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Paper:

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Title: Understanding the effect of touchdown distance and ankle joint kinematics on sprint acceleration performance through computer simulation

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Abstract

This study determined the effects of simulated technique manipulations on early acceleration performance. A planar seven-segment angle-driven model was developed and quantitatively evaluated based on the agreement of its output to empirical data from an international-level male sprinter (100 m personal best = 10.28 s). The model was then applied to independently assess the effects of manipulating touchdown distance (horizontal distance between the foot and centre of mass) and range of ankle joint dorsiflexion during early stance on horizontal external power production during stance. The model matched the empirical data with a mean difference of 5.2%. When the foot was placed progressively further forward at touchdown, horizontal power production continually reduced. When the foot was placed further back, power production initially increased (a peak increase of 0.7% occurred at 0.02 m further back) but decreased as the foot continued to touchdown further back. When the range of dorsiflexion during early stance was reduced, exponential increases in performance were observed. Increasing negative touchdown distance directs the ground reaction force more horizontally; however, a limit to the associated performance benefit exists. Reducing dorsiflexion, which required achievable increases in the peak ankle plantar flexor moment, appears potentially beneficial for improving early acceleration performance.

200 words.

Keywords**:** kinematics, kinetics, modelling, sprinting, technique

Introduction

Sprinting is a pure athletic endeavour where overall performance is determined by the ability to cover a short distance in the least possible time. The margins of success in international sprinting are often small and technique adjustments which could result in slight performance improvements are therefore of great interest to coaches and athletes. It has been demonstrated that the production of maximum external power from the very first step of a sprint is the most favourable strategy for optimum overall sprint performance (de Koning, de Groot, & van Ingen Schenau, 1992; van Ingen Schenau, de Koning, & de Groot, 1994; van Ingen Schenau, Jacobs, & de Koning, 1991). The techniques associated with a powerful early acceleration phase are therefore of clear relevance to overall sprint performance.

Empirical research has recently supported the importance of technical ability for early acceleration performance (Kugler & Janshen, 2010; Morin, Edouard, & Samozino, 2011; Rabita et al., 2015). These studies identified that the ability to direct the resultant ground reaction force (GRF) vector in a more horizontal direction was associated with higher levels of sprint acceleration performance, whereas the magnitude of the GRF vector was not. Furthermore, Kugler and Janshen (2010) suggested that a greater negative touchdown distance, i.e. planting the stance foot more posterior relative to the centre of mass (CM) at touchdown, facilitated a forward leaning position and the generation of greater horizontal propulsive forces. The knee joint has been linked to forward lean during the first stance phase (Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2013) and knee extensor moments and powers have recently been identified as an important feature of the first stance phase in well-trained and international-level sprinters (Bezodis, Salo, & Trewartha, 2014; Charalambous, Irwin, Bezodis, & Kerwin, 2012; Debaere et al., 2013). It is therefore possible that any effects of touchdown distance on early acceleration performance are related to knee joint mechanics at touchdown. Whilst it has been proposed that a large negative touchdown distance is favourable for early acceleration performance (Bezodis, Salo, & Trewartha, 2008; Kugler & Janshen, 2010), this has only been based on descriptive differences between sprinters. Furthermore, if such a strategy is beneficial for performance, it is conceivable that a limit may exist and that sprinters should not continually strive to increase the negative touchdown distance.

Whilst there are likely to be numerous aspects of technique which are important for early acceleration performance, one other important aspect proposed in the literature relates to the energy generating role of the ankle joint (Bezodis et al., 2014; Charalambous et al., 2012). The ankle goes through dorsiflexion followed by plantar flexion whilst a net plantar flexor moment is typically dominant throughout stance in every stance phase of a sprint. Bezodis et al. (2014) identified that the ankle generates up to four times more energy than it absorbs during the first stance phase compared to zero net energy generation during the mid-acceleration phase (Johnson & Buckley, 2001) and net energy absorption during the maximum velocity phase (Bezodis, Kerwin, & Salo, 2008). Charalambous et al. (2012) also determined that a ‘stiffer’ ankle whilst dorsiflexing during the early part of the first stance phase was positively related to higher horizontal CM velocities in a single sprinter. It is therefore conceivable that a reduction in ankle joint dorsiflexion during early stance could be another technical feature which is of benefit to early acceleration performance.

Whilst empirical evidence suggests that a large negative touchdown distance and reduced ankle joint dorsiflexion during early stance may be beneficial for early acceleration sprint performance, the effect of manipulating these aspects of technique on performance have not been determined. This is likely due to an understandable resistance to exploratory experimental manipulation of technique from coaches and athletes, particularly in elite sport (Kearney, 1999). Simulation modelling offers an alternative approach which allows the consideration of hypothetical situations to yield a more complete understanding than that possible experimentally (Yeadon & Challis, 1994) and which provides valuable preliminary evidence to determine the theoretical feasibility of potential applied interventions (Knudson, Elliott, & Hamill, 2014). Such models are typically customised based on empirical data from a single, highly-trained athlete. Model parameters and inputs are obtained from data on real performances and quantitative evaluation of the model output is performed against relevant aspects of the athlete’s technique and performance. Angle-driven simulation models have been previously used in other sports to systematically manipulate kinematic aspects of technique and determine the consequent effects on performance (e.g. Gittoes, Brewin, & Kerwin, 2006; Hiley & Yeadon, 2003a; 2003b; 2007). However, no such model exists which has been specifically designed and evaluated to investigate sprinting. The primary aim of this study was to determine the effects of manipulating touchdown distance and ankle joint dorsiflexion during the first stance phase of a maximal effort acceleration out of blocks. It was hypothesised that: 1) an increasingly large negative touchdown distance and 2) reduced ankle joint dorsiflexion during early stance would each independently lead to increases in first stance phase performance. In order to address this primary aim and these hypotheses, a prerequisite aim was to develop a computer simulation model and evaluate its representation of technique and performance during the first stance phase of a sprint.

