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The influence of swing leg motion on maximum running speed

--Manuscript Draft--

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Abstract:	The motion of the swing leg of elite sprinters at maximum speed is markedly different from that of slower sprinters, but the mechanisms by which this influences performance are unknown. The aim of this study was to use a computer simulation model to establish whether and, if so, how the motion of the swing leg influences maximum achievable running speed. A seven-segment planar computer model was constructed to simulate the stance phase of sprinting. Optimisation was used to maximise the running speed of the model using two different swing leg techniques, one representative of an elite sprint athlete, and the other of a college athlete. The maximum speed of the model increased when using the swing leg technique of the elite athlete compared with the technique of the college athlete (10.0 m.s $^{-1}$ vs 9.2 m.s $^{-1}$). This improvement in performance was due to greater horizontal displacement of the mass centre during stance (0.867 m vs 0.837 m), and an increase in average vertical ground force of 90 N (0.1 bodyweights). The increase in vertical force was due to a larger impact peak caused by more negative vertical momentum of the stance leg at touchdown, and subsequently greater torques in the joints of the stance leg which were placed in faster eccentric contractions and at angles closer to optimum during the first half of stance. It is likely that the swing leg technique contributes to the asymmetrical vertical ground reaction force traces observed in elite sprinters.

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FAO: Professor Farshid Guilak: Editor

I enclose a manuscript entitled "The influence of swing leg motion on maximum running speed" for publication as a Full Length Article in the Journal of Biomechanics. Both authors have made substantial contributions to all of the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted. The authors received no writing assistance. The manuscript, including related data, figures and tables has not been previously published and is not under consideration elsewhere.

Yours sincerely

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Referee Suggestions

For the manuscript entitled, “The influence of swing leg motion on maximum running speed”, submitted for publication in the Journal of Biomechanics the following would be suitable referees:

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Responses to reviewers

We would like to thank both reviewers for taking the time to review the paper, and for their constructive comments which have allowed us the improve the article, we have addressed each of your comments individually below. A manuscript with marked changes in red is included.

Reviewer #1: General Comments
The manuscript examines two different techniques of maximal sprinting, highlighting a technique change which could lead to performance enhancement. A model is used to determine the key factors, although some more analysis with the model could revealed more detail about the mechanism for enhancement.
We would be happy to add more details, but believed that the mechanisms by which performance was improved had been explained and quantified (e.g. lines 260-300). We hope that the responses to your specific comments below have clarified this, but please let us know if there is specific information you think should be added.

There is a parsimonious description of the joint actuators (lines 160-163), so the uninformed will not know what these are comprised of. Could the author present more model details, including model parameters in an appendix (supplemental material). This model of the net actions at the joints does not include a series elastic component, could such a model component have influenced your results?
More details have been included on the torque generator components and parameters in supplementary material. Torque generators did include series elastic components, please see lines 155-156.

Specific Comments
Line 25, Comment - "...the mechanism by which this difference influences...".
This has been changed.

Line 39, Comment - here and elsewhere mention is made of the asymmetric ground reaction force, but it is unclear why this is so important. For example, the vertical ground reaction force during walking is asymmetric but there is no swing leg, what is it about this asymmetry that is considered important?
This refers to the results of Clark and Weyand (2014) who found that the vertical ground force peak was earlier and larger in competitive sprinters than in non-sprint athletes who exhibited more symmetrical ground reaction forces, conforming to the predictions of a single spring-mass model. It is not necessarily the asymmetry of the waveform which is important per se, if the required impulse could be achieved with a symmetrical waveform this may also be effective, but it is a consistent feature of the technique of elite sprinters, so presumably it is not possible to achieve the same impulse with a symmetrical waveform and for this reason it is important. Some more explanation has been added to the introduction (lines 67-70).

Line 32, Comment - world wide in 2019 a 10.50 s 100 m would not rank in the top 800, I am not sure this is really elite.
The swing leg techniques were taken from an elite sprinter (Olympic 100 m finalist) and a sub-elite athlete to compare a genuinely elite athlete with one of a lower standard who exhibited a swing leg technique which differed visibly from those associated with elite athletes (lines 135-142). The model evaluation was carried out using data from the athlete you refer to above who was a highly trained sprinter, but as you say not quite elite. To highlight this further, the data collection section has been split into laboratory data collection (2.2) and the swing leg technique data collection (2.3). This has been further highlighted in the evaluation (Lines 178-179) and optimisation (Lines 205-206) sections.

Also the graphs have been altered so each case (laboratory data, matched simulation, and each optimised simulation) has a distinct line type associated with it.

Lines 50-68, Comment - you are drawing conclusions from studies which did two different things. Weyand et al. (2000) examined subjects running at their maximum speed, while Dorn et al. (2012) has their subjects run at four different speeds.
Although the focus of the Weyand et al. (2000) paper was on maximum speed sprinting, they also presented data which describes how stride length and frequency alter as speed increases (Fig 2, p. 1993).

Lines 50-68, Comment - Throughout this paragraph it is unclear if you are referring to maximum speed sprinting, or sprinters running at sub-maximal speeds. Could you edit to be clear what you are referring to.
The first half of the paragraph (lines 50-59) describes how technique changes with increasing speed for an individual runner up to the point at which maximum speed is reached. Words have been added to make this more explicit.

Line 128, Comment -a low-pass filter passes the frequency below a cut-off not above.
In this sentence 'above' referred to the filter, not the pass. This has been re-worded to avoid confusion.

Lines 130-132, Comment - was treadmill belt speed constant for these six strides?
Yes, the treadmill speed was constant for the duration of a trial.

Lines 145, Comment - for the swing leg did the shank component actually comprise the shank and foot as one segment?
The foot was omitted since the additional mass and inertia were low and likely to have a negligible effect on the results.

Lines 171-172, Comment - which parameters? The appropriateness of scaling using body mass depends on the parameters, but these are not presented.
Thank you for spotting this, it should have specified that CC torques (e.g. the overall outputs of the torque generators) was scaled, alongside series elastic component stiffness, this has been added to the text (Lines 172-175).

Lines 183-187, Comment - "squared differences" were presumably weighted not the differences, can you be explicit. Were other weighting schemes used? If so, did they give appreciably different results?
This has been changed to 'components' to avoid any potential for confusion (lines 186-187), since the components are defined previously.

Other weighting schemes were experimented with, but weighting the joint angles more heavily for instance resulted in a poorer match to performance outcomes (e.g. swing time, horizontal velocity), which were deemed to be important.

Lines 192-196, Comment - for the those unfamiliar with the simulated annealing algorithm a few words to orientate the reader to meaning of step length and temperature in this context would be useful.
Information has been added here (Lines 194-196).

Line 205, Comment - did the simulated annealing vary the activation parameters or determine them?

The parameters were varied by the algorithm until the acceptance criteria were met, at which point it could be considered to have determined them. This portion of the paragraph has been re-ordered to make this explicit (Lines 209-216).

Line 280, Comment - you have enough information in your model to assess the contribution of the swing leg to the ground reaction force, could you please provide some stronger evidence to support this statement.
As indicated in the response to the general comment above, we believed we had provided strong evidence for the effect of the swing leg technique on the ground force. If the initial statement seemed equivocal it was not because the model results are equivocal. The results clearly show that the swing leg technique altered the modelled vertical ground reaction force during the first half of stance due the mechanisms detailed in the discussion up to this point (Lines 260-282). We did not want to state unequivocally that the swing leg technique altered the shape of the ground force in sprinters 'in vivo' since this is a theoretical finding, although the model shows a mechanism by which it can and it would seem very likely that it does, so the wording has been changed to reflect this (Line 283). If there is evidence you think should have been provided which was not, please let us know what this is and we will be happy to add it.

Line 281, Comment - what aspect of asymmetry are you assigning here?
This referred to an increased ground force during the first half of stance, words have been added to the manuscript to clarify this (Line 285).

Line 302-304, Comment - it could also be the case that they need to activate these muscles more, so it not a strength issue but a coordination issue. To be able to make this statement you need examine the degree of activations in your model.
The swing leg in the model was angle-driven, and therefore did not have activation profiles. So, we could not investigate whether the different swing leg techniques were due solely to coordination differences or whether increased strength was also necessary. Additionally, the mechanical demands on the swing limb are greatest when generating angular momentum during flight (Dorn et al., 2012), and since the focus of this article is on the effect of the swing leg during stance, this was not captured in the simulations. However, as per the first half of the paragraph, it has been shown that the mechanical demands on the swing limb increase superlinearly with running speed and that elite sprinters have disproportionally large muscles which flex and extend the hip and flex the knee, so it would seem likely that training to increase the size and strength of these muscles would be beneficial, alongside technical training for coordination. Hence, we proposed both technical and strength training.

Line 306, Comment - compliance residing where?
The model is rigid but all body tissue: skin, muscle, fat, bone etc. is compliant to some extent. 'body tissue' has been added to the manuscript to clarify (Line 313).

Line 324, Comment - earlier you state these strength parameters were taken from a singe athlete, here you refer to athletes, which is it?
Strength parameters were taken from a single athlete and scaled to the athlete measured for this study (described in section 2.2). Different athletes in this case referred to the three separate athletes from which strength (1) and swing leg techniques (2) were taken. 'Different' has been changed to 'other' (Line 333).

Line 327, Comment - it not clear why the first-person plural personal pronoun is used here.
This has been removed (Line 333).

Lines 336-327, Comment - you did not determine what the muscles were doing specifically as you grouped functional groups into torque actuators at each joint. Therefore, you cannot comment in this way about the muscles being closer to their optimum lengths, presumably your torque actuators were closer to the angle at which they can produce their peak torque but this is not the same thing.
It is true that increases in torque were due to torque generator contractile components being at more advantageous angles and we can only speculate that this is likely to correspond to the muscles being at more advantageous lengths. The wording has been changed to remove reference to muscles (Lines 341-342).

Line 340, Comment - it not clear why the first-person plural personal pronoun is used here.
This has been removed (Line 345).

Line 343, Comment - you seem to be assuming the arms swing contributes to an increase in ground reaction force, the basis for stating this are not clear.
The basis for this was the mechanism by which the leg swing increased ground force in this study, and the previous investigations cited in the introduction (lines 88-103) which have found the arm swing to augment ground reaction forces during jumping.

Lines 424-425, Comment - could you provide more information for this reference.
Apologies for this oversight. Information has been added here, and the year has been amended from that in the thesis document to the date the degree was awarded as per the university website (Lines 431-432).

Figures 2 and 5, Comment - "Visual" is not needed in the figure legends.
This has been removed (Lines 449 and 453).

Reviewer #2: General Comments
This paper examined the importance and influence of leg swing motion on maximum speed running. The paper has a strong theoretical rationale given the theoretical limit that minimalizing swing time has on maximum speed. Additionally, this topic relevant to current research on maximum speed running and adds greater understanding and practical insights on how maximum speeds are achieved in human sprinting. The paper is generally very well written and structured but there are some aspects where minor corrections are required or greater clarity could be provided. These are described in the specific comments below.

Specific Comments

ln 60-68: You establish a very good rationale for the study here and link this to published work.
Thank you.

ln 89: In a vertical jump, (missing comma)
This has been added (Line 91).

ln92-93: "caused by a downwards reaction force..". I have some difficulty with this description. I am assuming the reaction force here is the ground reaction force and you describe how the arm swing augments the ground reaction force which in response augments the force of the extensor muscles. However the ground reaction force would tend to act upwards on the sprinter or predominantly upwards, so for me the idea of a downwards reaction force does not seem accurate (assuming this is coming from the ground). Can you please revisit this and clarify.

In this case, the downwards reaction force was from the arms to the torso via the shoulder joint, this has been clarified in the text (Line 95).

ln98-102: this example convinces me that the reaction force is from the ground and is generally acting upwards (predominantly upwards).
Yes, the theory is that the leg swing would increase vertical ground reaction force via the mechanisms outlined in the first half of this paragraph.

ln115: Minor point but why use the abbreviations ET and CT for elite athlete and College athlete.... nothing wrong really but the abbreviations are not really intuitive.
ET and CT corresponded to Elite athlete Technique and College athlete Technique respectively, but this may not have been clear from the description. The college athlete is now referred to as 'sub-elite' and new abbreviations for the swing leg techniques of the elite (SLT_E) and sub-elite (SLT_{SE}) athletes have been defined (Line 116) and used throughout the manuscript.

ln 113: You used an 80 N threshold to identified a temporal event, how do you cope with the delay in identifying the event caused in the force reaching 80 N? Perhaps you have evidence that such delays are not important?
Force rises very quickly during initial contact (~270 N within 0.001 s) so identifying touchdown with an 80 N threshold would result in a delay of only 0.5 ms when using a 2000 Hz sample rate which we considered negligible.

