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ESTIMATION OF KINEMATICS AND GROUND REACTION FORCES DURING SPRINT RUNNING

Nicos Haralabidis[1,2], Gil Serrancolí[3], Steffi L. Colyer[1,2], Ian N. Bezodis[4], Aki, I.T. Salo[5,1,2]
and Dario Cazzola[1,2]

[1]Department for Health, University of Bath, UK [2]CAMERA-Centre for the Analysis of Motion, Entertainment Research and Applications, University of Bath, UK [3]Department of Mechanical Engineering, Universitat Politècnica de Catalunya, Spain [4]Cardiff School of Sport, Cardiff Metropolitan University, Cardiff, Wales [5]KIHU Research Institute for Olympic Sports, Jyväskylä, Finland
Email: N.Haralabidis@bath.ac.uk

INTRODUCTION

The winning margin within track and field sprint running events is often very small. Coaches and athletes are therefore continually striving for improvements which can lead to overall performance enhancement. Predictive computer simulation and modelling approaches in sports biomechanics can be used to identify optimum techniques, explore the cause and effect relationships of technique modification and assess hypothetical 'what if' scenarios [1]. Predictive simulations utilising an optimal control approach have recently increased popularity within sports biomechanics [2,3], and also specifically within sprint running [4].

The first step to ensure realistic results from a simulation framework is to evaluate them against experimentally collected data. Data-tracking simulations using optimal control theory are an example of such an evaluation step [5]. The validity of predictive simulations is especially crucial within applied sports contexts, as they can be used to drive real world changes. However, very few previous studies have evaluated the accuracy of their simulation framework. The aim of the current study was therefore to assess the capability of reproducing experimentally measured joint kinematics and ground reaction forces during the acceleration phase of a sprint by solving a data-tracking problem.

METHODS

One male sprinter (age: 24 years; height: 1.79 m; mass: 72.2 kg; 100 m PB: 10.33 s) provided written informed consent to participate in the current study which was approved by the local research ethics committee. The athlete was asked to complete two successful maximal effort sprints on an indoor track whilst three-dimensional kinematics (250 Hz, Oqus, Qualisys AB, Sweden) and ground reaction forces (2000 Hz, Kistler, Switzerland) were collected between the 15-20 m mark. The data collected during the stance phase of the first sprint trial was used for the purposes of this study.

A generic full-body 37-DOF musculoskeletal model [6] was scaled in OpenSim (version 3.3, Stanford University, USA) [7] using marker data acquired during a standing static trial. The model was driven by 37 ideal joint actuators, and the knee flexion range of motion was increased up to 145°. A smoothed Hunt-Crossley contact model [8] was used to model the foot-ground interaction by means of attaching 6 spheres to each calcaneus segment. The contact model parameters (location of each sphere, and uniform sphere stiffness and dampening properties) were incorporated within the data-tracking problem as additional static design variables.

An inverse kinematics analysis was performed using the marker data from the contact phase. The resulting kinematics (pelvis position and orientation, and joint angles) were fitted using B-spline interpolation, from which joint velocities and accelerations were determined. The joint positions and velocities together with the ground reaction forces served as the experimental data for which the simulated model outputs were evaluated against.

A data-tracking simulation of the contact phase was performed by converting an optimal control problem into a nonlinear programming (NLP) problem using a direct collocation method. The current model possessed 74 states (37 generalised coordinates and 37 generalised velocities) and 37 actuator controls corresponding to each DOF. Each of the states and controls were discretised in time across 100 equally spaced nodes. The discretised states and controls, in addition to the contact model parameters, were the NLP design variables.

The dynamic constraints are typically written as a set of coupled first-order differential equations in an optimal control problem. For the current NLP problem, algebraic equality constraints were used to replace the differential equations using the trapezoid method in an explicit dynamic formulation [9]. The objective function was an integral over time (functional) containing weighted terms to minimise the squared difference between simulated and experimental kinematics and ground reaction forces, and minimise the squared joint torque controls. The NLP was solved by using the MATLAB optimisation function ‘fmincon’ with an interior-point solver (version 7.5, 2016b, MathWorks Inc., Natick, MA) in combination with OpenSim. Forward finite differences were used to approximate the objective function gradient and equality constraints Jacobian, and all calculations were parallelised across four cores using the MATLAB parallel computing toolbox (version 6.9).

RESULTS AND DISCUSSION

Our data-tracking simulation was able to reproduce the experimental data reasonably well as quantified by the root mean square error (RMSE) (Table 1). The magnitudes of these errors are in line with Lin et al. [9] who tracked experimental data during running, although our anterior-posterior ground reaction force error is higher by 0.05 BW. We anticipated larger errors in comparison to [9] due to the highly dynamic nature of sprint running. Nevertheless, if the results from predictive simulations are going to be implemented within sporting contexts, it is necessary that a simulation framework is first able to reproduce an athlete’s measured performance. From inspection of Fig 1 it is evident that the current framework was able to reproduce the ground reaction forces up to the latter portion of the contact phase. In future work we will aim to improve this.

Table 1. Root mean square error (RMSE) between experimental and simulated data. Maximum displacement and velocity errors are presented for the kinematics comparison.

Variable	RMSE
Pelvis Orientation	2°
Pelvis Translation	0.81 cm
Joint Angle	1°
Pelvis Orientation Velocity	23°s^{-1}
Pelvis Translation Velocity	0.24 ms^{-1}
Joint Angular Velocity	25°s^{-1}
Ant-Post GRF	0.07 BW
Vertical GRF	0.14 BW
Med-Lat GRF	0.01 BW

Negligible differences between the simulated and experimental kinematics data were achieved by placing tight bounds on the discretised states and by tracking them within the objective function. The simulated joint moments and residuals were not tracked within the current formulation, only minimized, and this resulted in oscillatory joint moments and residuals. We aim to improve on this aspect by tracking experimentally determined joint moments whilst also minimising residuals.

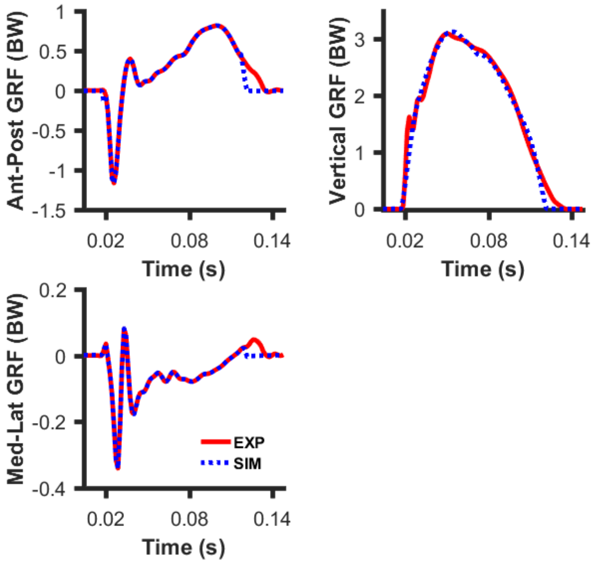

Fig 1: Experimental (solid red line) and simulated (dashed blue line) ground reaction forces during the contact phase.

CONCLUSIONS

We performed a data-tracking simulation of a sprint running contact phase whilst also simultaneously optimising the contact model parameters to assess its ability to reproduce experimental data. The results from the current study are promising, although improvements in either our model or NLP formulation are necessary to further improve the reproduction of experimental data prior to performing predictive simulations with a view to enhance *in silico* sprint running performance.

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