Methods

Empirical data were collected from an international-level male sprinter (age, 20 years; mass, 86.9 kg; height, 1.78 m; 100 m personal best, 10.28 s) to obtain appropriate simulation model parameters and allow a quantitative evaluation. The sprinter’s ability to accelerate was highlighted by the fact that he had reached the 60 m final of the European Indoor Championships in the previous season. Three maximal effort 30 m sprints from blocks were completed at an indoor track just prior to the competition phase of the indoor season. The sprinter provided written informed consent to participate and the study was approved by the University research ethics committee. Synchronised GRF and two-dimensional video data were collected. A simulation model was developed using input data and parameters obtained from the empirical collection and matching optimisations. Specific model outputs were evaluated against empirical data to ensure that the model appropriately reflected reality. Model-based simulations were then run by separately manipulating touchdown distance and ankle joint dorsiflexion during early stance to determine their effects on first stance phase performance and address the primary aim of this study.

Empirical data collection

Two digital video cameras (MotionPro® HS-1, Redlake, San Diego, CA, USA) were positioned in series with overlapping 2.5 m wide fields of view to obtain sagittal plane images (1280 × 1024 pixels) from the 'set' position until the end of the first stance phase at 200 Hz. Ground reaction forces from the first stance phase were obtained at 1000 Hz using a force platform (Kistler, 9287BA, 1000 Hz, Winterthur, Switzerland) covered with artificial track surface. A third camera (MotionPro® HS-1, Redlake, San Diego, CA, USA) was positioned perpendicular to the centre of the force platform to obtain images (800 × 600 pixels) of the lower leg and foot during ground contact inside a 0.9 m field of view. The three video cameras and the force platform were synchronised to within 1 ms using a custom designed trigger system. An experienced starter administered standard '*on your marks*' and '*set*' commands before pressing a trigger button which sent a signal to initiate and synchronise all devices and an audio signal to the athlete.

The raw video files were imported into digitising software (Peak Motus®, v. 8.5, Vicon, Oxford, UK), and were manually digitised at full resolution with a zoom factor of 2.0. For the 200 Hz cameras, twenty anatomical points were digitised (vertex, C7, shoulder, elbow, wrist, hip, knee, ankle and metatarsal-phalangeal (MTP) joint centres, fingertips and toes) from 10 frames prior to movement onset until 10 frames after first stance toe-off. For the 1000 Hz camera, the 5th MTP joint centre and toe were digitised from 10 frames prior to touchdown until 10 frames after toe-off. The raw digitised co-ordinates were projectively scaled and the resulting raw displacement time-histories were exported from Peak Motus® for subsequent analysis in Matlab™ (v. 7.4.0, The MathWorks™, Natick, MA, USA).

The raw horizontal and vertical displacement time-histories from the 200 Hz cameras were digitally filtered using a fourth-order Butterworth filter at 24 Hz. The filtered displacement data were combined with individual-specific segmental inertia data obtained from 95 direct measurements on the sprinter (Yeadon, 1990). The mass of each foot was increased by 0.2 kg to account for the spiked shoes and the division of spike mass was determined directly from the ratio of forefoot:rearfoot length. Whole body CM displacement time-histories were then calculated using the summation of segmental moments approach (Winter, 2005). Joint angles were determined and were resampled at 1000 Hz using an interpolating cubic spline before their derivatives were numerically determined. Touchdown distance was determined as the horizontal distance between the whole body CM and stance MTP at touchdown (recognised by vertical force increasing and remaining more than two standard deviations above the zero load level), with negative values indicating the MTP was behind the CM.

Model structure

A planar seven-segment angle-driven simulation model (Figure 1) was developed using Simulink® (v. 7.1, The Mathworks™, Natick, MA, USA). The model incorporated a two segment representation of the stance foot (Figure 1b) due to the importance of rotation around the MTP joint in sprinting (Bezodis, Salo, & Trewartha, 2012), along with stance shank, stance thigh and swing thigh segments. The swing foot was incorporated into the swing shank segment, and the head, arms and trunk were combined into a single segment (Figure 1a). The properties of each segment were defined based on the individual-specific segmental inertia data. Segments were connected at revolute joints which permitted motion in the sagittal plane. Ground contact was modelled at each end of the forefoot segment (i.e. beneath the distal end of the toe and the MTP joint) using spring-damper systems which represented the combined visco-elasticity of the soft tissue, spiked shoe and track surface (Figure 1b). The damping terms were additionally dependent on spring length because damping increases as a spring compresses (i.e. as an increased area of the spiked shoe and track come into contact) and to avoid discontinuity in the forces at touchdown (Marhefka & Orin, 1996). Furthermore, the horizontal spring-damper systems included a term related to the vertical spring displacement because larger horizontal forces are required to achieve a given horizontal displacement when vertical spring compression is greater due to greater frictional forces (Wilson, King, & Yeadon, 2006):

$$F_{x_i} = (-k_{x_i} x_i - c_{x_i} |x_i| \dot{x}_i) y_i \quad \text{(for } i = 1,2\text{)}$$

$$F_{y_i} = -k_{y_i} y_i - c_{y_i} |y_i| \dot{y}_i \quad \text{(for } i = 1,2\text{)}$$

where F_x and F_y are the horizontal and vertical forces, x and y are the horizontal and vertical displacements relative to the original contact point, $\dot{x}$ and $\dot{y}$ are the derivatives of x and y, k_x and k_y, c_x and c_y are the horizontal and vertical stiffness and damping coefficients, respectively, and i represents the contact point (i.e. the toe or MTP). The model initiated at toe touchdown and forces in the MTP spring-dampers were generated when the vertical MTP co-ordinate fell below a threshold level which was initially visually estimated (0.03 m) from empirical data. The model terminated when the vertical toe spring returned to its initial length.