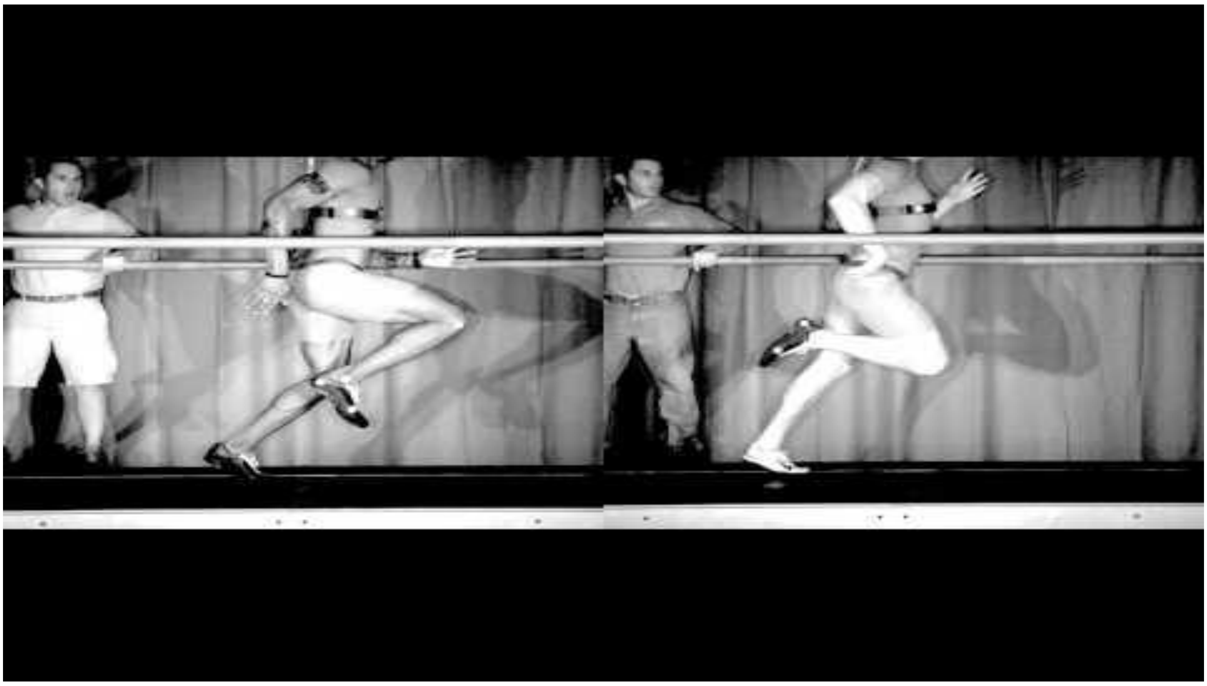
ln211 and figures: The captions are generally unclear (perhaps minimalistic) and could be improved to provide enough detail to help interpret tables and graphs without excessive relating to the main body text.
We did revisit these captions, but were unable to identify which information was unclear, if you could indicate which you feel are unclear and what they are missing we would be happy to amend them.

ln 301-304: I really like the inclusion of this sentence describing the practical relevance of the outcome of this study, however the phrase "devote time to technical and strength training associated with the swing phase of running" is vague. Many readers of JoB may not be able to translate this into specific exercise examples. If you could consider an example of what this would mean in a practical sense, I think it would help convey the practical relevance an a more concrete way. Are you suggesting for example exercises like resisted kicking movements?
Although we are not experts in strength and conditioning, it would seem intuitive to train the leg using open chain resistance exercises, with the body in a similar configuration to that used during sprinting, to ensure similar muscle lengths. A general recommendation has been added to the manuscript text (Lines 308-311) in the expectation that interested parties will be able to design appropriate protocols.

ln318-321 and figures: The fact that hip flexor activation and hip extensor relaxation at late stance phase did not occur in this simulation is a source of concern here since these muscle sequences are fundamental to sprint running. I think you are correct to highlight the idea that this had less impact on the ET than the CT which suggests the model is more suited to the ET.
As neither optimisation required the hip flexors to activate, this should not affect the study conclusions, especially since the main differences between sprinters and non-sprinters occur in the first half of stance. As described in the manuscript, the relative improvement when using ET is likely to increase with the inclusion of this factor as the ET hip extensor torque already decayed more during the latter portion of stance, whereas the CT model maintained a higher hip extension torque until toe-off (Figure 6). Words have been added to the manuscript to clarify these points (Lines 327-333).

The stick figure sequence in figure 4 (bottom) showing the simulated CT sequence demonstrates very poor sprint technique. I am not clear whether this is the result of the simulation or whether the CT had poor technique anyway?

The swing leg motion of the model using the sub-elite athlete's technique reflected the technique used by that athlete, see the image from the video below (elite sprinter on the left and sub-elite athlete on the right). The stance leg technique was chosen by the simulated annealing algorithm to maximise running speed with each swing leg technique.



In figure 2 you provide visual representations of the participant and the matched simulation but you did not state whether this was the ET or CT. Given the differences in performance of the model on ET and CT, I think you need to clarify which participant was illustrated in figure 2 (improve caption).

The matched simulation is neither ET nor CT, this was based on the experimental data described in lines 118-133. The purpose of this process was to evaluate the model before moving on to optimise performance with each of the two contrasting swing leg techniques displayed in the image above. A clarification of which swing leg technique was being used in each process has been added to the evaluation (Lines 178-179) and optimisation (Lines 205-206) sections of the methods.

ln 325: "In this regard" is verbose, perhaps "Since the aim..."

This has been altered (Lines 333-334).

Ln 332 -333: you can omit this first sentence of the conclusion, the reader will know the aim of the study by this point.

This has been deleted.

The influence of swing leg motion on maximum running speed

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Abstract

The motion of the swing leg of elite sprinters at maximum speed is markedly different from that of slower sprinters, but the mechanisms by which this difference influences performance are unknown. The aim of this study was to use a computer simulation model to establish whether and, if so, how the motion of the swing leg influences maximum achievable running speed. A seven-segment planar computer model was constructed to simulate the stance phase of sprinting. Optimisation was used to maximise the running speed of the model using two different swing leg techniques, one representative of an elite sprint athlete, and the other of a sub-elite athlete. The maximum speed of the model increased when using the swing leg technique of the elite athlete compared with the technique of the sub-elite athlete (10.0 $m.s^{-1}$ vs 9.2 $m.s^{-1}$). This improvement in performance was due to greater horizontal displacement of the mass centre during stance (0.867 m vs 0.837 m), and an increase in average vertical ground force of 90 N (0.1 bodyweights). The increase in vertical force was due to a larger impact peak caused by more negative vertical momentum of the stance leg at touchdown, and subsequently greater torques in the joints of the stance leg which were placed in faster eccentric contractions and at angles closer to optimum during the first half of stance. It is likely that the swing leg technique contributes to the asymmetrical vertical ground reaction force traces observed in elite sprinters.

Keywords: computer simulation, sprinting, optimisation, technique

1. Introduction

Maximal running speed in humans demonstrates great variability, Weyand et al. (2000) measured maximum speeds ranging from 6.2 to 11.1 $m.s^{-1}$ in a group of thirty three physically active men and women, and speeds of over 12 $m.s^{-1}$ have been recorded by elite male athletes in competition (Graubner and Nixdorf, 2011). This prompts the question of what allows some humans to run so much faster than others.

Running speed is the product of step length and step frequency and therefore faster speeds can be attained by increases in either or both. For an individual runner it has been observed that, at relatively low speeds, speed is increased primarily by increasing step length (Weyand et al., 2000; Dorn et al., 2012). The runner achieves this via increases in vertical ground forces which lead to increased vertical impulses and consequently flight times (Weyand et al., 2000; Dorn et al., 2012). At relatively higher speeds, the capacity to apply vertical ground forces plateaus and briefer stance times result in reduced vertical impulses and flight times; increases in speed after this point are due primarily to increases in step frequency, which continue until the maximum speed of the runner is reached (Weyand et al., 2000). Running speed is therefore theoretically limited by the ability to produce vertical ground force during brief stance times and the minimum swing time during which the limb can be repositioned for its subsequent stance phase. Weyand et al. (2000; 2010) showed that in humans it is the size of the vertical ground forces that differentiates between faster and slower runners, rather than the minimum swing time, which is similar for all runners at their top speeds. Furthermore it has subsequently been shown that it is not just the magnitude of the vertical ground force that differentiates between faster and slower runners, but also the shape of the vertical ground force-time graph where sprinters exhibit larger and earlier peaks in the first half of stance but do not differ from non-sprint athletes - who exhibit more symmetrical vertical ground force waveforms - during the second half of stance (Clark and Weyand, 2014).

Clear differences exist between the techniques of faster and slower sprinters, particularly in relation to the swing leg; the hip angle of the swing limb at touchdown of the contralateral leg has been shown to differentiate between elite and sub-elite sprinters and to be the largest single kinematic predictor of maximum running speed, despite exhibiting no differences in angular displacement and angular velocity throughout the stride (Sides, 2015). Trained sprinters exhibit a more flexed hip throughout the first half of swing, resulting in the thigh of the swing leg being closer to vertical at touchdown of the contralateral leg and closer to horizontal at contralateral toe-off (Kunz and Kauffman, 1981; Mann and Herman, 1985; Bushnell and Hunter, 2007; Sides, 2015). Furthermore, as running speed increases, the mechanical demands on the muscles of the swing leg, mainly at the hip, substantially increase, whereas those on the muscles of the stance leg plateau (Dorn et al., 2012; Schache et al., 2015) and it has been shown that muscle volumes of the hip flexors and extensors are extremely large in sprinters when compared with controls (Handsfield et al., 2017, Miller et al., 2020). These results indicate that, although the time taken to reposition the limb at maximum speed is similar in faster and slower runners, the kinematics and kinetics of the limb during this portion of the stride are different.

It has been shown that the motion of the swinging limbs can improve performance in standing (Harman et al., 1990; Ashby and Delp, 2006; Cheng et al., 2008; Domire and Challis, 2010) and running jumps (Dapena and Chung, 1988; Allen et al., 2010). In a vertical jump, an arm swing can improve performance by increasing the height and velocity of the whole-body centre of mass (CoM) at takeoff (Cheng et al., 2008; Domire and Challis, 2010). The increase in takeoff velocity caused by the arm swing is partly due to energy imparted directly to the CoM and partly caused by a downwards reaction force at the shoulder joint which augments the force of the extensor muscles of the stance legs by putting them in faster eccentric or slower concentric conditions (Cheng et al., 2008; Domire and Challis, 2010). The performance requirements of maximum speed running are different to vertical jumping in that the athlete is not attempting to maximise vertical velocity but to achieve sufficient vertical velocity to allow adequate flight and hence swing time to reposition the limb. However, it is conceivable that runners could use their swing leg to increase vertical ground force in the same way as an arm swing in vertical jumping, and therefore achieve the requisite vertical impulses during briefer stance phases, facilitating higher running speeds.

Despite the observed differences in technique between faster and slower runners and this theoretical rationale, there has been limited consideration of the effect swing leg motion might have on maximum running speed. Therefore, the aim of this study was to use computer simulation to investigate the influence of swing leg motion on maximum achievable running speed.

2. Methods

2.1. Study design

A computer model was developed to simulate the stance phase of sprinting. Optimisation was used in two ways: to evaluate the capacity of the model to match performance data collected on a sprinter; then to maximise the running speed of the model using two different swing leg techniques, one representative of an elite athlete (SLT_E), and the other of a sub-elite athlete (SLT_{SE}).

2.2. Laboratory data collection

Following Loughborough University Ethics Approvals (Human Participants) Sub-Committee guidelines and having given informed consent, a male athlete (28 years, 91.1 kg, 1.86 m, 100 m personal best time: 10.50 s) sprinted at 9.7 $m.s^{-1}$ on an instrumented treadmill (3DI, Treadmetrix, Utah, USA) recording three-dimensional ground reaction forces (2000 Hz). Sixty-five retroreflective markers were placed on the participant, and their positions were recorded (250 Hz) using sixteen infrared cameras (Vicon Vantage, Oxford Metrics, Oxford, UK), synchronised with the force data. A custom Vicon BodyBuilder model, composed of the head and trunk, upper and lower arm, thigh, shank, rearfoot, and toes, was written to extract segment and joint angles. Further analysis was performed in MATLAB (R2020a, Mathworks, MA, USA).

Kinetic and kinematic data were low-pass filtered with cut-offs of 50 Hz and 15 Hz respectively, using a fourth-order zero-lag Butterworth filter, interpolated, and resampled on the same time base at 1000 Hz using cubic splines. Six full strides on each leg were time normalised then averaged across strides and between legs to give representative data on one full stride at top speed. Contact was identified using an 80 N threshold in vertical force.

2.3. Swing leg technique data collection

To determine the effect of different swing leg techniques, a publicly available video of an elite athlete and a sub-elite athlete running at their respective top speeds was used (LocomotorLabSMU, 2012), as it illustrated typical differences in technique, with the hip joint of the elite athlete more flexed throughout stance. The hip, knee, ankle, and metatarsophalangeal (MTP) joint centres along with a point at the base of the neck representing the top of the trunk, were digitised using the open-source package

DLTdv7 (Hedrick, 2008). Segment and joint angle time histories were calculated, and quintic smoothing splines were fitted to these time histories.

2.4. Computer model

A seven-segment planar computer model was constructed to simulate the stance phase of sprinting (Figure 1). The seven segments comprised: the thigh, shank, rearfoot, and toe of the stance leg; the thigh, and shank of the swing leg; and a combined head, arms, and trunk (HAT) segment, containing the mass of the rest of the body. Segments were represented as one-dimensional rigid rods, except for the rearfoot which was two-dimensional, and were connected by frictionless pin joints. The foot-ground interface was modelled using horizontal and vertical spring-dampers situated at the MTP joint and the end of the toe (Allen et al., 2012).

*** insert Figure 1 here ***

The hip, knee, and ankle joints of the stance leg were actuated by mono-articular flexion and extension torque generators, representing the contractile components (CC) of the muscle-tendon units crossing the joint, in series with a rotational spring, representing the series elastic components (SEC). The MTP joint was actuated by a rotational spring-damper. The hip and knee joints of the swing leg were angle-driven using experimental data. To represent the arm swing, the position of the CoM of the HAT segment relative to the hip was also kinematically driven using experimental data.

The torque produced by each torque generator was a product of activation level (Yeadon and Hiley, 2000), and torque-angle (Forrester et al. 2011) and torque-angular velocity (Yeadon et al. 2006) relationships of the contractile component (see supplementary material for more details).

System equations of motion were formulated using Autolev (Kane and Levinson, 1985) and output as Fortran code. Inputs to the model were the initial conditions, representing CoM position and velocity and segment angles and angular velocities, and parameters specifying the activation of each torque generator as a function of time. The equations of motion were integrated forwards using a fourth order Runge-Kutta algorithm with a variable timestep.

Segmental inertia parameters were obtained from a previous data collection on the same participant (McErlain-Naylor, 2017). Torque generator parameters were taken from a previous study on a triple jump athlete (Allen, 2009), and CC torques and SEC stiffnesses were scaled linearly to body mass. Viscoelastic parameters were determined via optimisation (see Section 2.5). Model parameters are provided in the supplementary material.

2.5. Model Evaluation

The model was evaluated by minimising the difference between simulation output and experimental data collected on the participant. The swing leg was angle-driven using joint angle time histories from laboratory data. A simulated annealing algorithm, set to run in parallel (Higginson and Anderson, 2005), minimised a cost function by varying forty-two activation parameters, two MTP spring and eight contact spring parameters. The cost function comprised the sum of four components: the sum of the mean squared differences in hip, knee, ankle and MTP joint angle time histories; the mean squared difference in the global orientation angle time history; the absolute difference in horizontal CoM velocity; and the absolute difference in swing time. The orientation angle, CoM velocity, and swing time components were weighted one, two, and three orders of magnitude respectively higher than the joint angles component, with the aim of prioritising the match to the performance outcomes of swing time and horizontal velocity.

Flight time was calculated from the CoM vertical velocity at take-off and the difference in height of the CoM between take-off and touchdown using equations of constant acceleration. Swing time was the sum of two flight times and one stance time. Horizontal CoM velocity was the product of step length and step frequency.

