DEVELOPMENT, EVALUATION AND APPLICATION OF A SIMULATION MODEL OF A SPRINTER DURING THE FIRST STANCE PHASE

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This study aimed to investigate how alterations in kinematics at touchdown could improve the performance of an international-level sprinter during the first stance phase of a sprint. A seven-segment angle-driven simulation model was developed, and evaluation against empirical data revealed the model matched reality to within a mean value of 5.2%. A series of simulations altering the horizontal distance between the stance foot and the CM at touchdown were undertaken. By positioning the foot slightly further behind the CM, performance (external power) was improved due to favourable increases in horizontal force production and only small increases in stance duration. However, continuing to increase this distance between the foot and the CM led to decreased performance due to an inability to generate sufficient force despite continued increases in stance duration.

KEY WORDS: performance, simulation modelling, sprint start, technique.

INTRODUCTION: The start is an important part of an athletics sprint as sprinters strive to rapidly accelerate from a stationary position. Any small improvements in start performance can be critical to overall success – in the men's 100 m final at the 2004 Olympics there were only 0.04 s between the gold-medallist and the fourth placed sprinter – and therefore elite coaches strive to obtain any performance improvements. Several studies (e.g. Guissard et al., 1992) have directly altered the technique of a sprinter during the start, and observed the consequent effects on performance. However, due to the understandable opposition towards such experimental procedures from coaches, these studies have focussed on less-well-trained sprinters, and their application may thus be limited for internationally-competitive sprinters.

In recent years, there has been an increased use of theoretical models to investigate the performances of highly-trained athletes (e.g. Hiley and Yeadon, 2003). Computer simulation models have been applied in an attempt to determine how changes to specific inputs (such as technique variables) can affect certain performance-related outputs, thus allowing the identification of adjustments which could lead to performance improvement. However, simulation models should not be applied before evaluation of how well they represent the true system of interest (Yeadon and King, 2002). The first aim of this study was therefore to develop a simulation model of a sprinter, and evaluate its accuracy against empirical data collected from an international-level sprinter during the first stance phase of a sprint.

Based on empirical data collected from international-level sprinters, it has previously been suggested that positioning the stance foot further behind the whole body centre of mass (CM) at the onset of the first stance phase (i.e. an increasingly *negative* touchdown distance) could be beneficial for performance (Bezodis et al., 2008). In order to further investigate this, the second aim of this study was to use the evaluated simulation model to determine how changes in touchdown distance affected performance.

METHODS: Three international-level sprinters completed a series of maximal 30 m sprints commencing from blocks. Ground reaction forces were collected from the first stance phase using a force platform (Kistler, 9287BA; 1000 Hz). Two digital video cameras (Redlake, MotionPro HS-1; 200 Hz) were positioned in series to obtain high-resolution images from the set position until the end of the first stance phase. Twenty anatomical points were digitised, and the resulting displacement time-histories were scaled, digitally filtered, and combined with individual-specific segmental inertia data (Yeadon, 1990) to calculate CM motion. These kinetic, kinematic and anthropometric data provided sufficient data with which to customise a simulation model and to facilitate the undertaking of a quantitative evaluation of the model.

A seven-segment 2D simulation model (Figure 1a) was developed in Simulink® (v. 7.1), with its structure determined through quantitative and qualitative analyses of the empirical data from all three sprinters. The foot-ground interface was modelled using a two segment foot with horizontal and vertical spring-damper systems at the hallux and the MTP joint (Figure 1b). The model was customised using data from the sprinter exhibiting the highest levels of performance (age = 20 yr, mass = 86.9 kg, height = 1.78 m, 100 m PB = 10.28 s). Input data (joint positions and velocities at touchdown) were obtained from one empirical trial, and the model was driven using angular acceleration time-histories at each of the six joints. Five terms of a Fourier series were combined with each of the empirical angular accelerations, thus allowing slight adjustments to account for any small digitising error. The Fourier series co-efficients and the remaining input data (visco-elastic co-efficients for the foot-ground interface) were obtained through matching optimisations using a pattern search algorithm to determine the values which facilitated the closest match between the model and reality.