****Figure 1 near here****

Model parameters

Initial conditions for the model included horizontal and vertical velocities of the stance toe at touchdown and forefoot angle and angular velocity. Each joint was angle-driven using initial joint angular positions, initial angular velocities and the angular-acceleration time-histories throughout stance. Similar to Wilson et al. (2006), these joint angular acceleration time-histories were allowed to vary from empirical data from the instant of touchdown using a combination of five sine and cosine terms (ε):

$$\varepsilon_j(t) = j_1 \sin(t) + j_2 \cos(2t) + j_3 \sin(3t) + j_4 \cos(4t) + j_5 \sin(5t) \qquad \text{(for j = 1,6)}$$

where j_n is the coefficient for the term of frequency n Hz at joint j. The coefficients applied to the angular acceleration input parameters were allowed to vary between ± 1250°/s^2 (approximately 1% of the highest empirically recorded peak angular accelerations). Input data from each empirical trial (hereafter Trial 1, 2 and 3) were separately used in matching optimisations to determine the required coefficients for the toe and MTP horizontal and vertical spring-damper systems and the angular acceleration functions at each joint which provided the closest match between the model and each empirical trial. All horizontal foot-ground interface stiffness and damping coefficients were allowed to vary between 0 and 1.0 × 10^6 N/m^2 and Ns/m^3, respectively, and all vertical stiffness and damping coefficients between 0 and 1.0 × 10^5 N/m and Ns/m^2, respectively. Similar to previous procedures (Wilson et al., 2006; Yeadon & King, 2002), variation was also permitted in the touchdown estimates of linear toe velocity (± 0.25 m/s), forefoot angle (± 1º) and forefoot angular velocity (± 25º/s), as well as the threshold level at which the MTP was deemed to have made contact with the track (± 0.01 m).

Model evaluation

A variable-step Runge-Kutte integration algorithm was used to advance the model and a Latin Hypercube optimisation algorithm (McKay, Beckman, & Conover, 1979) was used to find an optimum match with reality within the specified limits. The closeness of the match between the model and empirical data from Trial 1 was evaluated using five kinetic and kinematic criteria (Table 1) based on previous model evaluations (Yeadon & King, 2002; Wilson et al., 2006; Hiley & Yeadon, 2007) as well as the specific application of this model. The orientation criterion provided an additional kinematic indication of any systematic effect of the cumulative configuration differences whilst the GRF accuracy criterion verified that accurate impulses were not achieved as a result of large fluctuations above and below the empirical GRF. The power criterion was used as an objective and appropriate measure of first stance phase performance (Bezodis, Salo, & Trewartha, 2010; de Koning et al., 1992; van Ingen Schenau et al., 1991; 1994). Errors in degrees were equated to those in percent (e.g. Wilson et al., 2006; Yeadon & King, 2002) and the mean value of the five criteria yielded an overall score reflective of the closeness of the match between the model and empirical data. To quantify the robustness of the optimised foot-ground interface parameters, an independent re-optimisation analysis was undertaken using the optimised spring-damper coefficients obtained from the two empirical trials which were not used in the initial evaluation (i.e. Trials 2 and 3). These coefficients were independently determined using the same methods as previously outlined, and were then used in the foot-ground interface alongside the remaining input data from Trial 1, which was again allowed to vary within the previously described predetermined limits. The accuracy of this match was evaluated using the five criteria described in Table 1.

****Table 1 near here****

Simulations using the model

To determine the effects of touchdown distance on average horizontal external power production during the first stance phase, the initial knee joint angle was systematically varied at touchdown by ±10° in 1° increments. This varied touchdown distance from -0.9 to -14.1 cm (an increasingly negative number represents the foot further behind the CM at touchdown; touchdown distance was -7.3 cm in the matched optimisation). Manipulations were made to the knee joint due to its aforementioned importance in the first stance phase (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013), particularly in relation to the lean of the body relative to the stance foot (Debaere et al., 2013). To determine the effects of ankle joint dorsiflexion during early stance on average horizontal external power production during the first stance phase, the ankle joint angular acceleration time-history from the matched optimisation was combined with the following function:

$$\varepsilon(t) = a \cdot \cos\frac{t}{2} - b \cdot sin\frac{t}{4}$$

Coefficients a and b were adjusted to yield ankle angular acceleration input data for five simulations which reduced the amount of dorsiflexion during early stance without altering the overall net change in ankle angle throughout stance. All simulations started from the matched optimisation ankle angle of 98º and ended at the matched optimisation angle of 149º, but the minimum ankle angle during stance ranged from 84º to 90º (compared to 82º in the matched optimisation; see Figure 2). For all simulations, the remaining input data used the values from the matched optimisation. Each simulation was advanced until the stance toe left the ground and ground contact was terminated. The effect of the simulated changes on selected output variables were identified to allow the primary aim of this paper to be addressed.