The initial temperature for simulated annealing, which governed the likelihood of accepting a solution which was worse than the current one, was chosen to give an appropriately sized search space around trial points, so that roughly 50% of all function evaluations were accepted (Goffe et al., 1994) and the number of cycles before a temperature reduction was determined through preliminary tests aiming to minimise the computing time while still finding the optimum. All other parameters were left at their default values.

Viscoelastic parameters obtained from this evaluation process were used in all subsequent optimisations.

2.6. Model Optimisation

Optimisations were carried out to establish the maximum running speed achievable by the model whilst angle-driving the swing leg using joint angle time histories obtained by digitisation of each of the two techniques from video data (LocomotorLabSMU, 2012). To establish maximum running speed, initial horizontal velocity was incrementally increased by 0.1 $m.s^{-1}$ from the matched simulation whilst all other initial conditions remained the same. The model was considered capable of running at a given speed if the loss in horizontal velocity during stance was less than 0.01 $m.s^{-1}$ and the swing time from laboratory data was matched to within 0.001 s, bounds picked from the variation in the laboratory data. Swing time was kept constant as this has been shown to be similar for all runners at their top speeds (Weyand et al., 2000). After each velocity increment, forty-two activation parameters were varied by the simulated annealing algorithm until the acceptance criteria were met, and maximum speed was the highest speed at which the model could meet these conditions.

3. Results

3.1. Model Evaluation

The matched simulation showed good agreement with the laboratory data (Figure 2 and supplementary animations). Horizontal velocity (9.66 $m.s^{-1}$) was closely matched to the laboratory data (9.67 $m.s^{-1}$). The swing time matched exactly (0.374 s) however, stance time was shorter (0.091 s vs 0.110 s), and flight time was longer (0.141 s vs 0.132 s) than the laboratory data. Orientation and configuration angle time histories were all matched to within a root mean squared error (RMSE) of 5° or less (Figure 3). It was concluded that the model was sufficiently accurate to be used to explore the effects of technique on performance.

*** insert Figure 2 here ***

*** insert Figure 3 here ***

3.2. Model Optimisation

The maximum speed of the model when using SLT_{SE} was 9.2 $m.s^{-1}$ compared with 10.0 $m.s^{-1}$ when using SLT_E (Figure 4 and supplementary animations). Stance time was slightly shorter and flight time and vertical impulse slightly larger using SLT_E (Table 1). The vertical whole-body CoM displacement did not differ between the two techniques, but the horizontal displacement was greater with SLT_E (Table 1).

*** insert Figure 4 here ***

*** insert Table 1 here ***

Using SLT_E, the model produced an average of 90 N (0.1 bodyweights) more vertical ground force during stance. This increase was due to higher forces in the first half of stance, offsetting lower forces during the second half, giving a net positive effect (Figure 5). When using SLT_E, the initial vertical momentum of the stance limb was more negative (-32.1 $kg.m.s^{-1}$ vs -28.5 $kg.m.s^{-1}$) which led to a larger vertical impact force peak (Figure 5). Average extensor torques at the knee and ankle were higher using SLT_E, whereas the average extensor torque at the hip was lower (Table 1).

*** insert Figure 5 here ***

Activations of the stance leg torque generators were virtually identical in both techniques, with the hip and ankle extensors fully active and the flexors inactive for the duration of stance, resulting in net extension torques at these joints. Both the extensor and flexor torque generators were activated at the knee, leading to a period of net extension followed by flexion torques (Figure 6). As well as the extensor torque being higher with SLT_E, the average flexion torque was also lower, despite similar activations between techniques. This led to an even greater net extension torque during the first half of stance (Figure 6).

*** insert Figure 6 here ***

Angular velocities of the CC were more eccentric at the knee and ankle but more concentric at the hip with SLT_E (Figure 7). The higher eccentric CC angular velocities put the CC angle closer to its optimal position at the knee and ankle for the majority of stance (Figure 7).

*** insert Figure 7 here ***

4. Discussion

The results showed that a 0.8 $m.s^{-1}$ or 9% improvement in running speed can be gained solely from changing how the swing leg moves during stance (Table 1). The increase in speed was a result of an increase in the average vertical ground force of 90 N, or 0.1 bodyweights, allowing the necessary vertical impulse required to maintain swing time to be generated in a briefer stance phase (Table 1).

The vertical ground force impact peak was found to be larger when using SLT_E. It has been shown that the size of the vertical impact force peak during running can be accurately predicted using momentum changes of the lower leg (Clark et al., 2014). Since the vertical momentum of the whole-body CoM at touchdown remained constant for all simulations, the more positive swing leg momentum with SLT_E resulted in a more negative stance leg momentum and consequently a larger impact peak. This was a passive effect since stance leg joint torques did not differ during impact (Figures 5 and 6).

As activations of the torque generators were almost identical between the two techniques, the increases in torque following impact were due to CCs operating at angles closer to optimal and at faster eccentric or slower concentric angular velocities

(Figure 7). Faster eccentric CC angular velocities at the ankle and knee which placed the CC further up the ascending limb of the torque-angle curve were seen with SLT_E (Figure 7). The opposite was the case at the hip however as the higher concentric angular velocity of the extensor CC meant that torque was reduced (Table 1, Figure 7). As there was a net increase in vertical force with SLT_E, this is consistent with previous findings that the hip torque contributes little to the vertical ground force (Dorn et al., 2012).

When considered together, these model results indicate that swing leg motion can contribute to the asymmetrical vertical ground force patterns observed in sprinters, characterised by larger and earlier peaks in the first half of stance. The action of the swing leg increased ground force and stance leg torques mainly during impact and when the knee and ankle were operating eccentrically during the early part of stance (Figures 5 and 6), which is where the pattern of vertical force in sprinters differs substantially from the symmetrical pattern predicted by a spring-mass model and exhibited by non-sprint athletes (Clark and Weyand, 2014).

The vertical whole-body CoM displacement during stance was similar between techniques (Table 1). This was despite the CoM of the swing leg rising 7.3 cm with SLT_E but lowering 3.4 cm with SLT_{SE}. The positive vertical momentum of the CoM of the swing leg in SLT_E made the vertical momentum of the rest of the body more negative, delaying takeoff (Figure 4) and leading to a larger horizontal displacement of the whole-body CoM (Table 1). Prolonging stance results in a reduction in the required flight time and hence vertical impulse to maintain a given swing time. It is also possible that the increased hip flexion angle and gravitational potential energy of the swing leg with SLT_E will facilitate an increase in the negative vertical momentum of the limb and consequent impact force at the subsequent touchdown.

The mechanical demands on the swing limb required to achieve SLT_E were beyond the scope of this study, but joint torques and work done by the swing leg have been shown to increase superlinearly with running speed (Dorn et al., 2012) and the muscles which flex and extend the hip, and flex the knee, have been shown to be substantially larger in sprinters compared with controls (Handsfield et al., 2017, Miller et al., 2020). These findings, in addition to the results of this study, would suggest that athletes wishing to increase their running speed should devote time to technical and strength training associated with the swing phase of running. Strength training could take the form of open-chain resistance exercises of the hip flexors and extensors, and the knee flexors, with the body in a similar configuration to that employed during sprinting to ensure comparable muscle lengths throughout the movements.

The main limitation of the model was that it was unable to match stance time closely (Table 1). This is likely to be due to a lack of body tissue compliance in the model, which has been shown previously to result in briefer stance times in simulations of triple jumping (Allen et al., 2012). This also meant that the vertical ground reaction force rose unrealistically quickly, leading to higher forces than are typically observed in sprinters (Weyand et al., 2000). Nevertheless, the stance times were within the range of those reported in the literature (Sides, 2015) and the model was able to match performance outcomes well; since the aim was to compare two techniques these limitations should not affect the study conclusions. Another limitation of the briefer stance times was that the angle-driven joints did not complete the same movement amplitude as the performance, since they were functions of time, however since most of the differences occurred early in stance this is also unlikely to have affected the conclusions. The optimisations were not required to prepare the stance limb for its subsequent swing phase, and it has been shown in sprinters that the hip flexors activate, and the hip extensors relax during late stance (Bezodis et al., 2008) which was not observed in this study, but both optimisations were subject to the same constraints and therefore this should not affect the study conclusions, if anything including this constraint would be likely to affect the outcomes with SLT_E less since the hip torque decayed further during late stance in this simulation than with SLT_{SE} (Figure 6). Lastly, the model inertia parameters and the performance data were taken at different times from the same athlete, and the strength parameters and swing leg techniques were taken from other athletes, which may seem inconsistent. However, since the aim of this study was not to optimise the technique of one participant, but to compare the effects of contrasting swing leg techniques typically associated with faster and slower sprinters, model parameters only needed to be representative of a sprint athlete.

5. Conclusion

The results showed that using the swing leg technique of an elite sprinter can augment the vertical ground force passive impact peak by increasing the negative vertical momentum of the stance leg at touchdown, putting the joints of the stance leg in faster eccentric conditions, placing them closer to their optimum angles for torque production, and allowing more torque and vertical ground force to be produced in the early portion of stance, increase the horizontal displacement of the mass centre during stance, and ultimately increase the maximum running speed. Athletes aiming to increase their maximum running speed should devote time to training associated with the swing phase of running. Future work could investigate the effect of swing leg technique on the subsequent stance phase, and the contribution of the arm swing to increases in ground force.

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List of figure captions

Figure 1. Seven-segment model with viscoelastic springs under the MTP joint and toes. Open circles represent torque-driven joints. Filled circles represent angle-driven joints. Grey circle represents a viscoelastic rotational spring. Half-filled circle indicates torque- and angle-driven hip joints of the stance and swing leg, respectively.

Figure 2. Comparison between participant (top) and matched simulation (bottom). Circle represents whole-body CoM.

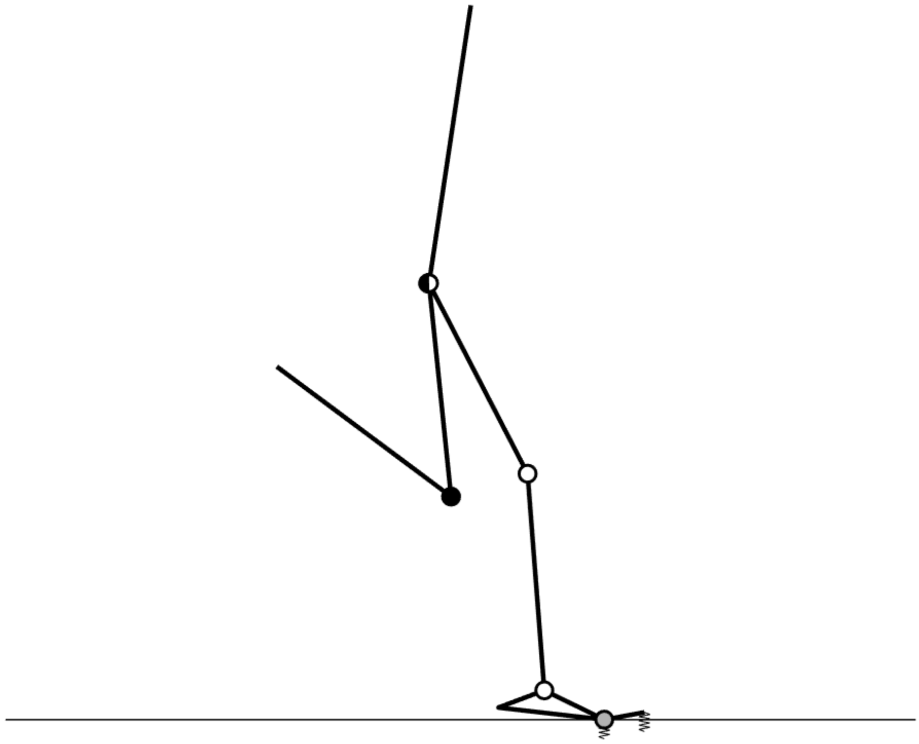
Figure 3. Orientation and configuration angles of the participant (dash-dot line) and matched simulation (dotted line) techniques.

Figure 4. Comparison between optimised simulations using SLT_E (top) and SLT_{SE} (bottom). Circle represents whole-body CoM.

Figure 5. Vertical force in optimised simulations using SLT_E (solid line) and SLT_{SE} (dashed line).

Figure 6. Stance leg net joint torques in optimised simulations using SLT_E (solid line) and SLT_{SE} (dashed line). Extension torques are positive.

Figure 7. Angle and angular velocities of the CC in optimised simulations using SLT_E (solid line) and SLT_{SE} (dashed line) superimposed on the normalised tetanic torque-angle-angular velocity surface for each extensor torque generator. Positive angular velocities represent eccentric contractions. Stars represent touchdown.