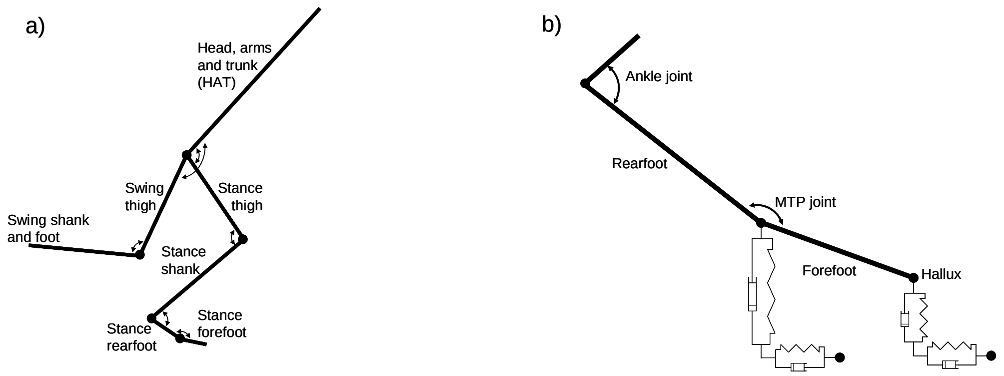

Figure 1. Illustration of the structure of a) the seven segment model, including b) the system used to model ground contact.

The accuracy of the simulation model was evaluated against the empirical data based on five specific criteria: *configuration* (mean RMS difference in angular displacements at the six joints throughout stance), *orientation* (RMS difference in absolute angle of the trunk throughout stance), *force accuracy* (mean RMS difference in horizontal and vertical ground reaction forces throughout stance, expressed as a percentage of force excursion), *impulse* (mean percentage difference in horizontal and vertical impulse production during stance) and *performance* (percentage difference in average horizontal external power production during stance – power was identified as an objective measure of sprint start performance by Bezodis et al., 2007). Assuming errors in percentages were equal to those in degrees (Yeadon and King, 2002), an overall evaluation score was calculated. To address the second aim of this study, knee joint angle at touchdown was manipulated by ±10° at 1° intervals from the empirically-recorded value (88.8°), whilst all other inputs and initial conditions remained constant. This simulated 20 touchdown distances deviating from a median empirical value (-0.073 m; i.e. CM 7.3 cm ahead of the foot), with the extreme touchdown distances being -0.009 m and -0.141 m. Model output data from all 20 simulations were expressed relative to the output associated with the empirical touchdown distance (-0.073 m). In addition to outputting power data to determine how performance levels changed, further variables were also output in an attempt to understand and explain why changes in performance occurred.

RESULTS: The model was able to replicate reality to within a mean value of 5.2% (*configuration* = 5.7°, *orientation* = 8.6°, *force accuracy* = 8.3%, *impulse* = 1.4%, *performance* = 2.0%). Graphical representations of the *force accuracy* (and thus *impulse*) criteria are presented in Figure 2.

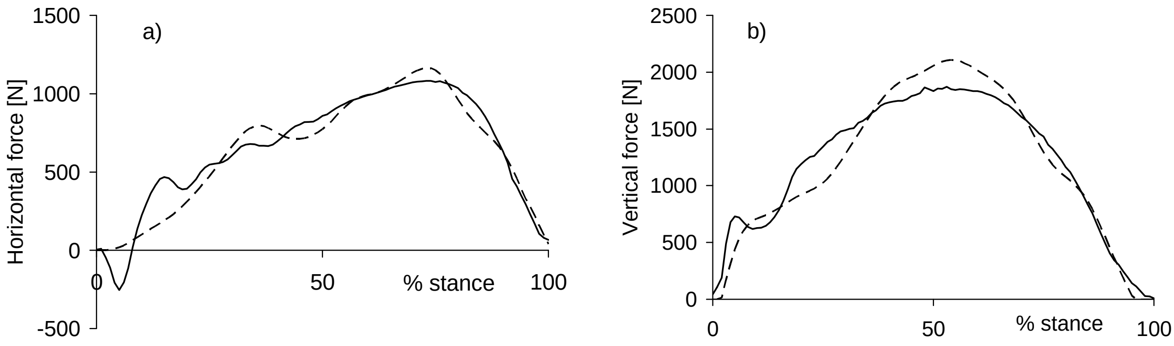

Figure 2. Empirical (solid line) and modelled (dashed line) a) horizontal and b) vertical ground reaction force time-histories throughout the stance phase.