****Figure 2 near here****

Results

A mean evaluation score of 5.2% was obtained between the empirical data from Trial 1 and the matched optimisation. This evaluation comprised a mean difference of 5.7° in configuration throughout stance (Figure 3), 8.6° in orientation throughout stance, 8.3% in the overall GRF accuracy (Figure 4), 1.4% in the mean stance phase horizontal and vertical impulses, and 2.0% in average horizontal external power during stance. The optimised spring-damper coefficients used for modelling the foot-ground interface in each of the three trials are presented in Table 2. When assessing the foot-ground interface parameters, the overall evaluation scores for the two independent evaluations using the spring-damper coefficients from the matching optimisations of Trials 2 and 3 with the remaining input data from Trial 1 were 7.4% and 7.0%. Values for the five individual criteria from each of these independent evaluations are presented in Table 3.

****Figure 3 near here****

****Figure 4 near here****

****Table 2 near here****

****Table 3 near here****

In the first set of simulations, a curvilinear relationship was identified between touchdown distance and horizontal external power (Figure 5a). When the foot was positioned less far behind the CM at touchdown than in the matched optimisation, horizontal external power production progressively decreased. When the foot was positioned further behind the CM at touchdown than in the matched optimisation, horizontal external power production initially increased before reaching a peak value (a 0.7% increase relative to the matched optimisation at 0.02 m further back). Beyond this, horizontal external power production began to decrease again. The change in the ratio of force (the horizontal component of the GRF expressed as a percentage of the total GRF magnitude and averaged over the entire stance phase; Morin et al., 2011) associated with each of these simulations is presented in Figure 5b. In the second set of simulations, as ankle joint dorsiflexion during early stance was reduced, horizontal external power exponentially increased (Figure 6a). The peak resultant plantar flexor moments associated with each of these simulations were extracted from the model and also displayed an exponential increase (Figure 6b).

****Figures 5a and 5b near here****

****Figures 6a and 6b near here****

Discussion and Implications

This study developed and evaluated a simulation model in order to systematically determine the effects of manipulations to touchdown distance and ankle joint dorsiflexion during early stance on average horizontal external power production during the first stance phase. Using empirical input data from an international-level sprinter, the model was quantitatively demonstrated to match reality closely based on five criteria that were specific to early acceleration technique and performance. The movement pattern of this sprinter during the first stance phase (see sprinter B, Bezodis et al., 2014 for detailed stance leg joint mechanics from the same empirical data collection) is clearly representative of that exhibited by other international-level and highly-trained sprinters (e.g. Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013). These simulation results therefore provide preliminary evidence to support and inform the design of future experimental research and applied interventions (Knudson et al., 2014) with other participants from this population. However, a further benefit of this novel, exploratory research is that it demonstrates that this simulation model provides a means for assessing the efficacy of individual technique manipulations when appropriate input parameters have been obtained. Hypothesis 1 was partly accepted as it was found that positioning the stance foot increasingly further behind the CM at touchdown led to small improvements in horizontal external power generation, but that this was only true up a point. Beyond this, horizontal external power began to decrease again. Hypothesis 2 was accepted as reductions in the range of dorsiflexion during early stance were shown to increase the horizontal external power generated. This required greater peak resultant plantar flexor moments which increased considerably as the reductions in dorsiflexion were systematically increased.

The touchdown distance simulations revealed a curvilinear relationship with horizontal external power (Figure 5a). This provided some support for the previous suggestions (Bezodis et al., 2008; Kugler & Janshen, 2010) upon which hypothesis 1 was devised that placing the foot further behind the CM at touchdown leads to increases in horizontal external power production. However, an optimum touchdown distance was found to exist, beyond which increasingly negative touchdown distances were associated with reductions in horizontal external power production. A clear relationship existed between touchdown distance and the ratio of force (Figure 5b): as the foot was positioned further behind the CM at touchdown, the ratio of the horizontal component of the GRF to the total GRF magnitude increased. The range in ratio of force values across all simulations is comparable to the range exhibited during the first stance phase (approximately 35 to 55%) by the nine international- and national-level sprinters analysed by Rabita et al. (2015), providing further confidence in the structure and outputs of the model. It has previously been identified that a high ratio of force is associated with superior sprint acceleration performance (Kugler & Janshen, 2010; Morin et al., 2011; Rabita et al., 2015) and the current simulation results identify touchdown distance as a specific technical factor which affects the ratio of force produced. Given that horizontal external power exhibited a curvilinear relationship with touchdown distance, continuing to increase the ratio of force through greater negative touchdown distances did not lead to continued performance improvements. Further analysis of the model outputs revealed that the magnitude of the stance-averaged resultant GRF production was less at the greater negative touchdown distances where the ratio of force was highest. During sprint acceleration, it has been suggested that provided sufficient vertical impulse is produced, all remaining strength should be directed towards the production of propulsive horizontal impulse (Hunter, Marshall, & McNair, 2005). The reduction in horizontal external power production as touchdown distance became increasingly negative could therefore be reflective of an inability of the sprinter to generate sufficient vertical impulse from this touchdown position. It is conceivable that the body configurations at the larger negative touchdown distances are associated with poor force producing capabilities *per se* but further investigation is needed as factors such as specific muscle length and velocity changes cannot be accounted for with the current modelling approach. Coaches and researchers should be encouraged to explore strategies for manipulating foot placement with a view to finding the optimum touchdown distance for a given sprinter. Although the trajectory of the CM is not visible to coaches, its path during the first flight phase is fully determined at block exit. This first flight phase provides sufficient duration (Bezodis, Salo, & Trewartha, 2015) for technical adjustments at the leading swing knee to alter the location of the foot relative to the CM at touchdown. However, caution is advised not to over-increase the negative touchdown distance as placing the foot too posteriorly may be detrimental to performance.