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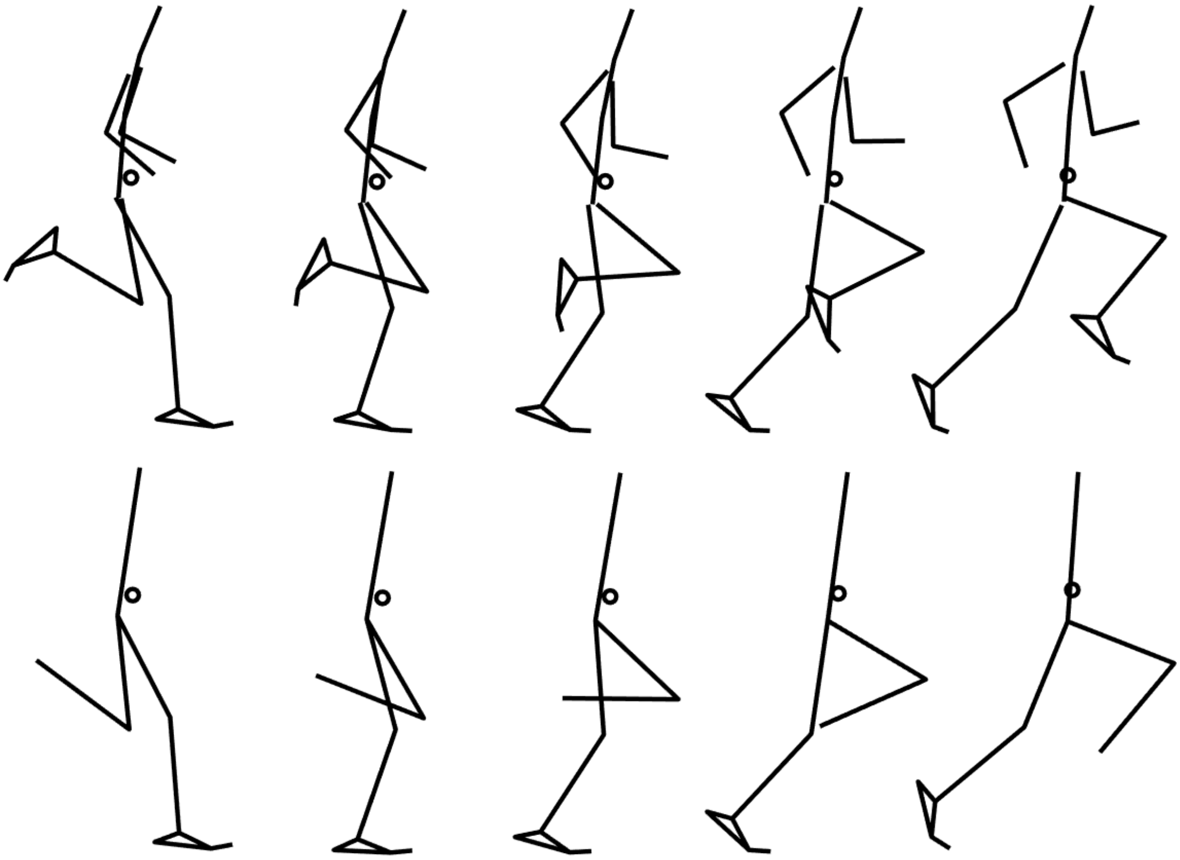
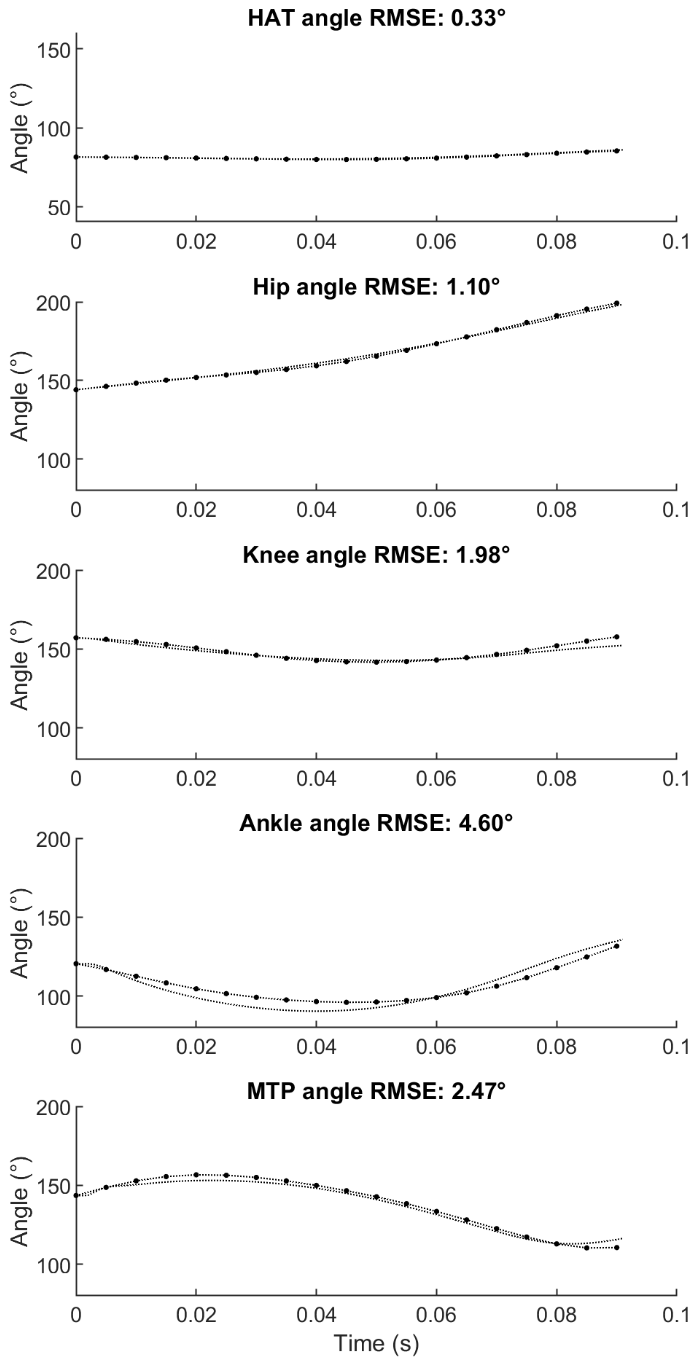


Figure 2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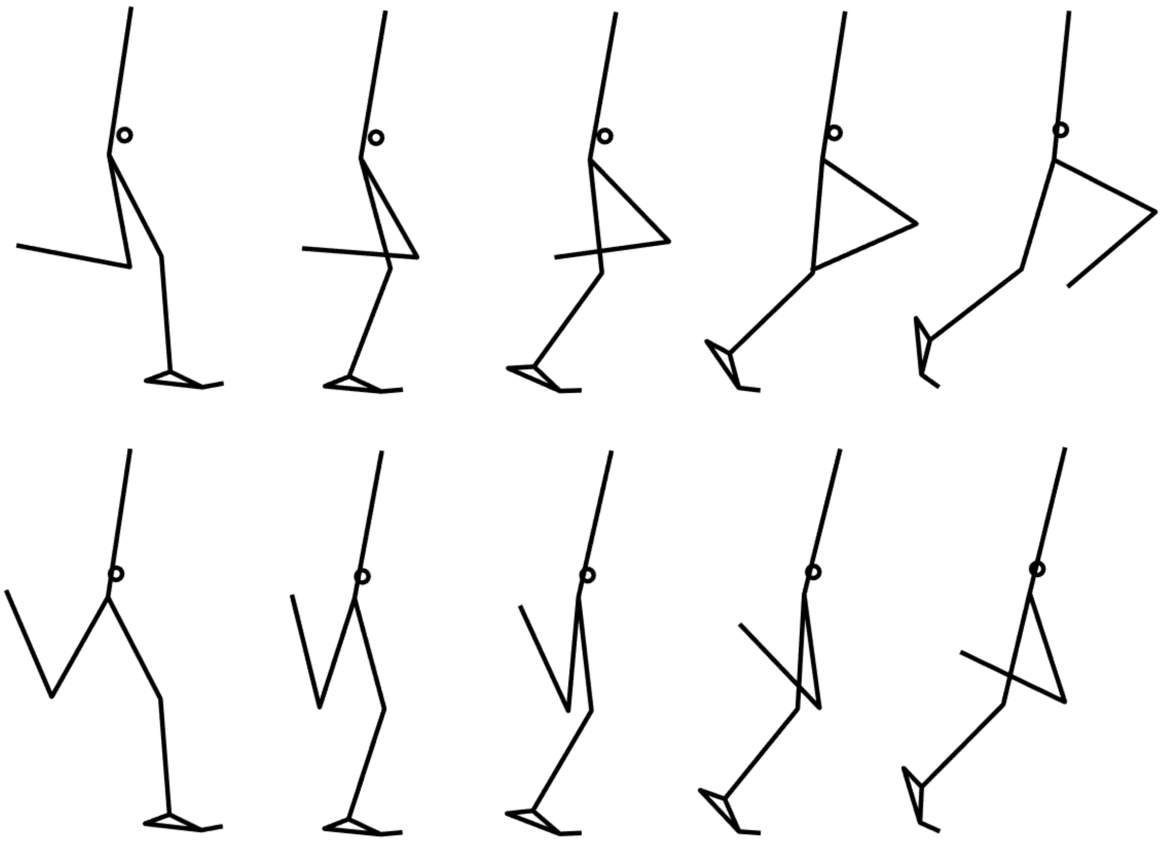
Hip angle RMSE: 1.10°
Knee angle RMSE: 1.98°
Ankle angle RMSE: 4.60°
MTP angle RMSE: 2.47°
Angle (°)
Time (s)
50
100
150
200
0
0.02
0.04
0.06
0.08
0.1

Figure 3



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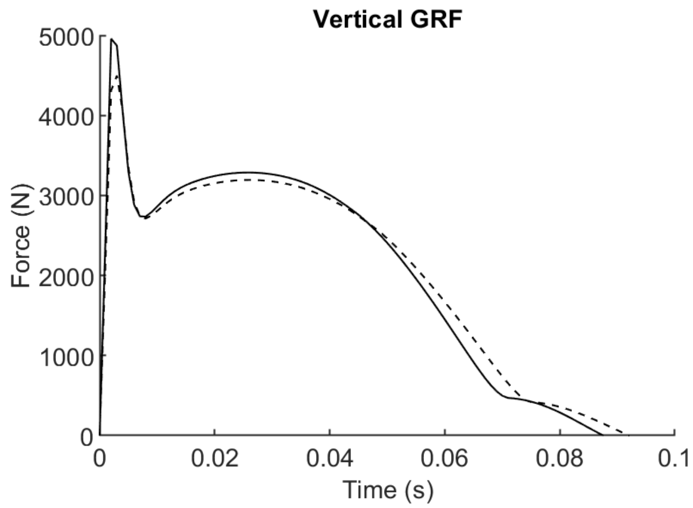
Vertical GRF
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4000
3000
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Force (N)
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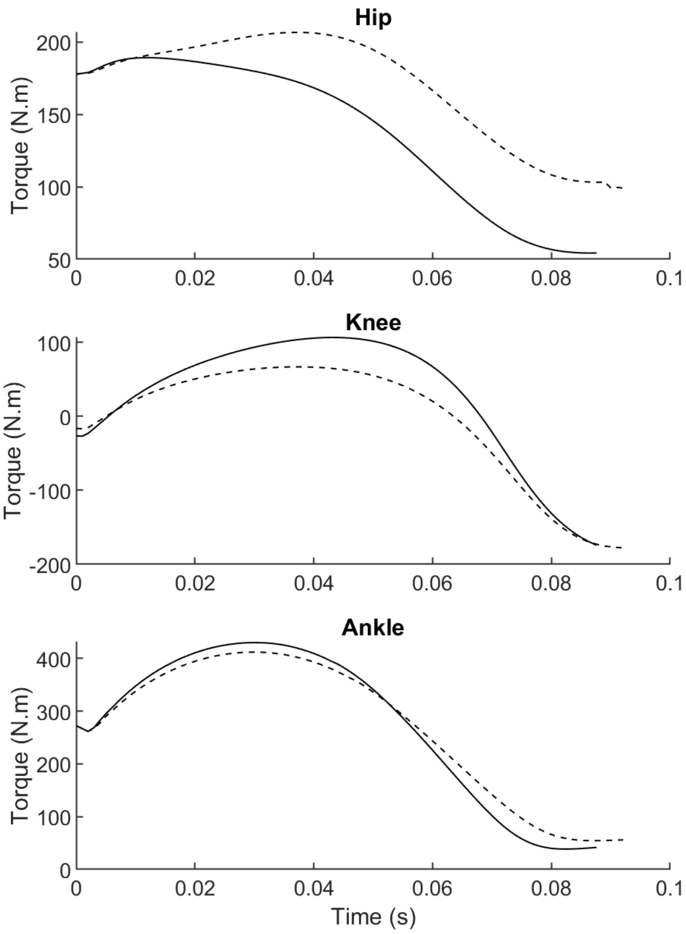
0.08
0.1
Time (s)

Figure 5


Hip
Torque (N.m)
200
150
100
50
0
0.02
0.04
0.06
0.08
0.1
Knee
Torque (N.m)
100
0
-100
-200
0
0.02
0.04
0.06
0.08
0.1
Ankle
Torque (N.m)
400
300
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0.04
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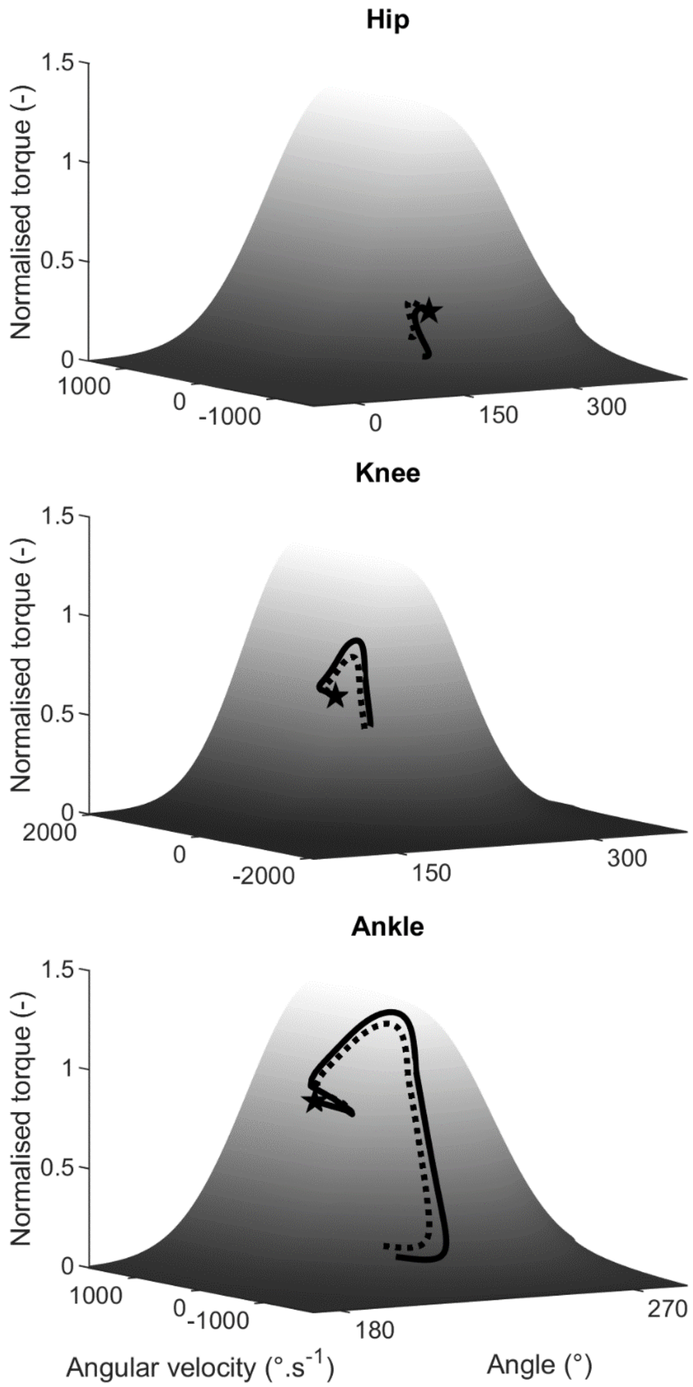
Time (s)

