A Case Study on Human Gait CoP and GRF Progression During Single-Limb Support — Comparison between Experiment, Multi-Sphere and Continuous Rolling Surface Contact

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This paper extends previous results for a novel method presented by the authors for foot-ground contact modelling based on a rolling surface model ([1], [2]), instead of using several sphere-ground contact elements (e.g. [3], [4], [5]). The advantages of the novel method are its continuity, higher computational performance and similarity to the experimental foot rolling behaviour during gait. In [2], the direct dynamics of a single-limb support gait phase was computed and compared to the elastic spheres approach, showing good agreement for the angles and their time derivatives. In this paper, we extend these computations by considering also the progression of the centre of pressure (CoP) and of the ground reaction force (GRF), and comparing these between experiments, multiple sphere contact, and continuous rolling surface. Moreover, a parameter study is performed by varying the mass properties and the initial velocities at the beginning of the forward dynamics simulation phase.

The main idea of the present approach is based on the observation that smooth and roughly repetitive behaviour of foot inclination angle vs. Center of Pressure (CoP) progression occurs during gait, indicating that the foot continuously "rolls" on the ground through a hidden surface with varying curvature, rather than resting flat on the ground at any instant. Fig. 1a) shows some typical trajectories of the rolling curvature radius over the CoP progression, the latter measured in percentage from heel strike to toe off. One can recognize a quite reproducible rolling behaviour from small curvature at heel strike to large curvature at mid-phase to small curvature again at toe-off. Regarding the averages (Fig. 1b), it is also interesting to note that the curvature change resembles a Gaussian bell function. In the present study, a short (right) single-limb support phase (Fig. 1c) starting with the left foot just after toe off (14% of gait cycle) and ending shortly before the left leg hits the ground (45% of gait cycle) is regarded. In this way, no impacts need to be considered and only the qualitative behaviour of the different foot-ground models is analysed. All parameters and initial conditions are set as discussed in [2], where angles $\varphi_{\mathrm{h}}^{\mathrm{R}}, \varphi_{\mathrm{kn}}^{\mathrm{R}}, \varphi_{\mathrm{h}}^{\mathrm{L}}, \varphi_{\mathrm{kn}}^{\mathrm{L}}, \varphi_{\mathrm{an}}^{\mathrm{L}}, \varphi_{\mathrm{H}}$ are kinematically driven from measurement, angle $\varphi_{\mathrm{an}}^{\mathrm{R}}$ is dynamically driven by a best-fit torque time-history such that the measured motion is regained by forward dynamics, and the motion of the pelvis $x_{\mathrm{SKY}}, y_{\mathrm{SKY}}, \varphi_{\mathrm{SKY}}$ with respect to the "sky" are free DoF for sphere contact and mixed free (φ_{SKY}) and dependent variables ($x_{\mathrm{SKY}}, y_{\mathrm{SKY}}$) for rolling surface. Mass distribution was chosen according to [6].

Fig. 2 shows results for Center of Pressure (CoP) and vertical Ground Reaction Force (GRF) progression over gait cycle for both methods at different parameter settings, and experimental data. One can see that the continuous rolling surface model (dashed green curves) resembles quite well the global behaviour of the multiple sphere model (dot-dashed red curves), but that both fail to follow the experimental data (solid blue curves). After about 40% of gait cycle, the continuous rolling surface does not follow well anymore the multi-sphere simulation, but this is due to the missing toe DoF which was not included in this study and is planned for future extensions. Moreover, the results show that the sphere model leads to "chattering" due to stick-slick behaviour between the multiple spheres on the ground, while the time histories for the continuous model are perfectly smooth along the complete foot-ground contact phase. This is of importance not only for computational efficiency but also for devising controllers mimicking neuromuscular feedback in forward dynamic simulations. Of interest was also how the simulation behaviour changes when model parameters are varied. Shown in Fig. 2a,b are results for total mass variations from -40% to +50% and in Fig. 2c,d results for initial velocity variations of CoP progression from $-0.5m/s$ to $0.5m/s$ around the reference of zero. One can recognize that variations in total mass and initial velocities produce discrepancies in a similar or even larger scale as those arising from the foot model. This seems to suggest that it is more important how the foot/ankle motion is controlled than how the foot-ground contact is modelled, and that simple, continuous rolling surface contact models for foot-ground interaction might be as good or even better in precision than multiple-sphere contact models, while warranting continuity and avoiding jerky CoP and GRF time histories. By completing such continuous foot rolling models with toe DoF, impact and slip-stick effects, an interesting alternative approach to foot-ground interaction for forward gait dynamics can thus arise.