The simulations which manipulated ankle joint dorsiflexion during early stance provided support for the empirically-based assertions of Charalambous et al. (2012) and Bezodis et al. (2014) upon which hypothesis 2 was devised. As the amount of dorsiflexion exhibited at the ankle joint during early stance was progressively reduced, average horizontal external power was found to increase exponentially (Figure 6a). Further investigation of the model outputs revealed that this initially occurred due to a reduction in ground contact time without a corresponding decrease in the net horizontal impulse generated. At greater reductions in dorsiflexion, performance was enhanced due to both a shorter ground contact time and greater net horizontal impulse generation. Reducing dorsiflexion during early stance likely requires a ‘stiffer’ ankle joint (Charalambous et al., 2012). The peak resultant ankle plantar flexor moments associated with each simulation were 7, 16, 30, 56 and 80 Nm greater than the matched optimisation (299 Nm), respectively (Figure 6b). Resultant plantar flexor moments have been shown to be higher in other exercises (e.g. maximal hopping, group mean = 345 Nm; Farley & Morgenroth, 1999) than they are in the first stance phase. Although the higher end of the current simulated increases in peak resultant plantar flexor moment may therefore be an unrealistic expectation, even the smallest simulated reduction in dorsiflexion was beneficial for performance and was associated with only a 7 Nm increase in the peak resultant plantar flexor moment. This suggests that any reduction in ankle dorsiflexion during early stance could be beneficial for horizontal external power production and sprinters could therefore seek to increase their reactive plantar flexor strength through plyometric training if endeavouring to improve early acceleration performance. Although small reductions in ankle dorsiflexion may be difficult to accurately quantify, coaches could seek to monitor this through changes to contact time or ground reaction forces given the appropriate equipment.

The current overall difference between the model and empirical data (5.2%) can be considered a close match compared with previously published kinetic and kinematic evaluations of angle-driven models containing ground contact (e.g. 5.6 – 9.4%; Wilson et al., 2006). The five individual criteria indicated that no single kinematic or kinetic aspect of the model was matched considerably better than the others. The optimised foot-ground interface spring-damper coefficients (Table 2) cannot be directly compared to previously published angle-driven models containing ground contact due to the model-specific nature of the foot-ground interface (i.e. two-segment structure of the foot, dependence of damping terms on spring lengths, dependence of horizontal springs on vertical spring displacements in the current model). The values obtained offer a sensible and relatively consistent representation of ground contact with large horizontal forces consistently generated in the toe springs and large vertical forces consistently due to the stiffness of the MTP springs once the MTP had made contact with the ground (Table 2). Ultimately, the appropriateness of the foot-ground interface should be considered in the context of modelled GRF profiles. The current evaluation score for GRF accuracy (8.3%) compares favourably against previous angle-driven models which have used a single-segment foot to model ground contact and returned values of 9 to 22% using an identical GRF accuracy criterion (Gittoes et al., 2006; Wilson et al., 2006). The impulse criterion scores (1.4%) further confirm the systematic closeness of the current match. This good representation of the external kinetics may in part be due to the novel inclusion of a two-segment foot in the current model. Such an approach could therefore improve the modelling of ground contact in other activities where considerable MTP motion exists but has previously been overlooked.

The variation in the optimised spring-damper coefficients between trials (Table 2) is consistent with previous detailed evaluations of multiple trials. In a landing model, optimised stiffness coefficients ranging from 3.9×10^5 to 1.9×10^9 N/m, and 9.5×10^4 to 2.0×10^9 N/m at the toe and heel, respectively and damping coefficients ranging from 1.6×10^5 to 1.9×10^8 Ns/m, and 1.0×10^4 to 2.0×10^7 Ns/m at the toe and heel, respectively, were determined between different trials (Gittoes, 2004). These results confirm that foot-ground interface spring-damper coefficients are typically trial-specific, even when trials have been collected from a single participant (Yeadon, Kong, & King, 2006). Although this highlights the need for simulation models to initially be customised to an individual using empirical data from specific trials, the results of the current independent re-optimisation analysis confirmed that this model was relatively insensitive to these parameters (the global error of 5.2% increased to a maximum of 7.4%). These independent re-optimisation results (Table 3) indicated that the use of independent foot-ground interface spring-damper coefficients from different trials still yielded accurate model output data. The model is clearly not overly sensitive to changes in these input parameters, and the fact that none of the individual evaluation criteria increased markedly more than any of the others (Table 3) as a result of these independent alterations again supports the robustness of this model.

As with any theoretical investigations, by simplifying the human body into a computer-based representation, several assumptions were made. The two-dimensional nature of the model is consistent with the majority of empirical sprint acceleration research where sagittal plane motion is of primary concern and non-sagittal forces are negligible (Debaere et al., 2013;

Rabita et al., 2015). The head, arms and trunk were combined in to a single segment, but dividing the foot into two segments about the MTP joint helped to provide realistic representations of the ground reaction forces. An angle-driven approach to actuate the model was adopted due to the applied aims of this study as kinematic aspects of technique cannot be directly manipulated with a torque- or muscle-driven model (Yeadon & King, 2002). This approach therefore provided the most appropriate means with which to address our technique-related hypotheses and is most appropriate to practical training situations in which the coaching cues are generally kinematic in nature. For questions with a strength-related focus, this model can now be adapted so it can be driven by joint torques and there is potential to seek to develop a version driven by muscle actuators. This angle-driven model provides a useful framework which can now be used to investigate the importance of other aspects of technique for early acceleration performance.