Figure 6

480 

481

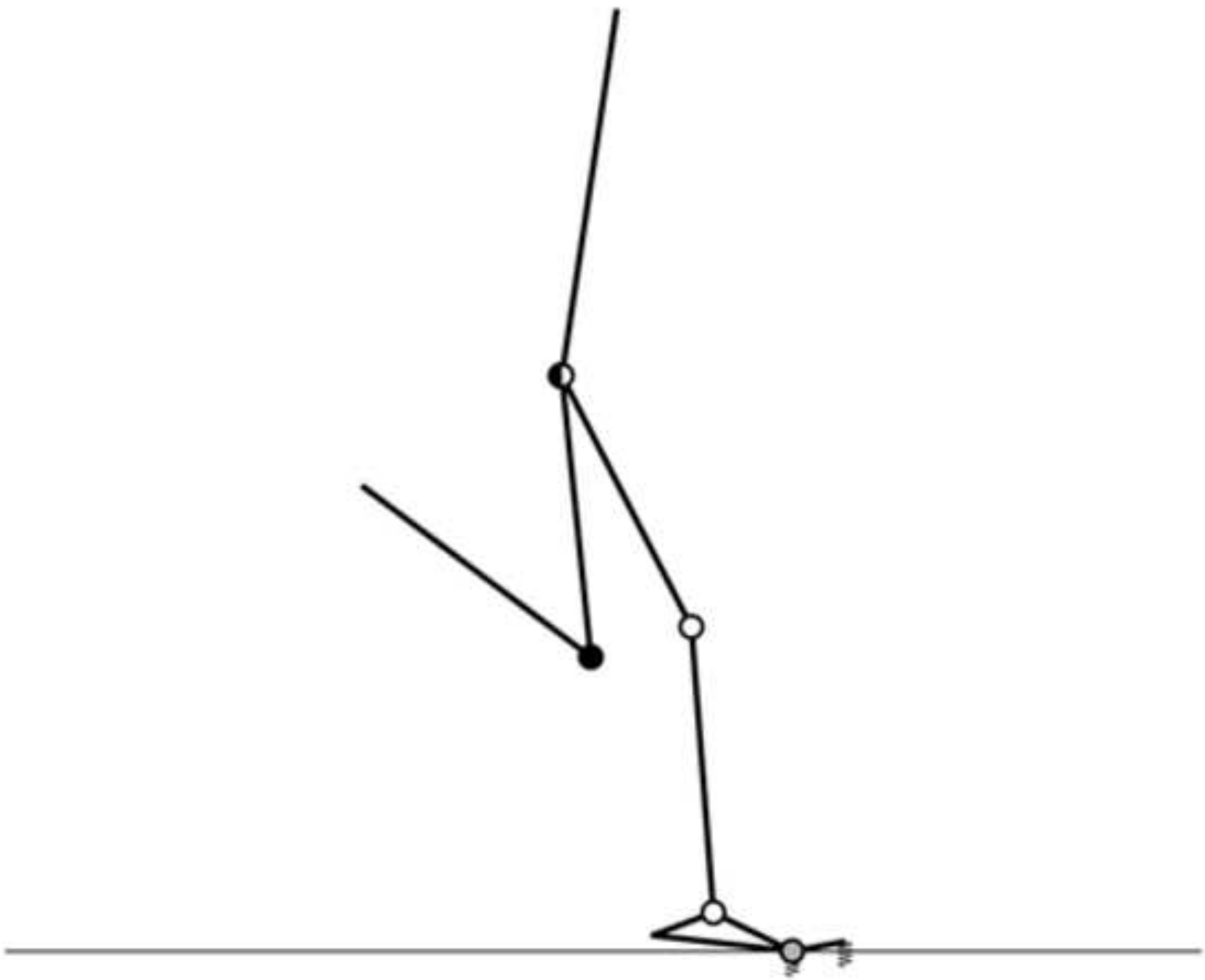
482 Figure 7

483

Table 1. Comparison between the two swing leg techniques for selected variables.

	Elite athlete	Sub-elite athlete
Horizontal velocity (m.s^{-1})	10.0	9.2
Swing time (s)	0.374	0.374
Stance time (s)	0.088	0.092
Flight time (s)	0.143	0.141
Horizontal CoM displacement (m)	0.866	0.837
Vertical CoM displacement (m)	0.021	0.022
Vertical impulse (N.s)	111.7	109.8
Mean vertical force (N)	2123	2033
Mean hip extensor torque (N.m)	138.2	168.6
Mean knee extensor torque (N.m)	208.8	186.3
Mean ankle extensor torque (N.m)	277.2	267.8

Figure 1



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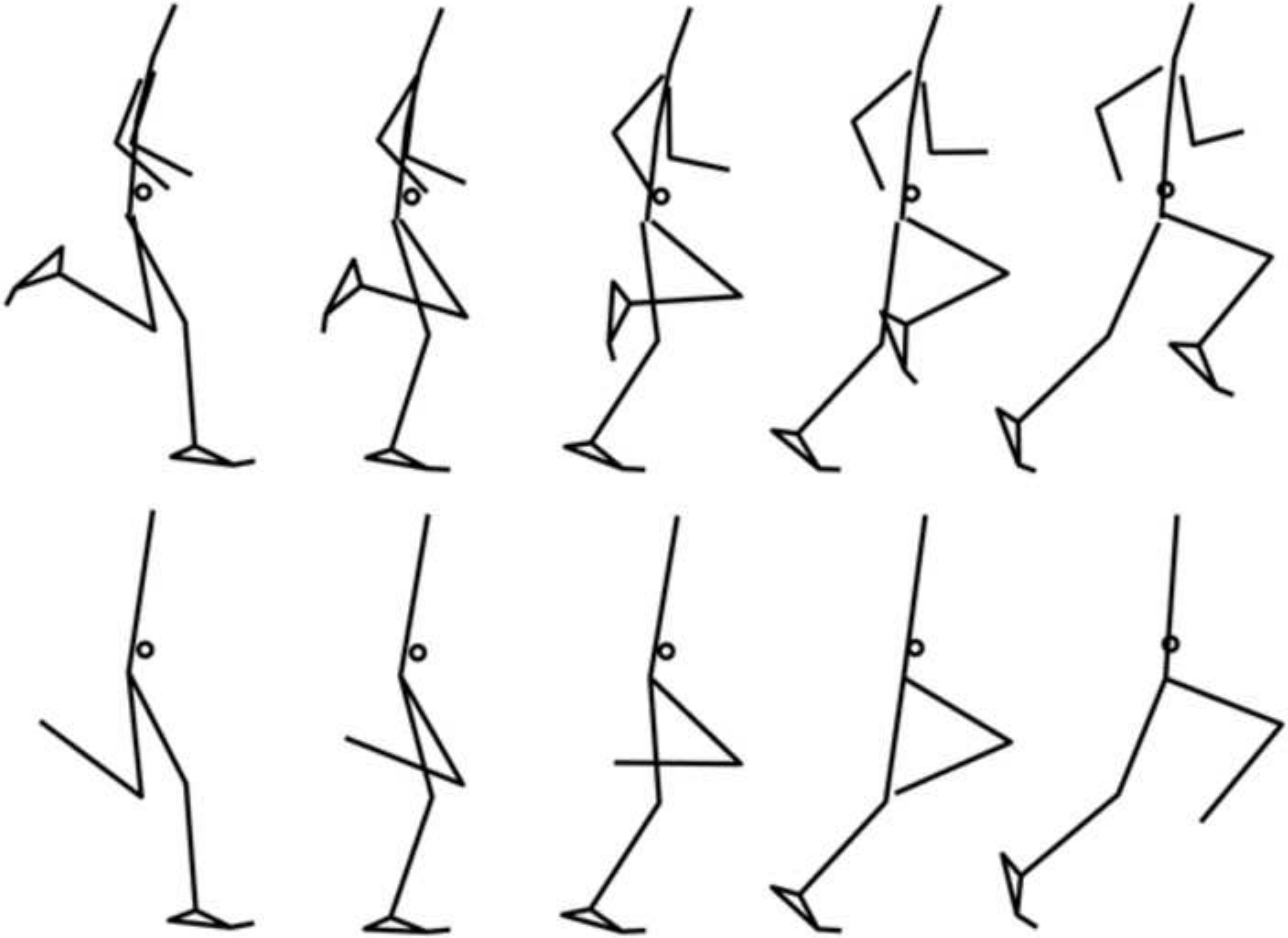

Figure 4

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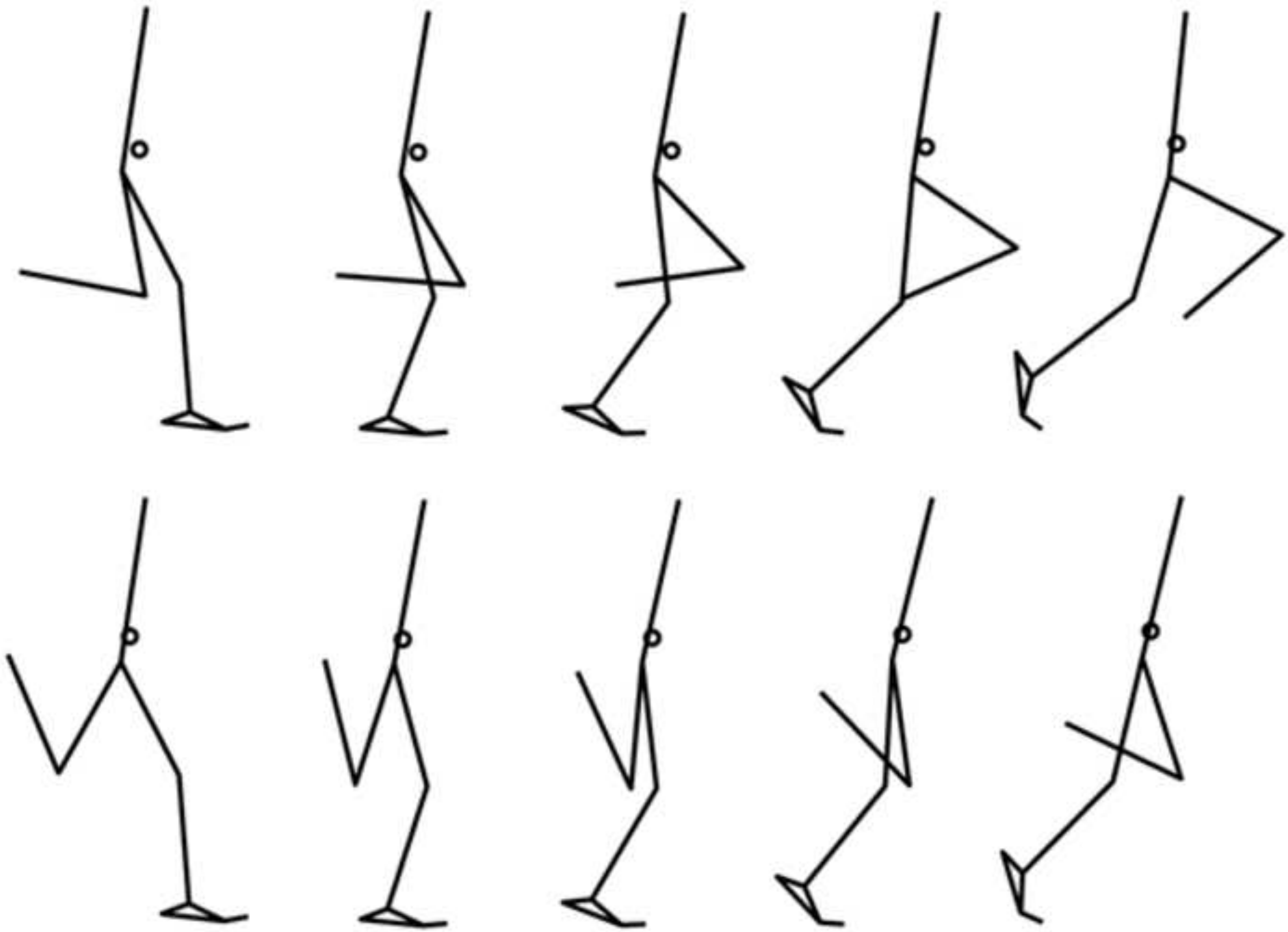

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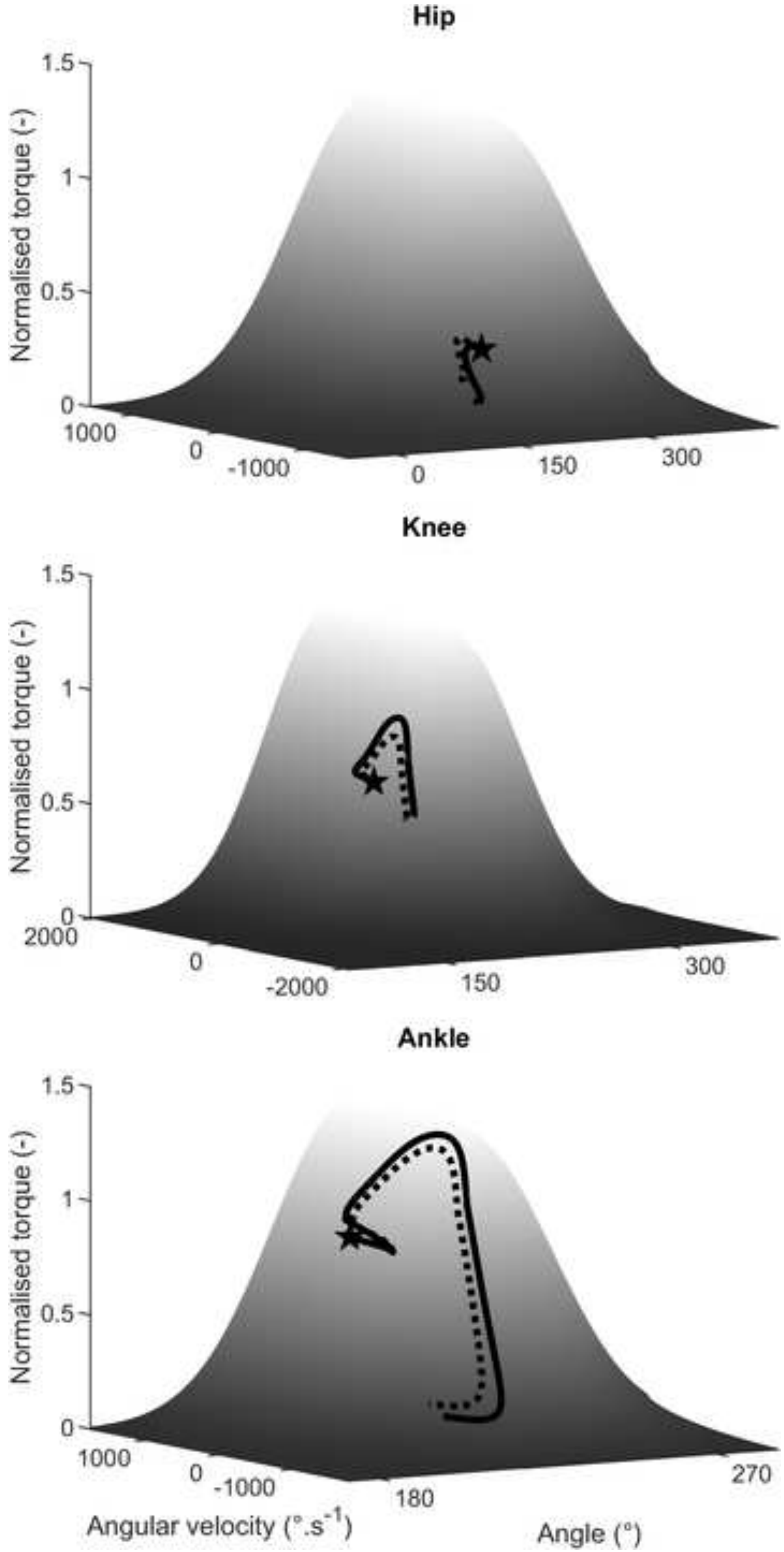

