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

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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. In this paper, an alternative approach using disk-plane contacts as previously proposed in [3] and fitted for dynamic situations during walking and running in [4] is further analyzed. The paper shows two new results: (a) from experimental measurements, it is shown that there is a typical, more or less recurring kinematical rolling behaviour of the foot with respect to the ground in terms of sagittal foot inclination angle α over CoP (Center of Pressure) forward progression, yielding a kind of kinematical coupling between them, and (b) that this behaviour can be quite well replicated by a surrogate rolling surface of exponentially-shaped curvature profile. This paper concentrates on the sagittal projection of foot motion during normal walking, regarding only the fitting of the disk model during heel contact. Further steps, as the extension of the surface fitting procedure for the whole foot contact period as well for lateral foot rolling shall be discussed in future publications.

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. CoM 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. Noting than the slope of curves in the α/CoP diagram can be interpreted as being proportional to the curvature of a corresponding surface rolling on the plane, one can observe from Fig. 1b) four typical foot contact phases during normal walking: (1) a heel-contact phase in which there is

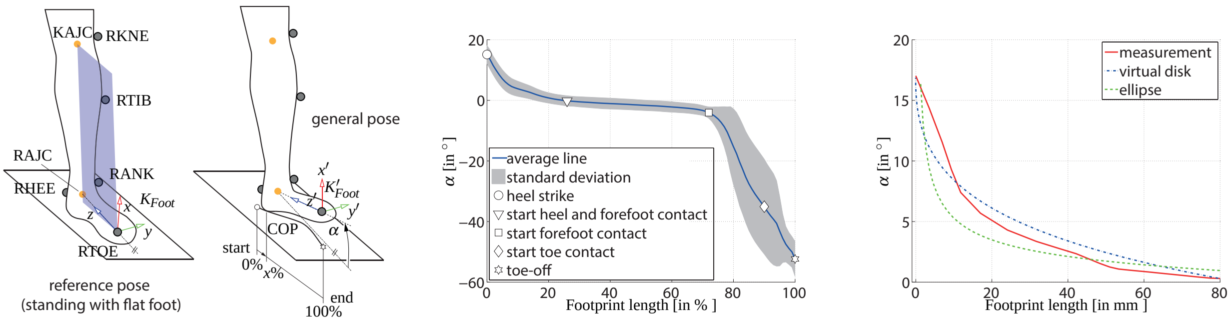

Figure 1: Foot rolling behaviour measures and fitting: (a) Definition of foot inclination angle α and CoP progression x as percentage of total footprint length, (b) average and standard deviation of foot inclination angle α over CoP progession for barefoot walking trial of nine healthy subjects, (c)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

a clear rolling behaviour with a decaying rolling-surface 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 increases and metatarsal joint starts deflecting, and (4) a forefoot/toe contact phase in which the metatarsal joint is strongly active leading to large curvatures. During phases 1 and 2, only small deflections to this kinematical rolling behaviour are observed, while during phases 3 and 4, there are mayor discrepancies which show that the metatarsal joint is being actively controlled.

In this paper a surrogate rolling surface for phase 1 (heel contact) is sought for. As the surrogate rolling surface is synthetic, any geometrical shaping method such as by ellipsoids, B-splines, etc. can be used. Here, a very simple and efficient alternative approach proposed in [3] is regarded which consists of using a virtual planar contact disk with exponentially decaying radius $r(\alpha) = r_0(1 - e^{-C\alpha})$, where r_0 and C are shaping parameters. The pose of the virtual disk at angle α is determined by stating that the virtual disk touches the ground without slip at the immaterial contact point P (Fig. 2a). Let $r^\star$ be the distance of P from to the disk contact point $C^\star$ at $\alpha = 0$. For an infinitesimal increase $\mathrm{d}\alpha$, the virtual point P must progress by $r^{\star\prime} = r'\cos\alpha\,\mathrm{d}\alpha$ outwards, where this progression is the projection of the increase of the radius $r(\alpha)$ on the plane and $(\cdot)' = \partial/\partial\alpha$. Moreover, the material rolling point Ω of the rolling surface currently having velocity zero 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 for the location of the rolling point Ω in terms of α

$$\widehat{r}^\star = r^\star + r'\sin\alpha \quad , \quad \text{with} \quad r^\star(\alpha) = \int_0^\alpha r'(\bar{\alpha})\,\cos\bar{\alpha}\,\mathrm{d}\bar{\alpha} \;=\; \frac{r_0 C}{1+C^2}\left[\sin\alpha\, e^{-C\alpha} + C\,(1 - \cos\alpha\, e^{-C\alpha})\right] \quad . \qquad (1)$$

The resulting rolling surface in 3D is shown in Fig. 2b). Fig. 1c) shows a best-fit of the shaping parameters r_0 and C for a measured α/CoP curve, together with a best-fit of an ellipsoid profile. One can see that the virtual disk follows better the measured curve than the ellipsoidal surface. Also, the virtual disk leads to an explicit formula for roll arc over roll angle, which is not possible for ellipsoid contact surfaces. Thus, the approach seems to yield a workable and efficient approach to approximate foot rolling behaviour during heel contact. This can be be extended to full foot contact in future work, as well as with additional shaping parameters for better fit with experiments.

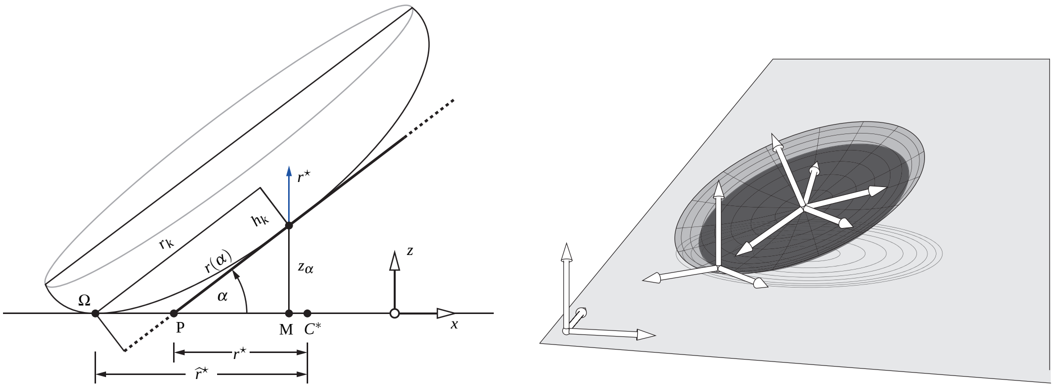

Figure 2: Rolling surface (a) in the sagittal plane, (b) spatial surface

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.