Conclusion

The current study has developed, evaluated and applied a simulation model to investigate and further the understanding of early acceleration technique and performance. The first set of simulations extended previous empirical research which had advocated the production of a more horizontally-directed GRF vector by identifying alterations to touchdown distance as a means of achieving this. However, the simulation results provided preliminary evidence suggesting the existence of potential limits to the benefits of positioning the foot further behind the CM at touchdown and coaches should be wary of encouraging foot placement too far behind the CM where performance benefits may be reduced. The second set of simulations provided preliminary evidence for the beneficial effects of reducing ankle joint dorsiflexion during early stance on early acceleration performance and identified the need for coaches to increase ankle plantar flexor strength to facilitate this. Intervention studies are required to extend these findings and to determine how coaches could affect early acceleration performance through specific technical or physical training interventions related to the above features.

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Tables

Table 1. Definition of the five criteria used to evaluate the agreement of the optimised kinetic and kinematic match between the model and empirical data.

Criterion	Definition
Configuration	The mean RMS difference between the model and empirical joint angle time-histories at each 1% of stance from the six joints.
Orientation	The RMS difference between the model and empirical HAT segment angle at each 1% of stance.
Impulse	The average percentage difference between the model and empirical vertical and net horizontal impulses from the entire stance phase
Ground reaction force accuracy	The RMS difference between the model and empirical horizontal and vertical ground reaction forces at each 1% of stance, expressed as a percentage of the total force excursion.
Power	The percentage difference between the model and empirical average horizontal external power generated during stance.

RMS: Root mean square; HAT: head, arms and trunk.

Table 2. Optimised stiffness and damping coefficients for the representation of the foot-ground interface from the matching optimisations for all three trials.

Parameter	Trial 1	Trial 2	Trial 3
Horizontal toe stiffness (N/m^2)	235,850	914,274	196,843
Horizontal MTP stiffness (N/m^2)	239,990	1,327	7,031
Horizontal toe damping (Ns/m^3)	110,310	544,526	55,458
Horizontal MTP damping (Ns/m^3)	0	4,008	0
Vertical toe stiffness (N/m)	60	3,565	11,594
Vertical MTP stiffness (N/m)	48,661	35,024	28,902
Vertical toe damping (Ns/m^2)	42	46	51
Vertical MTP damping (Ns/m^2)	15,590	894	245

Table 3. Evaluation scores from the independent re-optimisation of Trial 1 using of spring-damper coefficients from Trials 2 and 3.

	With Trial 2 coefficients	With Trial 3 coefficients
Configuration	8.1°	7.1°
Orientation	11.5°	10.6°
Impulse	2.3%	4.6%
Ground reaction force accuracy	14.3%	9.4%
Horizontal external power	1.0%	3.3%
Mean	7.4%	7.0%

Figures

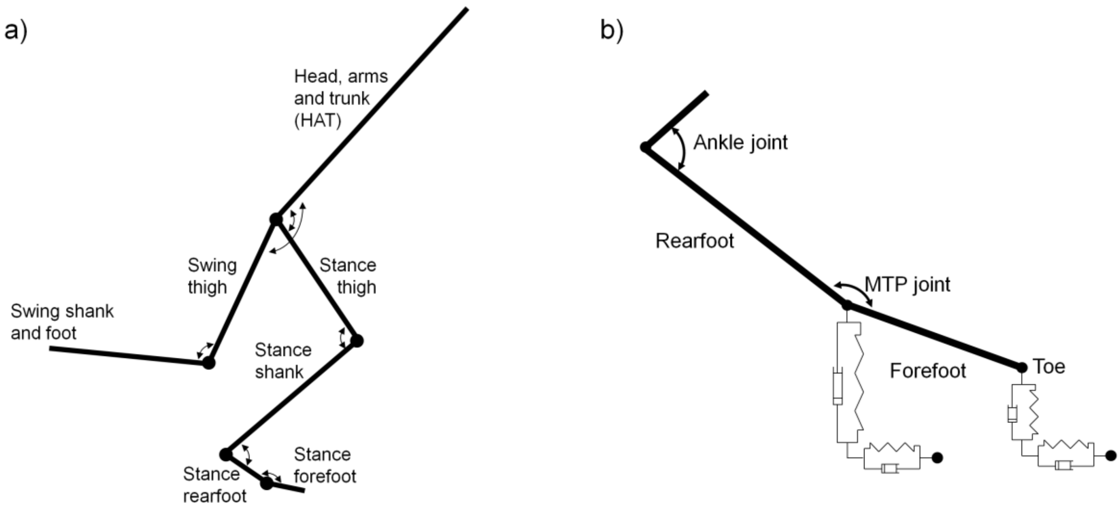

Figure 1. a) Basic structure of the seven-segment simulation model. b) Structure used to represent ground contact which comprised horizontal and vertical spring-damper systems between the foot and the ground at the toe (distal hallux) and MTP joint.