Hip
Normalised torque (-)
1.5
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0.5
0
1000
0
-1000
0
150
300
Knee
Normalised torque (-)
1.5
1
0.5
0
2000
0
-2000
150
300
Ankle
Normalised torque (-)
1.5
1
0.5
0
1000
0
-1000
180
270
Angular velocity (°.s^{-1})
Angle (°)

Figure 3

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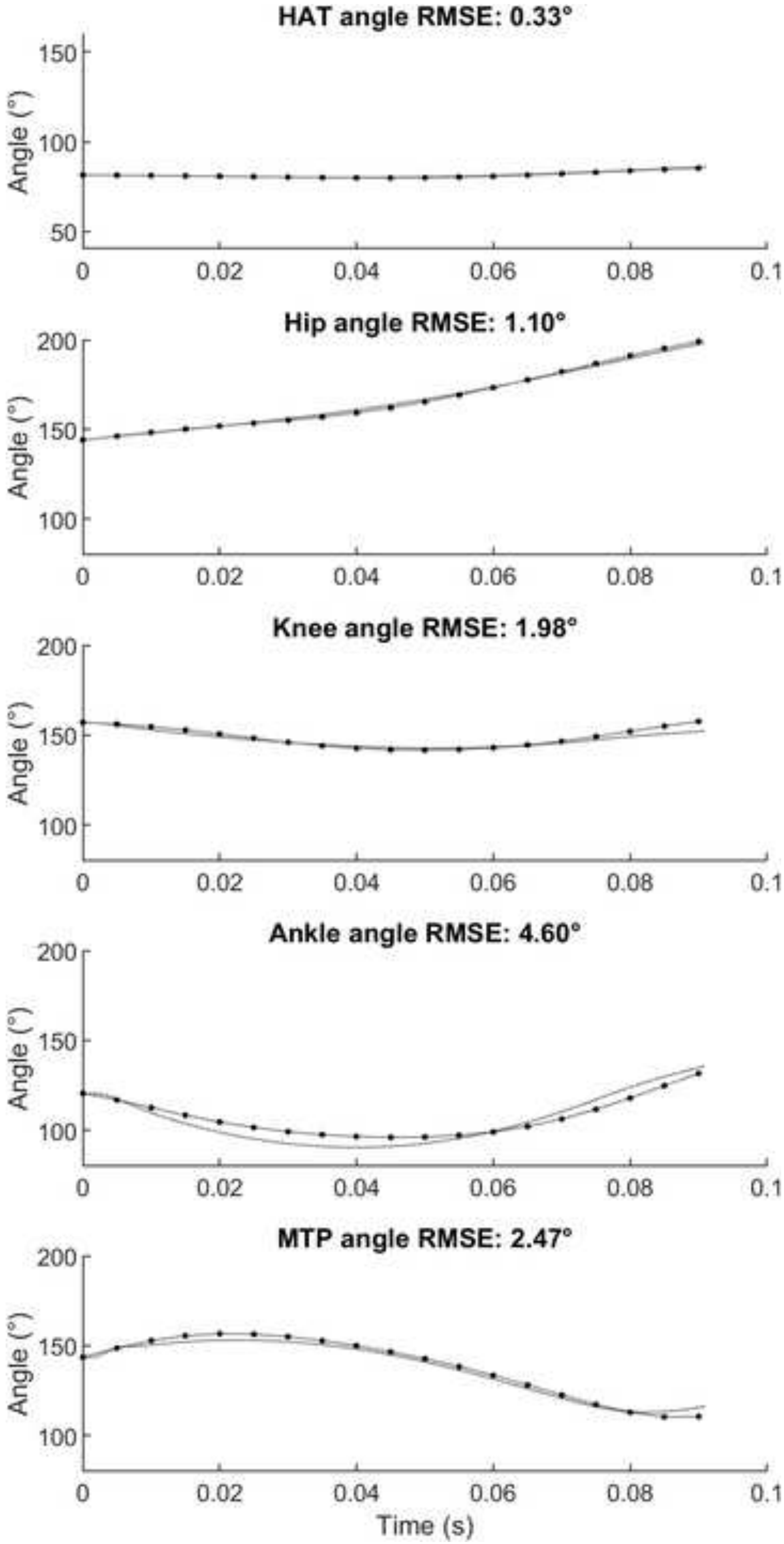

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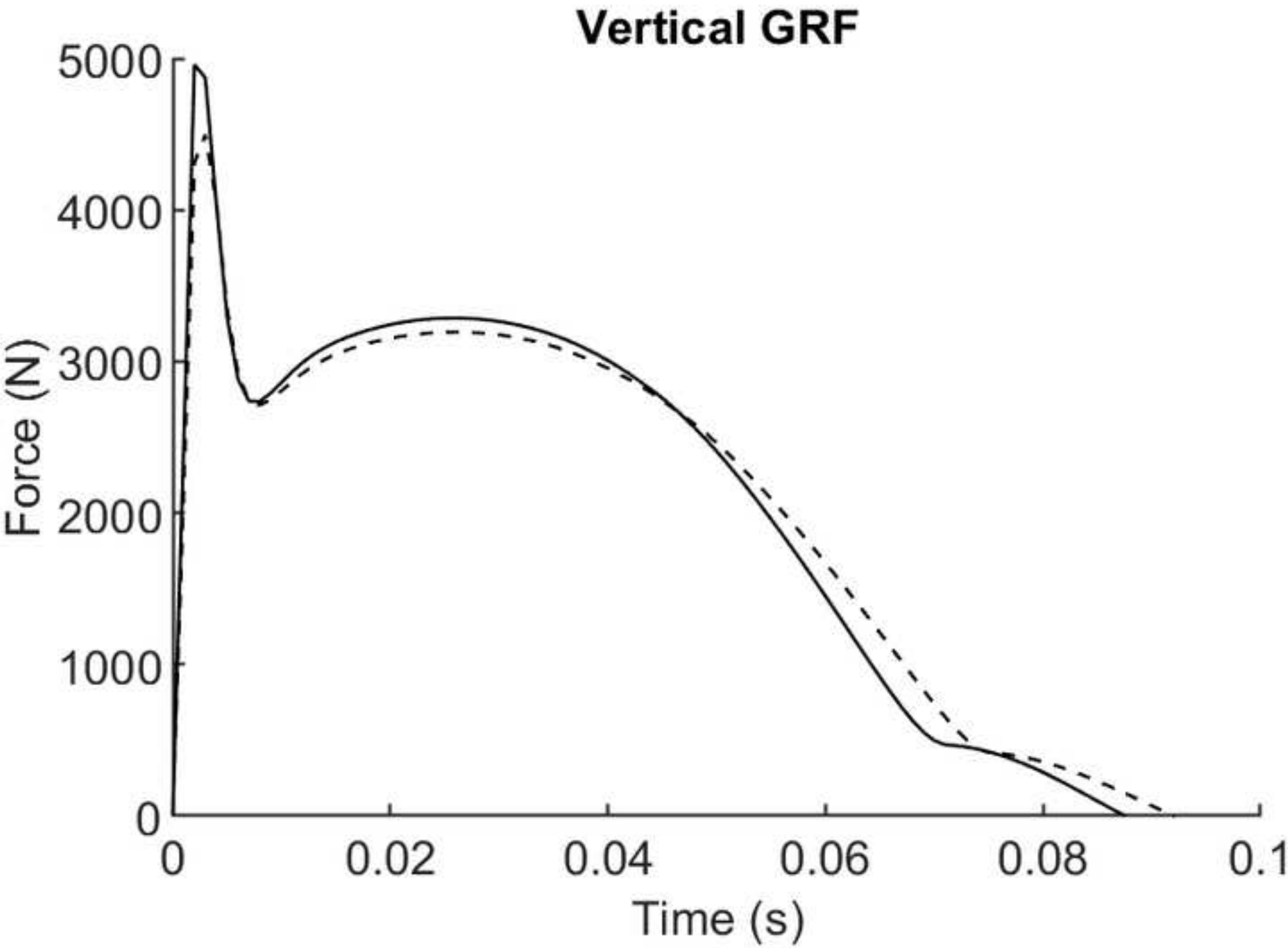
Vertical GRF
Force (N)
5000
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Time (s)

Figure 6

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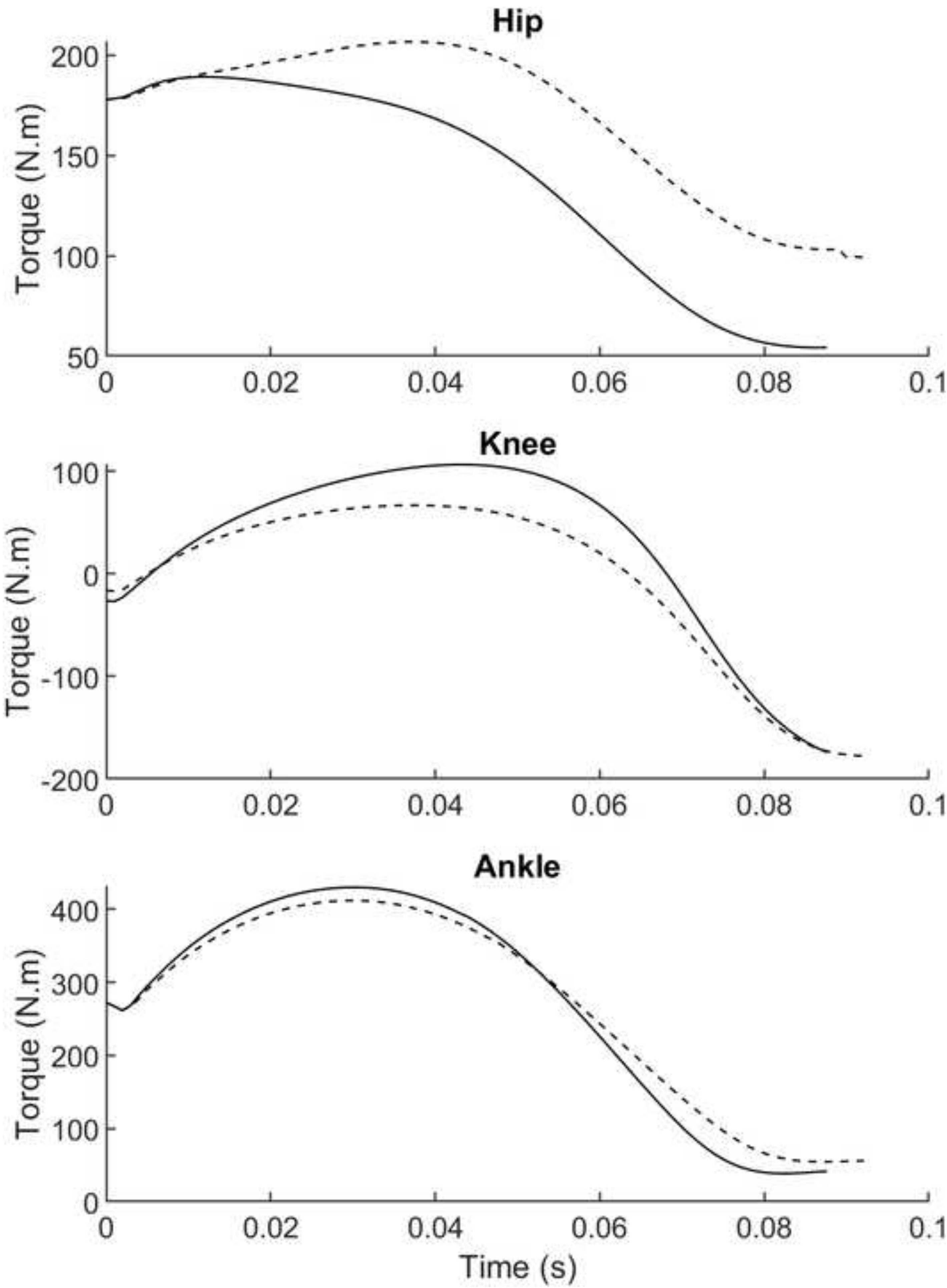

The influence of swing leg motion on maximum running speed

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Abstract

The motion of the swing leg of elite sprinters at maximum speed is markedly different from that of slower sprinters, but the mechanisms by which this difference influences performance are unknown. The aim of this study was to use a computer simulation model to establish whether and, if so, how the motion of the swing leg influences maximum achievable running speed. A seven-segment planar computer model was constructed to simulate the stance phase of sprinting. Optimisation was used to maximise the running speed of the model using two different swing leg techniques, one representative of an elite sprint athlete, and the other of a sub-elite athlete. The maximum speed of the model increased when using the swing leg technique of the elite athlete compared with the technique of the sub-elite athlete (10.0 $m.s^{-1}$ vs 9.2 $m.s^{-1}$). This improvement in performance was due to greater horizontal displacement of the mass centre during stance (0.867 m vs 0.837 m), and an increase in average vertical ground force of 90 N (0.1 bodyweights). The increase in vertical force was due to a larger impact peak caused by more negative vertical momentum of the stance leg at touchdown, and subsequently greater torques in the joints of the stance leg which were placed in faster eccentric contractions and at angles closer to optimum during the first half of stance. It is likely that the swing leg technique contributes to the asymmetrical vertical ground reaction force traces observed in elite sprinters.