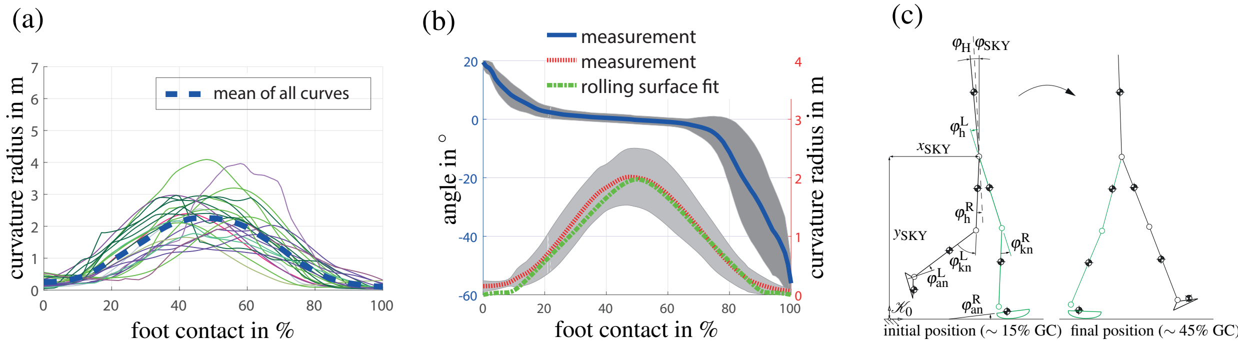

Figure 1: (a) experimental foot rolling results of 22 foot contacts of 7 healthy walkers (b) average and standard deviation of 7 healthy walkers (c) start and final position of the forward dynamic simulation model (from [2]).

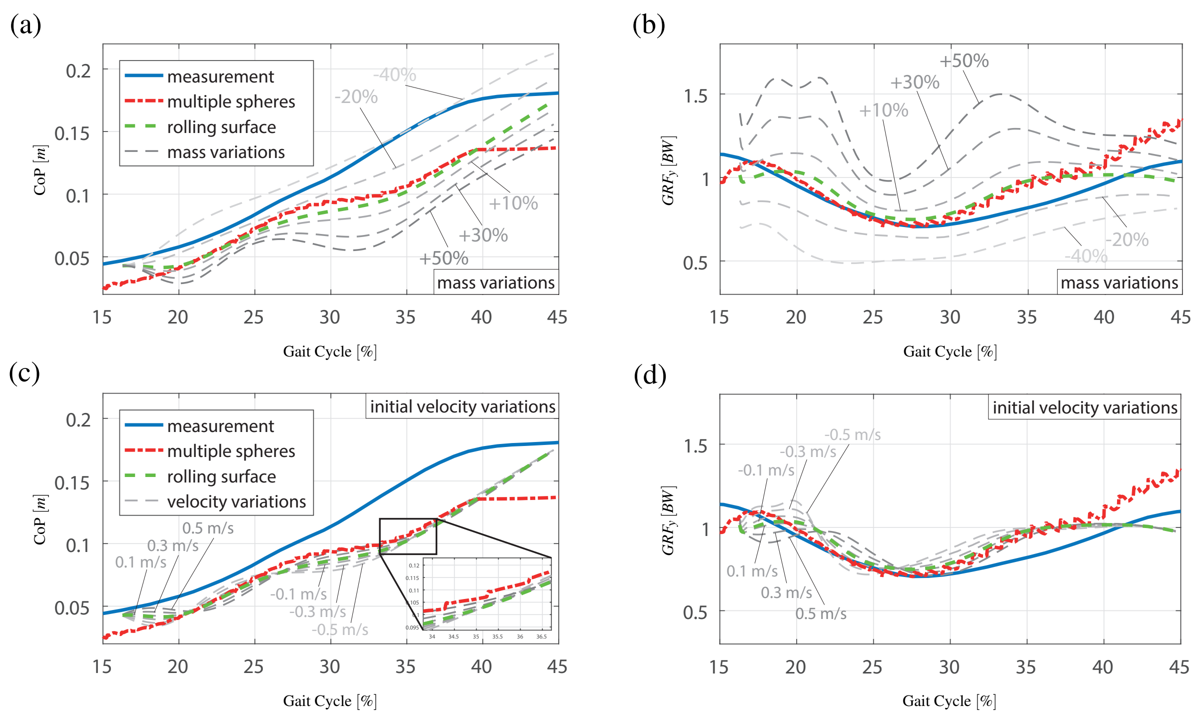

Figure 2: CoP progression and GRF_y over gait cycle for the two models and experiment: a/b – mass variations; c/d – initial CoP velocity variations

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