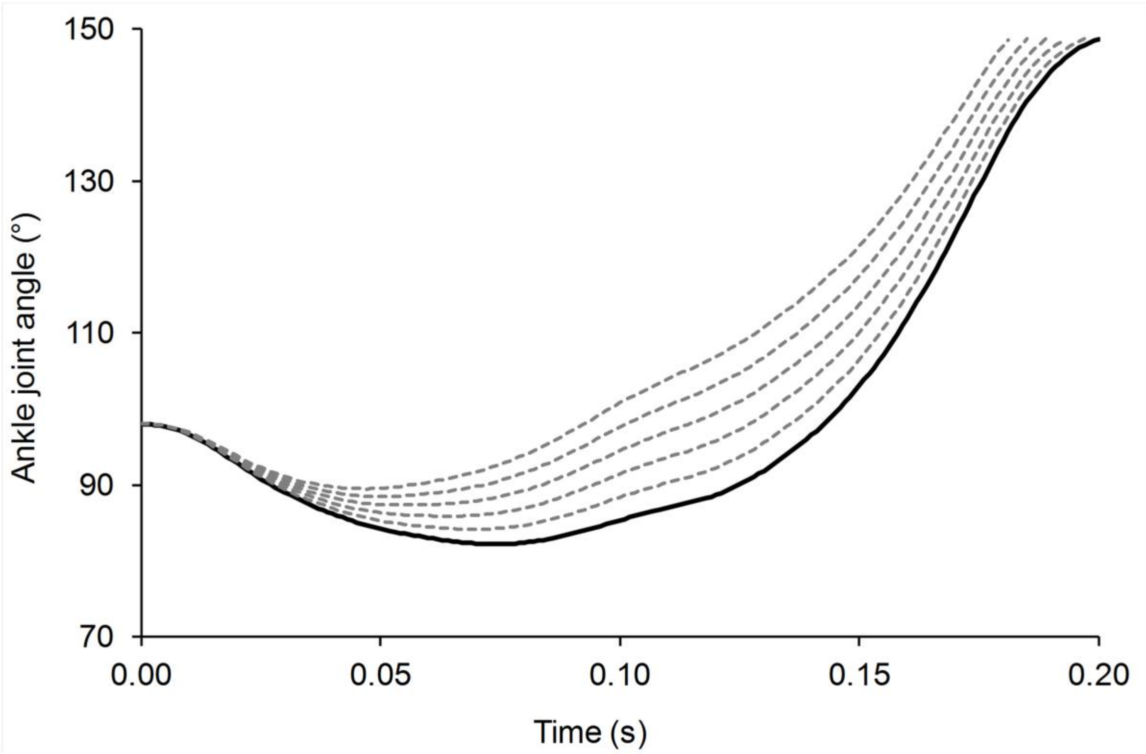

Figure 2. The ankle joint angle time histories from the matched optimisation (solid black line) and each of the five simulations (dotted grey lines) after addition of the respective sine and cosine terms.

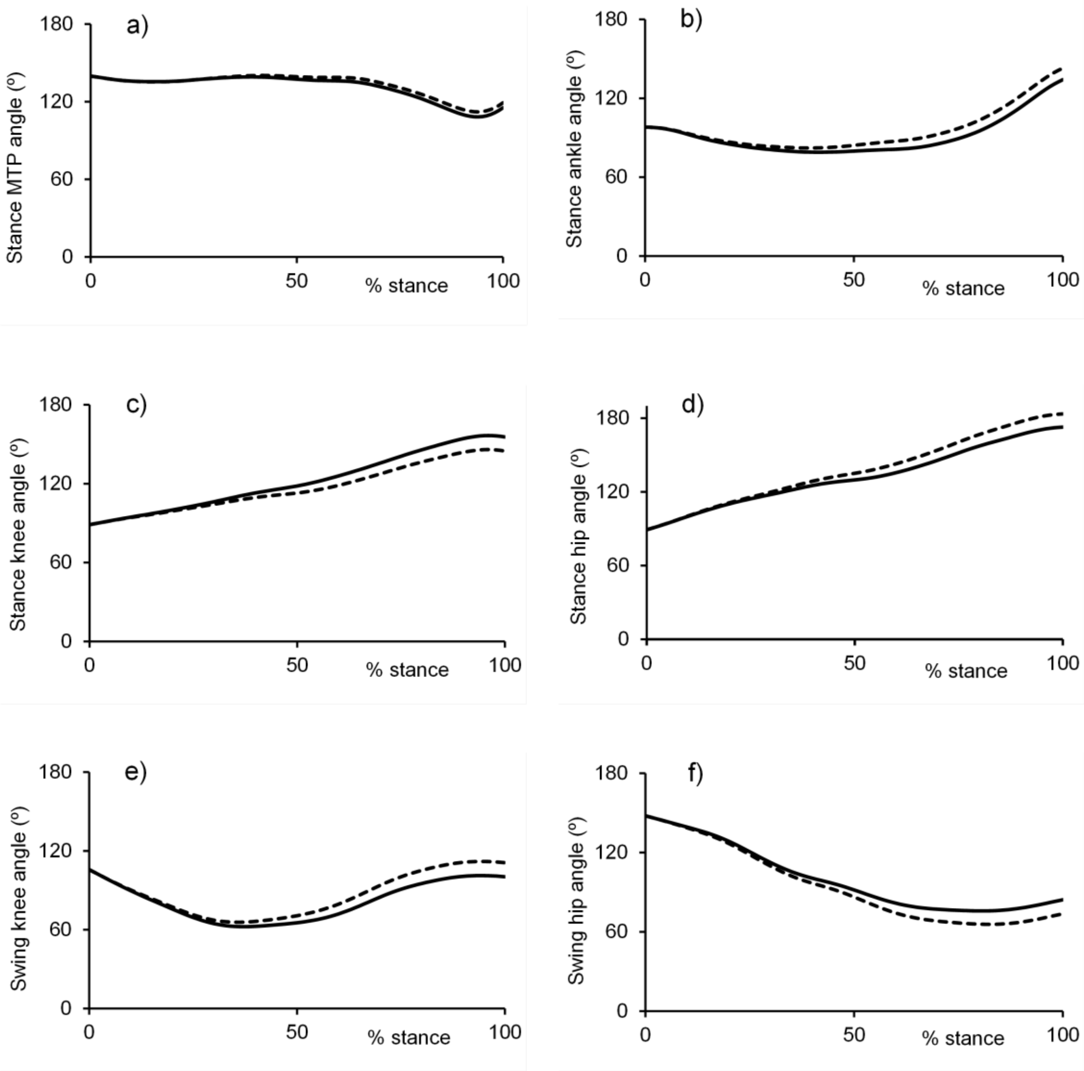

Figure 3a-f. Joint angle time histories for the six angle-driven joints from the matching optimisation (empirical data = solid line, model data = dotted line).