In the simulations using the evaluated model, a curvilinear relationship was observed between touchdown distance and performance (Figure 3a). As the foot was positioned further behind the CM at touchdown, performance levels (i.e. power production) increased towards a peak value at a touchdown distance of -0.093 m. However, performance levels began to decrease beyond this, falling below original levels as touchdown distances exceeded -0.107 m. All simulations starting with the foot less far behind the CM at touchdown than in the empirical trial were associated with reductions in performance. The changes in velocity achieved during stance followed a curvilinear trend similar to that observed for power, whereas stance duration followed a more linear pattern, with stance duration increasing as the distance between the foot and the CM at touchdown also increased (Figure 3a).

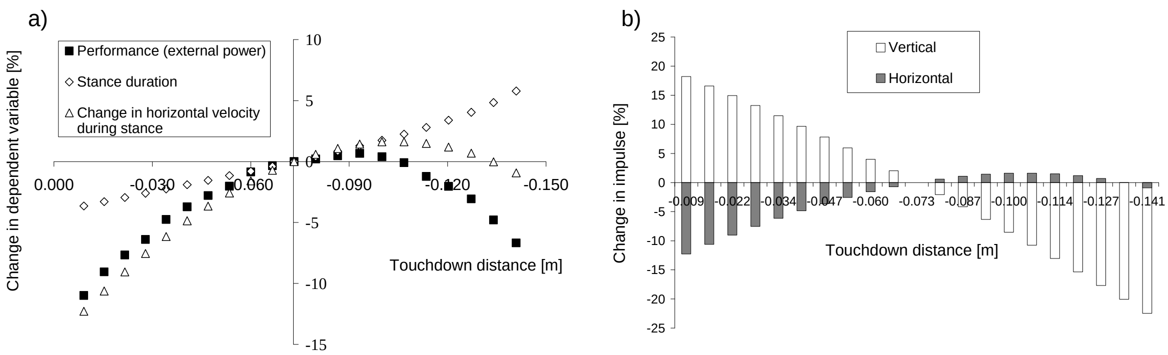

Figure 3. The effect of altering touchdown distance on a) performance (i.e. average horizontal external power), change in horizontal velocity during stance and total stance duration, and b) horizontal and vertical impulse production during stance.

A linear relationship existed between touchdown distance and vertical impulse production. Vertical impulse increased as the foot was placed less far behind the CM at touchdown compared to the empirical trial, and decreased when the foot was further behind the CM (Figure 3b). In contrast to vertical impulse, horizontal impulse production decreased when the foot was placed less far behind the CM than in the empirical trial. However, the overall relationship between touchdown distance and horizontal impulse was curvilinear - the largest horizontal impulses were associated with a touchdown distance of -0.107 m, with magnitudes reducing as the distance between the foot and the CM increased further (Figure 3b).

DISCUSSION: The evaluation results revealed that the chosen model structure was sufficient for simulating the motion of a sprinter during the first stance phase. When compared with previous detailed evaluations of angle-driven models (e.g. Wilson et al., 2006), the overall difference (5.2%) indicated a close match between the model and reality. The five individual criteria indicated that no single aspect of the model was matched considerably worse than the others, and thus both kinematic and kinetic variables were accurately represented. Most importantly, the evaluation yielded confidence in the accuracy of the model, and thus in the results obtained when applying the model to investigate how changes to technique could affect performance.

Model-based simulations suggested that it would be possible for this international-level sprinter to further improve his performance during the first stance phase by commencing stance with his stance foot positioned slightly further behind the CM. This facilitated a slight increase in horizontal impulse production which, although associated with small increases in stance duration, was largely due to greater force production (as evident by the greater power production). However, as the distance between the stance foot and the CM increased further, insufficient impulse could be generated, and performance levels consequently decreased. The model outputs suggested that these performance reductions were due to an inability to generate sufficient force (horizontally and vertically), despite increases in stance duration.

CONCLUSION: The evaluation results revealed that a simulation model could be confidently used to theorise how an international-level sprinter could improve performance during the first stance phase of a sprint. Application of the model confirmed previous suggestions (Bezodis et al., 2008) that landing with the stance foot further behind the CM could lead to performance improvements. By analysing additional outputs, it was identified that the improvements in performance were due to a favourable increase in horizontal impulse production. However, as this distance increased further, performance levels decreased, which appeared to be due to the sprinter being in a less favourable position for generating force against the track. The results of this study can be used to inform the training programme of the international-level sprinter, by encouraging a slight repositioning of the foot relative to the CM at touchdown. The existing model provides a useful framework which, with appropriate input data, can be customised to any individual sprinter. Additionally, the model could be applied to ascertain further potentially beneficial technique adjustments, and algorithms could be used to vary several inputs in an attempt to identify a technique associated with optimal performance.

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