Keywords: computer simulation, sprinting, optimisation, technique

1. Introduction

Maximal running speed in humans demonstrates great variability, Weyand et al. (2000) measured maximum speeds ranging from 6.2 to 11.1 $m.s^{-1}$ in a group of thirty three physically active men and women, and speeds of over 12 $m.s^{-1}$ have been recorded by elite male athletes in competition (Graubner and Nixdorf, 2011). This prompts the question of what allows some humans to run so much faster than others.

Running speed is the product of step length and step frequency and therefore faster speeds can be attained by increases in either or both. For an individual runner it has been observed that, at relatively low speeds, speed is increased primarily by increasing step length (Weyand et al., 2000; Dorn et al., 2012). The runner achieves this via increases in vertical ground forces which lead to increased vertical impulses and consequently flight times (Weyand et al., 2000; Dorn et al., 2012). At relatively higher speeds, the capacity to apply vertical ground forces plateaus and briefer stance times result in reduced vertical impulses and flight times; increases in speed after this point are due primarily to increases in step frequency, which continue until the maximum speed of the runner is reached (Weyand et al., 2000). Running speed is therefore theoretically limited by the ability to produce vertical ground force during brief stance times and the minimum swing time during which the limb can be repositioned for its subsequent stance phase. Weyand et al. (2000; 2010) showed that in humans it is the size of the vertical ground forces that differentiates between faster and slower runners, rather than the minimum swing time, which is similar for all runners at their top speeds. Furthermore it has subsequently been shown that it is not just the magnitude of the vertical ground force that differentiates between faster and slower runners, but also the shape of the vertical ground force-time graph where sprinters exhibit larger and earlier peaks in the first half of stance but do not differ from non-sprint athletes - who exhibit more symmetrical vertical ground force waveforms - during the second half of stance (Clark and Weyand, 2014).

Clear differences exist between the techniques of faster and slower sprinters, particularly in relation to the swing leg; the hip angle of the swing limb at touchdown of the contralateral leg has been shown to differentiate between elite and sub-elite sprinters and to be the largest single kinematic predictor of maximum running speed, despite exhibiting no differences in angular displacement and angular velocity throughout the stride (Sides, 2015). Trained sprinters exhibit a more flexed hip throughout the first half of swing, resulting in the thigh of the swing leg being closer to vertical at touchdown of the contralateral leg and closer to horizontal at contralateral toe-off (Kunz and Kauffman, 1981; Mann and Herman, 1985; Bushnell and Hunter, 2007; Sides, 2015). Furthermore, as running speed increases, the mechanical demands on the muscles of the swing leg, mainly at the hip, substantially increase, whereas those on the muscles of the stance leg plateau (Dorn et al., 2012; Schache et al., 2015) and it has been shown that muscle volumes of the hip flexors and extensors are extremely large in sprinters when compared with controls (Handsfield et al., 2017, Miller et al., 2020). These results indicate that, although the time taken to reposition the limb at maximum speed is similar in faster and slower runners, the kinematics and kinetics of the limb during this portion of the stride are different.

It has been shown that the motion of the swinging limbs can improve performance in standing (Harman et al., 1990; Ashby and Delp, 2006; Cheng et al., 2008; Domire and Challis, 2010) and running jumps (Dapena and Chung, 1988; Allen et al., 2010). In a vertical jump, an arm swing can improve performance by increasing the height and velocity of the whole-body centre of mass (CoM) at takeoff (Cheng et al., 2008; Domire and Challis, 2010). The increase in takeoff velocity caused by the arm swing is partly due to energy imparted directly to the CoM and partly caused by a downwards reaction force at the shoulder joint which augments the force of the extensor muscles of the stance legs by putting them in faster eccentric or slower concentric conditions (Cheng et al., 2008; Domire and Challis, 2010). The performance requirements of maximum speed running are different to vertical jumping in that the athlete is not attempting to maximise vertical velocity but to achieve sufficient vertical velocity to allow adequate flight and hence swing time to reposition the limb. However, it is conceivable that runners could use their swing leg to increase vertical ground force in the same way as an arm swing in vertical jumping, and therefore achieve the requisite vertical impulses during briefer stance phases, facilitating higher running speeds.

Despite the observed differences in technique between faster and slower runners and this theoretical rationale, there has been limited consideration of the effect swing leg motion might have on maximum running speed. Therefore, the aim of this study was to use computer simulation to investigate the influence of swing leg motion on maximum achievable running speed.

2. Methods

2.1. Study design

A computer model was developed to simulate the stance phase of sprinting. Optimisation was used in two ways: to evaluate the capacity of the model to match performance data collected on a sprinter; then to maximise the running speed of the model using two different swing leg techniques, one representative of an elite athlete (SLT_E), and the other of a sub-elite athlete (SLT_{SE}).

2.2. Laboratory data collection

Following Loughborough University Ethics Approvals (Human Participants) Sub-Committee guidelines and having given informed consent, a male athlete (28 years, 91.1 kg, 1.86 m, 100 m personal best time: 10.50 s) sprinted at 9.7 $m.s^{-1}$ on an instrumented treadmill (3DI, Treadmetrix, Utah, USA) recording three-dimensional ground reaction forces (2000 Hz). Sixty-five retroreflective markers were placed on the participant, and their positions were recorded (250 Hz) using sixteen infrared cameras (Vicon Vantage, Oxford Metrics, Oxford, UK), synchronised with the force data. A custom Vicon BodyBuilder model, composed of the head and trunk, upper and lower arm, thigh, shank, rearfoot, and toes, was written to extract segment and joint angles. Further analysis was performed in MATLAB (R2020a, Mathworks, MA, USA).

Kinetic and kinematic data were low-pass filtered with cut-offs of 50 Hz and 15 Hz respectively, using a fourth-order zero-lag Butterworth filter, interpolated, and resampled on the same time base at 1000 Hz using cubic splines. Six full strides on each leg were time normalised then averaged across strides and between legs to give representative data on one full stride at top speed. Contact was identified using an 80 N threshold in vertical force.

2.3. Swing leg technique data collection

To determine the effect of different swing leg techniques, a publicly available video of an elite athlete and a sub-elite athlete running at their respective top speeds was used (LocomotorLabSMU, 2012), as it illustrated typical differences in technique, with the hip joint of the elite athlete more flexed throughout stance. The hip, knee, ankle, and metatarsophalangeal (MTP) joint centres along with a point at the base of the neck representing the top of the trunk, were digitised using the open-source package

DLTdv7 (Hedrick, 2008). Segment and joint angle time histories were calculated, and quintic smoothing splines were fitted to these time histories.

2.4. Computer model

A seven-segment planar computer model was constructed to simulate the stance phase of sprinting (Figure 1). The seven segments comprised: the thigh, shank, rearfoot, and toe of the stance leg; the thigh, and shank of the swing leg; and a combined head, arms, and trunk (HAT) segment, containing the mass of the rest of the body. Segments were represented as one-dimensional rigid rods, except for the rearfoot which was two-dimensional, and were connected by frictionless pin joints. The foot-ground interface was modelled using horizontal and vertical spring-dampers situated at the MTP joint and the end of the toe (Allen et al., 2012).

*** insert Figure 1 here ***

The hip, knee, and ankle joints of the stance leg were actuated by mono-articular flexion and extension torque generators, representing the contractile components (CC) of the muscle-tendon units crossing the joint, in series with a rotational spring, representing the series elastic components (SEC). The MTP joint was actuated by a rotational spring-damper. The hip and knee joints of the swing leg were angle-driven using experimental data. To represent the arm swing, the position of the CoM of the HAT segment relative to the hip was also kinematically driven using experimental data.

The torque produced by each torque generator was a product of activation level (Yeadon and Hiley, 2000), and torque-angle (Forrester et al. 2011) and torque-angular velocity (Yeadon et al. 2006) relationships of the contractile component (see supplementary material for more details).

System equations of motion were formulated using Autolev (Kane and Levinson, 1985) and output as Fortran code. Inputs to the model were the initial conditions, representing CoM position and velocity and segment angles and angular velocities, and parameters specifying the activation of each torque generator as a function of time. The equations of motion were integrated forwards using a fourth order Runge-Kutta algorithm with a variable timestep.

Segmental inertia parameters were obtained from a previous data collection on the same participant (McErlain-Naylor, 2017). Torque generator parameters were taken from a previous study on a triple jump athlete (Allen, 2009), and CC torques and SEC stiffnesses were scaled linearly to body mass. Viscoelastic parameters were determined via optimisation (see Section 2.5). Model parameters are provided in the supplementary material.

2.5. Model Evaluation

The model was evaluated by minimising the difference between simulation output and experimental data collected on the participant. The swing leg was angle-driven using joint angle time histories from laboratory data. A simulated annealing algorithm, set to run in parallel (Higginson and Anderson, 2005), minimised a cost function by varying forty-two activation parameters, two MTP spring and eight contact spring parameters. The cost function comprised the sum of four components: the sum of the mean squared differences in hip, knee, ankle and MTP joint angle time histories; the mean squared difference in the global orientation angle time history; the absolute difference in horizontal CoM velocity; and the absolute difference in swing time. The orientation angle, CoM velocity, and swing time components were weighted one, two, and three orders of magnitude respectively higher than the joint angles component, with the aim of prioritising the match to the performance outcomes of swing time and horizontal velocity.

Flight time was calculated from the CoM vertical velocity at take-off and the difference in height of the CoM between take-off and touchdown using equations of constant acceleration. Swing time was the sum of two flight times and one stance time. Horizontal CoM velocity was the product of step length and step frequency.

The initial temperature for simulated annealing, which governed the likelihood of accepting a solution which was worse than the current one, was chosen to give an appropriately sized search space around trial points, so that roughly 50% of all function evaluations were accepted (Goffe et al., 1994) and the number of cycles before a temperature reduction was determined through preliminary tests aiming to minimise the computing time while still finding the optimum. All other parameters were left at their default values.

Viscoelastic parameters obtained from this evaluation process were used in all subsequent optimisations.

2.6. Model Optimisation

Optimisations were carried out to establish the maximum running speed achievable by the model whilst angle-driving the swing leg using joint angle time histories obtained by digitisation of each of the two techniques from video data (LocomotorLabSMU, 2012). To establish maximum running speed, initial horizontal velocity was incrementally increased by 0.1 $m.s^{-1}$ from the matched simulation whilst all other initial conditions remained the same. The model was considered capable of running at a given speed if the loss in horizontal velocity during stance was less than 0.01 $m.s^{-1}$ and the swing time from laboratory data was matched to within 0.001 s, bounds picked from the variation in the laboratory data. Swing time was kept constant as this has been shown to be similar for all runners at their top speeds (Weyand et al., 2000). After each velocity increment, forty-two activation parameters were varied by the simulated annealing algorithm until the acceptance criteria were met, and maximum speed was the highest speed at which the model could meet these conditions.

3. Results

3.1. *Model Evaluation*

The matched simulation showed good agreement with the laboratory data (Figure 2 and supplementary animations). Horizontal velocity (9.66 $m.s^{-1}$) was closely matched to the laboratory data (9.67 $m.s^{-1}$). The swing time matched exactly (0.374 s) however, stance time was shorter (0.091 s vs 0.110 s), and flight time was longer (0.141 s vs 0.132 s) than the laboratory data. Orientation and configuration angle time histories were all matched to within a root mean squared error (RMSE) of 5° or less (Figure 3). It was concluded that the model was sufficiently accurate to be used to explore the effects of technique on performance.

*** insert Figure 2 here ***

*** insert Figure 3 here ***

3.2. *Model Optimisation*

The maximum speed of the model when using SLT_{SE} was 9.2 m.s^{-1} compared with 10.0 m.s^{-1} when using SLT_{E} (Figure 4 and supplementary animations). Stance time was slightly shorter and flight time and vertical impulse slightly larger using SLT_{E} (Table 1). The vertical whole-body CoM displacement did not differ between the two techniques, but the horizontal displacement was greater with SLT_{E} (Table 1).

*** insert Figure 4 here ***

*** insert Table 1 here ***

Using SLT_{E}, the model produced an average of 90 N (0.1 bodyweights) more vertical ground force during stance. This increase was due to higher forces in the first half of stance, offsetting lower forces during the second half, giving a net positive effect (Figure 5). When using SLT_{E}, the initial vertical momentum of the stance limb was more negative (-32.1 kg.m.s^{-1} vs -28.5 kg.m.s^{-1}) which led to a larger vertical impact force peak (Figure 5). Average extensor torques at the knee and ankle were higher using SLT_{E}, whereas the average extensor torque at the hip was lower (Table 1).

*** insert Figure 5 here ***

Activations of the stance leg torque generators were virtually identical in both techniques, with the hip and ankle extensors fully active and the flexors inactive for the duration of stance, resulting in net extension torques at these joints. Both the extensor and flexor torque generators were activated at the knee, leading to a period of net extension followed by flexion torques (Figure 6). As well as the extensor torque being higher with SLT_{E}, the average flexion torque was also lower, despite similar activations between techniques. This led to an even greater net extension torque during the first half of stance (Figure 6).

*** insert Figure 6 here ***

Angular velocities of the CC were more eccentric at the knee and ankle but more concentric at the hip with SLT_E (Figure 7). The higher eccentric CC angular velocities put the CC angle closer to its optimal position at the knee and ankle for the majority of stance (Figure 7).

*** insert Figure 7 here ***

4. Discussion

The results showed that a 0.8 $m.s^{-1}$ or 9% improvement in running speed can be gained solely from changing how the swing leg moves during stance (Table 1). The increase in speed was a result of an increase in the average vertical ground force of 90 N, or 0.1 bodyweights, allowing the necessary vertical impulse required to maintain swing time to be generated in a briefer stance phase (Table 1).

The vertical ground force impact peak was found to be larger when using SLT_E. It has been shown that the size of the vertical impact force peak during running can be accurately predicted using momentum changes of the lower leg (Clark et al., 2014). Since the vertical momentum of the whole-body CoM at touchdown remained constant for all simulations, the more positive swing leg momentum with SLT_E resulted in a more negative stance leg momentum and consequently a larger impact peak. This was a passive effect since stance leg joint torques did not differ during impact (Figures 5 and 6).