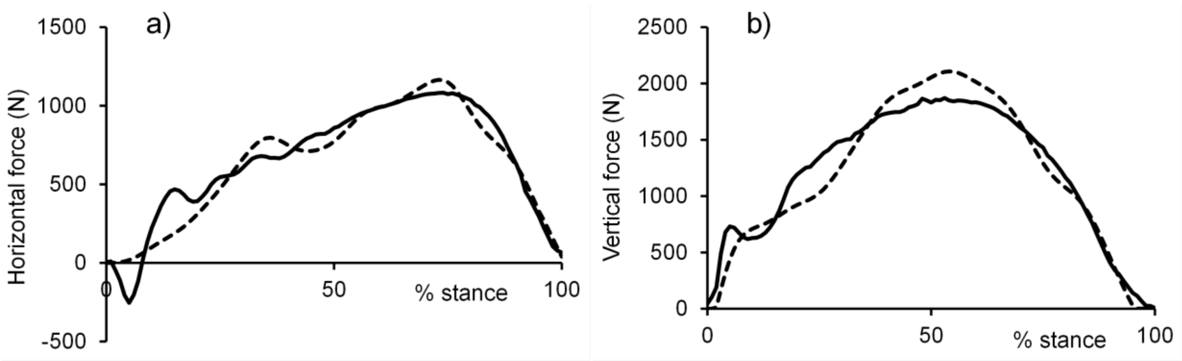

Figure 4a-b. Horizontal (a) and vertical (b) ground reaction force time-histories from the matching optimisation (empirical data = solid line, model data = dotted line).

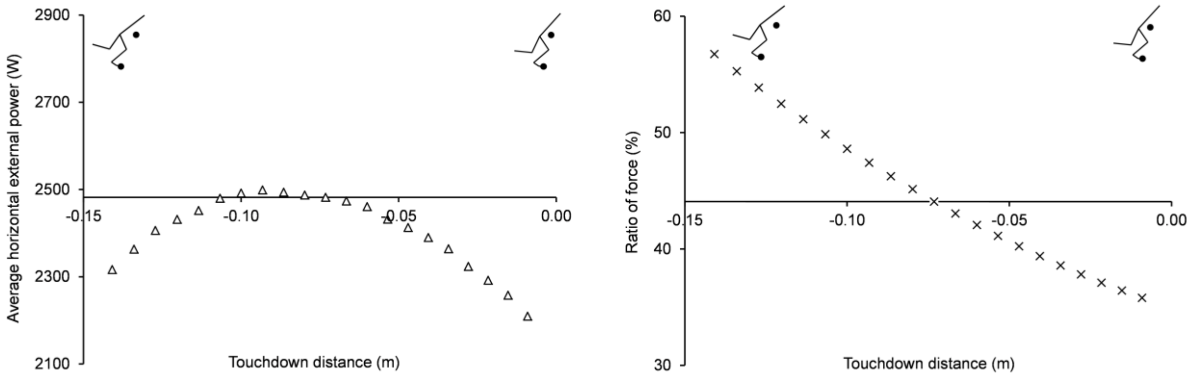

Figure 5. The effect of simulated changes in touchdown distance on (a) average horizontal external power. and (b) ratio of force. The stick figures provide illustrations (not to scale) of the positions of the centre of mass and MTP joint, the horizontal distance between which is the touchdown distance (i.e. a greater negative value represents the stance toe further behind the CM at touchdown).

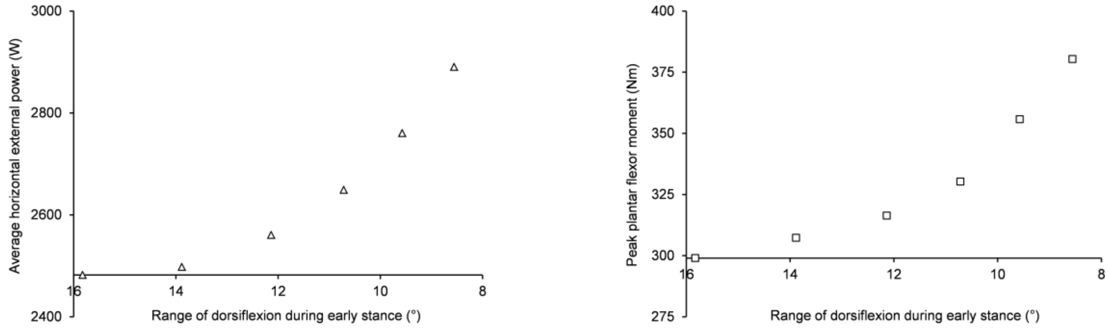

Figure 6. The effect of simulated changes in ankle joint dorsiflexion during early stance on (a) average horizontal external power and (b) and peak resultant plantar flexor moment.