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Kalman smoothing improves the estimation of joint kinematics and kinetics in marker-based human gait analysis

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ABSTRACT

We developed a Kalman smoothing algorithm to improve estimates of joint kinematics from measured marker trajectories during motion analysis. Kalman smoothing estimates are based on complete marker trajectories. This is an improvement over other techniques, such as the global optimisation method (GOM), Kalman filtering, and local marker estimation (LME), where the estimate at each time instant is only based on part of the marker trajectories. We applied GOM, Kalman filtering, LME, and Kalman smoothing to marker trajectories from both simulated and experimental gait motion, to estimate the joint kinematics of a ten segment biomechanical model, with 21 degrees of freedom. Three simulated marker trajectories were studied: without errors, with instrumental errors, and with soft tissue artefacts (STA). Two modelling errors were studied: increased thigh length and hip centre dislocation. We calculated estimation errors from the known joint kinematics in the simulation study. Compared with other techniques, Kalman smoothing reduced the estimation errors for the joint positions, by more than 50% for the simulated marker trajectories without errors and with instrumental errors. Compared with GOM, Kalman smoothing reduced the estimation errors for the joint moments by more than 35%. Compared with Kalman filtering and LME, Kalman smoothing reduced the estimation errors for the joint accelerations by at least 50%. Our simulation results show that the use of Kalman smoothing substantially improves the estimates of joint kinematics and kinetics compared with previously proposed techniques (GOM, Kalman filtering, and LME) for both simulated, with and without modelling errors, and experimentally measured gait motion.

1. Introduction

Inverse kinematics, the estimation of joint kinematics based on measured trajectories of skin-mounted markers, is complicated by instrumental errors and soft tissue artefacts (STA) (Cappozzo et al., 1996; Chiari et al., 2005; Leardini et al., 2005).

Different techniques to reduce the effect of these errors on the estimated joint kinematics have been proposed (Chiari et al., 2005; Leardini et al., 2005). Spoor and Veldpaus (1980) estimated the positions and orientations of each body segment separately using a segmental optimisation method (SOM). SOM minimises the marker displacement in the segmental reference frame between any two time instants. Lu and O'Connor (1999) used a multi-link model relating the marker positions to the generalized co-ordinates that describe the motion of the body segments along the degrees of freedom (DOFs). At each time instant, their global optimisation method (GOM) estimates all generalized co-ordinates at once from a weighted nonlinear least-squares fit between the measured marker positions and those predicted by the model. GOM outperformed SOM in simulation for a serial three-link model (pelvis, thigh, and shank) joined by two spherical joints (hip and knee), suggesting that imposed joint constraints reduce the effect of errors. Cerveri et al. (2003a, b) used a Kalman filter to estimate joint kinematics. Kalman filtering (KF) is based on a measurement model obtained from the biomechanical model and a process model, which includes prior knowledge about the smoothness of the motion. In addition, the generalized co-ordinates, velocities, and accelerations are estimated simultaneously. Cerveri et al. (2005) proposed local marker estimation (LME), an extension of KF to estimate marker displacements in the segmental reference frames to account for STA. In their simulation study (Cerveri et al., 2005) in which systematic, sinusoidal perturbations added to the three thigh markers modelled STA, LME estimates were at least 50% more accurate than SOM estimates.

KF has two potential advantages over GOM. Firstly, including knowledge about motion smoothness may improve the accuracy of estimated joint kinematics. Secondly, estimating accelerations

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Abbreviations: DOF, degree of freedom; GOM, global optimisation method; KF, Kalman filtering; KS, Kalman smoothing; LME, local marker estimation; RMS, root mean square; SOM, segmental optimisation method; STA, soft tissue artefacts

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Appendix A. Supporting Information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jbiomech.2008.09.035.

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