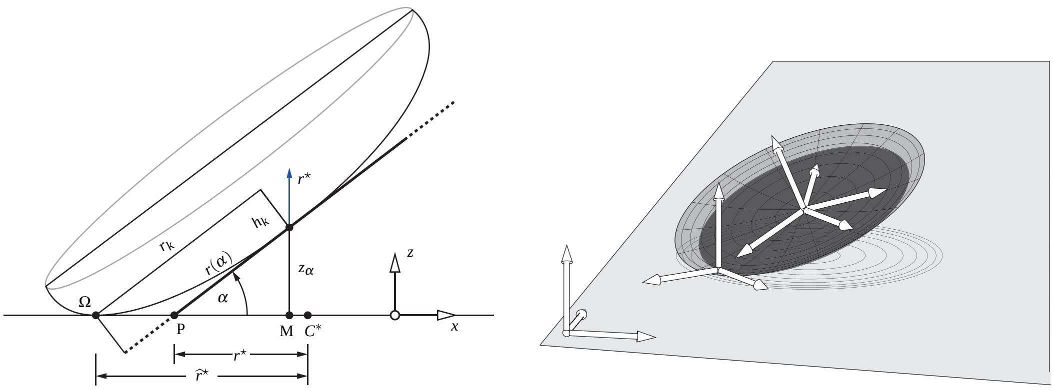

Figure 2: Exponential radius rolling surface (a) in the sagittal plane, (b) as spatial surface

References

[1] M. Millard, J. McPhee, and E. Kubica, "Multi-step forward dynamic gait simulation," *Multibody Dynamics*, pp. 25–43, 2008.

[2] R. Pàmies-Vilà, J. M. Font-Llagunes, U. Lugrís, and J. Cuadrado, "Parameter identification method for a three-dimensional foot–ground contact model," *Mechanism and Machine Theory*, vol. 75, pp. 107–116, 2014.

[3] A. Kecskeméthy, "Integrating efficient kinematics in biomechanics of human motions," *Procedia IUTAM*, vol. 2, pp. 86–92, 2011.

[4] M. Millard and A. Kecskeméthy, "A 3D foot-ground model using disk contacts," in *Proceedings of the Interdisciplinary Application of Kinematics IAK 2013*, (Lima, Peru), pp. 161–169, September 9–11 2013.