As activations of the torque generators were almost identical between the two techniques, the increases in torque following impact were due to CCs operating at angles closer to optimal and at faster eccentric or slower concentric angular velocities

(Figure 7). Faster eccentric CC angular velocities at the ankle and knee which placed the CC further up the ascending limb of the torque-angle curve were seen with SLT_E (Figure 7). The opposite was the case at the hip however as the higher concentric angular velocity of the extensor CC meant that torque was reduced (Table 1, Figure 7). As there was a net increase in vertical force with SLT_E, this is consistent with previous findings that the hip torque contributes little to the vertical ground force (Dorn et al., 2012).

When considered together, these model results indicate that swing leg motion can contribute to the asymmetrical vertical ground force patterns observed in sprinters, characterised by larger and earlier peaks in the first half of stance. The action of the swing leg increased ground force and stance leg torques mainly during impact and when the knee and ankle were operating eccentrically during the early part of stance (Figures 5 and 6), which is where the pattern of vertical force in sprinters differs substantially from the symmetrical pattern predicted by a spring-mass model and exhibited by non-sprint athletes (Clark and Weyand, 2014).

The vertical whole-body CoM displacement during stance was similar between techniques (Table 1). This was despite the CoM of the swing leg rising 7.3 cm with SLT_E but lowering 3.4 cm with SLT_{SE}. The positive vertical momentum of the CoM of the swing leg in SLT_E made the vertical momentum of the rest of the body more negative, delaying takeoff (Figure 4) and leading to a larger horizontal displacement of the whole-body CoM (Table 1). Prolonging stance results in a reduction in the required flight time and hence vertical impulse to maintain a given swing time. It is also possible that the increased hip flexion angle and gravitational potential energy of the swing leg with SLT_E will facilitate an increase in the negative vertical momentum of the limb and consequent impact force at the subsequent touchdown.

The mechanical demands on the swing limb required to achieve SLT_E were beyond the scope of this study, but joint torques and work done by the swing leg have been shown to increase superlinearly with running speed (Dorn et al., 2012) and the muscles which flex and extend the hip, and flex the knee, have been shown to be substantially larger in sprinters compared with controls (Handsfield et al., 2017, Miller et al., 2020). These findings, in addition to the results of this study, would suggest that athletes wishing to increase their running speed should devote time to technical and strength training associated with the swing phase of running. Strength training could take the form of open-chain resistance exercises of the hip flexors and extensors, and the knee flexors, with the body in a similar configuration to that employed during sprinting to ensure comparable muscle lengths throughout the movements.

The main limitation of the model was that it was unable to match stance time closely (Table 1). This is likely to be due to a lack of body tissue compliance in the model, which has been shown previously to result in briefer stance times in simulations of triple jumping (Allen et al., 2012). This also meant that the vertical ground reaction force rose unrealistically quickly, leading to higher forces than are typically observed in sprinters (Weyand et al., 2000). Nevertheless, the stance times were within the range of those reported in the literature (Sides, 2015) and the model was able to match performance outcomes well; since the aim was to compare two techniques these limitations should not affect the study conclusions. Another limitation of the briefer stance times was that the angle-driven joints did not complete the same movement amplitude as the performance, since they were functions of time, however since most of the differences occurred early in stance this is also unlikely to have affected the conclusions. The optimisations were not required to prepare the stance limb for its subsequent swing phase, and it has been shown in sprinters that the hip flexors activate, and the hip extensors relax during late stance (Bezodis et al., 2008) which was not observed in this study, but both optimisations were subject to the same constraints and therefore this should not affect the study conclusions, if anything including this constraint would be likely to affect the outcomes with SLT_E less since the hip torque decayed further during late stance in this simulation than with SLT_{SE} (Figure 6). Lastly, the model inertia parameters and the performance data were taken at different times from the same athlete, and the strength parameters and swing leg techniques were taken from other athletes, which may seem inconsistent. However, since the aim of this study was not to optimise the technique of one participant, but to compare the effects of contrasting swing leg techniques typically associated with faster and slower sprinters, model parameters only needed to be representative of a sprint athlete.

5. Conclusion

The results showed that using the swing leg technique of an elite sprinter can augment the vertical ground force passive impact peak by increasing the negative vertical momentum of the stance leg at touchdown, putting the joints of the stance leg in faster eccentric conditions, placing them closer to their optimum angles for torque production, and allowing more torque and vertical ground force to be produced in the early portion of stance, increase the horizontal displacement of the mass centre during stance, and ultimately increase the maximum running speed. Athletes aiming to increase their maximum running speed should devote time to training associated with the swing phase of running. Future work could investigate the effect of swing leg technique on the subsequent stance phase, and the contribution of the arm swing to increases in ground force.

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List of figure captions

Figure 1. Seven-segment model with viscoelastic springs under the MTP joint and toes. Open circles represent torque-driven joints. Filled circles represent angle-driven joints. Grey circle represents a viscoelastic rotational spring. Half-filled circle indicates torque- and angle-driven hip joints of the stance and swing leg, respectively.

Figure 2. Comparison between participant (top) and matched simulation (bottom). Circle represents whole-body CoM.

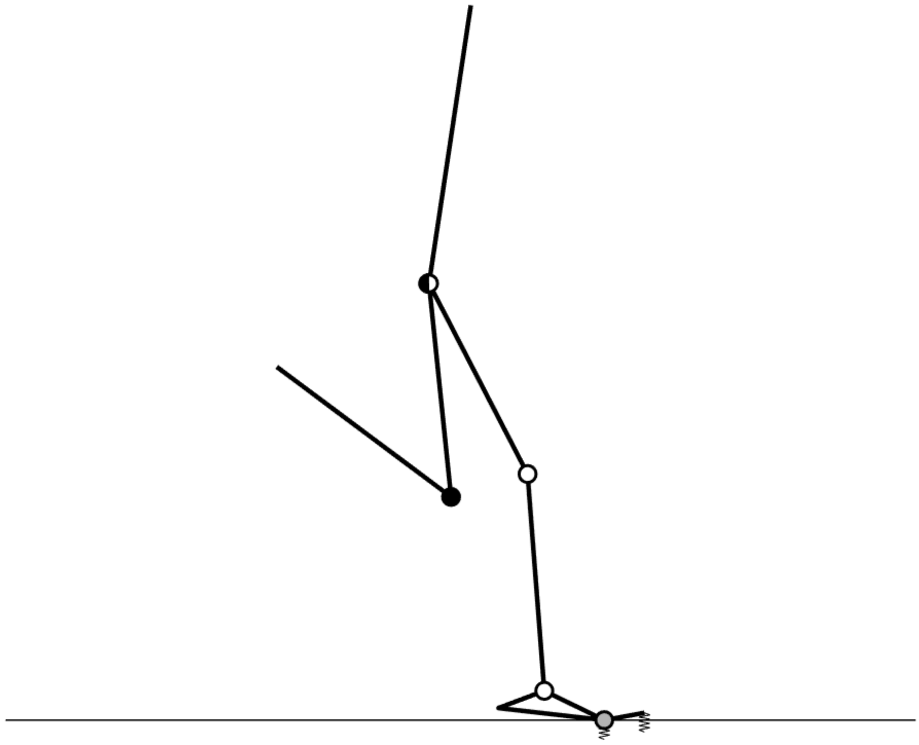
Figure 3. Orientation and configuration angles of the participant (dash-dot line) and matched simulation (dotted line) techniques.

Figure 4. Comparison between optimised simulations using SLT_E (top) and SLT_{SE} (bottom). Circle represents whole-body CoM.

Figure 5. Vertical force in optimised simulations using SLT_E (solid line) and SLT_{SE} (dashed line).

Figure 6. Stance leg net joint torques in optimised simulations using SLT_E (solid line) and SLT_{SE} (dashed line). Extension torques are positive.

Figure 7. Angle and angular velocities of the CC in optimised simulations using SLT_E (solid line) and SLT_{SE} (dashed line) superimposed on the normalised tetanic torque-angle-angular velocity surface for each extensor torque generator. Positive angular velocities represent eccentric contractions. Stars represent touchdown.



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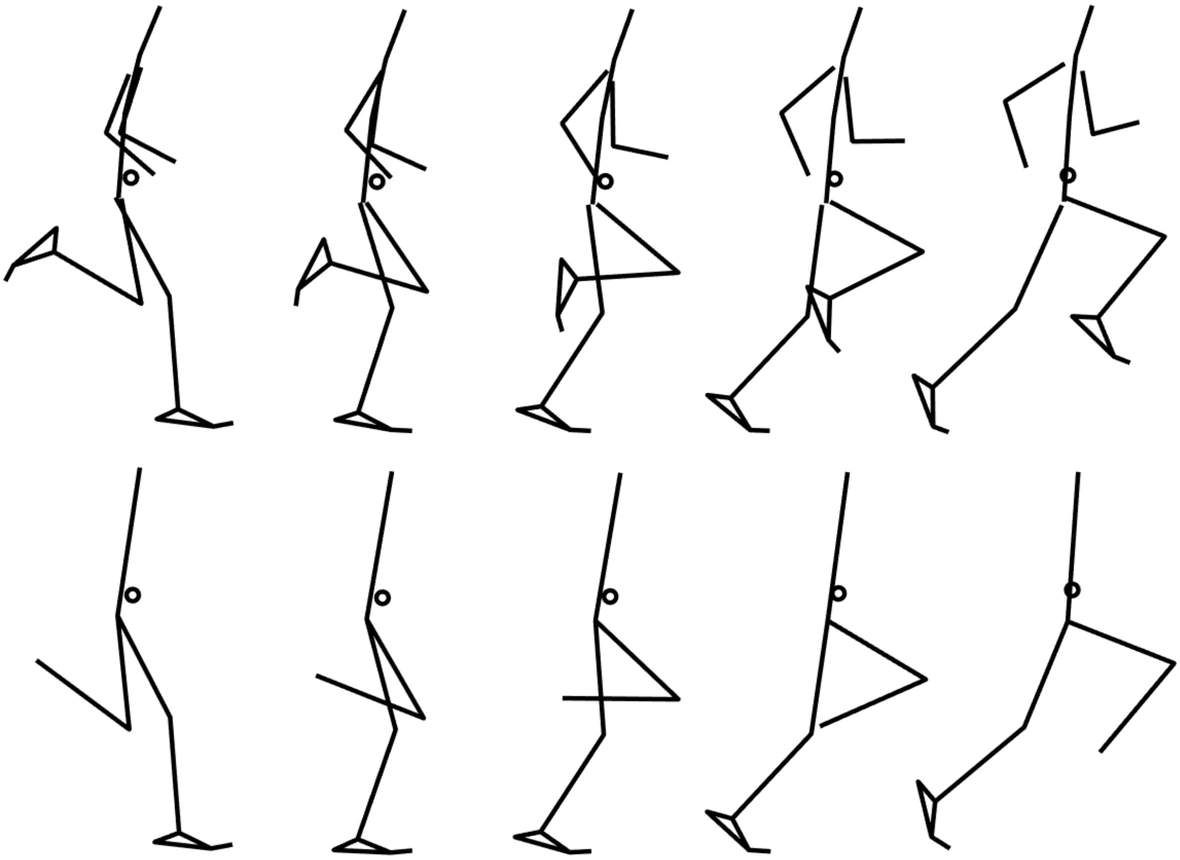
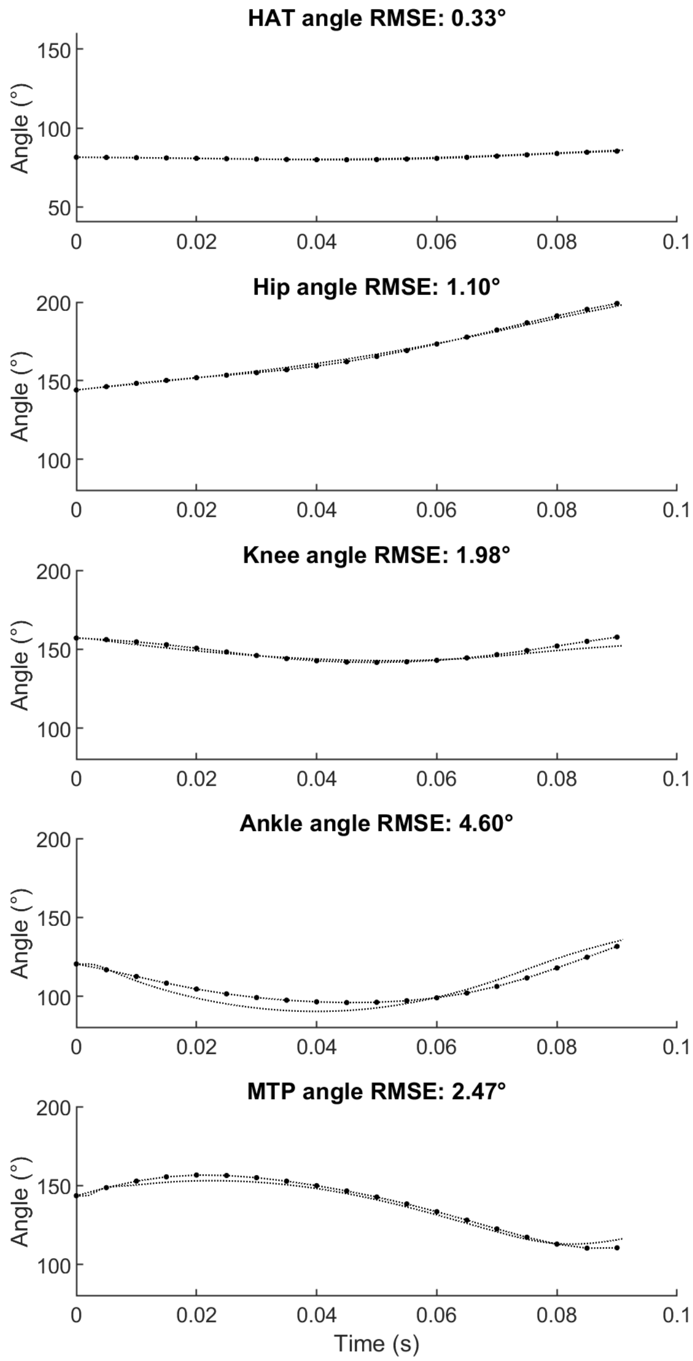


Figure 2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Hip angle RMSE: 1.10°
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Ankle angle RMSE: 4.60°
MTP angle RMSE: 2.47°
Angle (°)
Time (s)

Figure 3

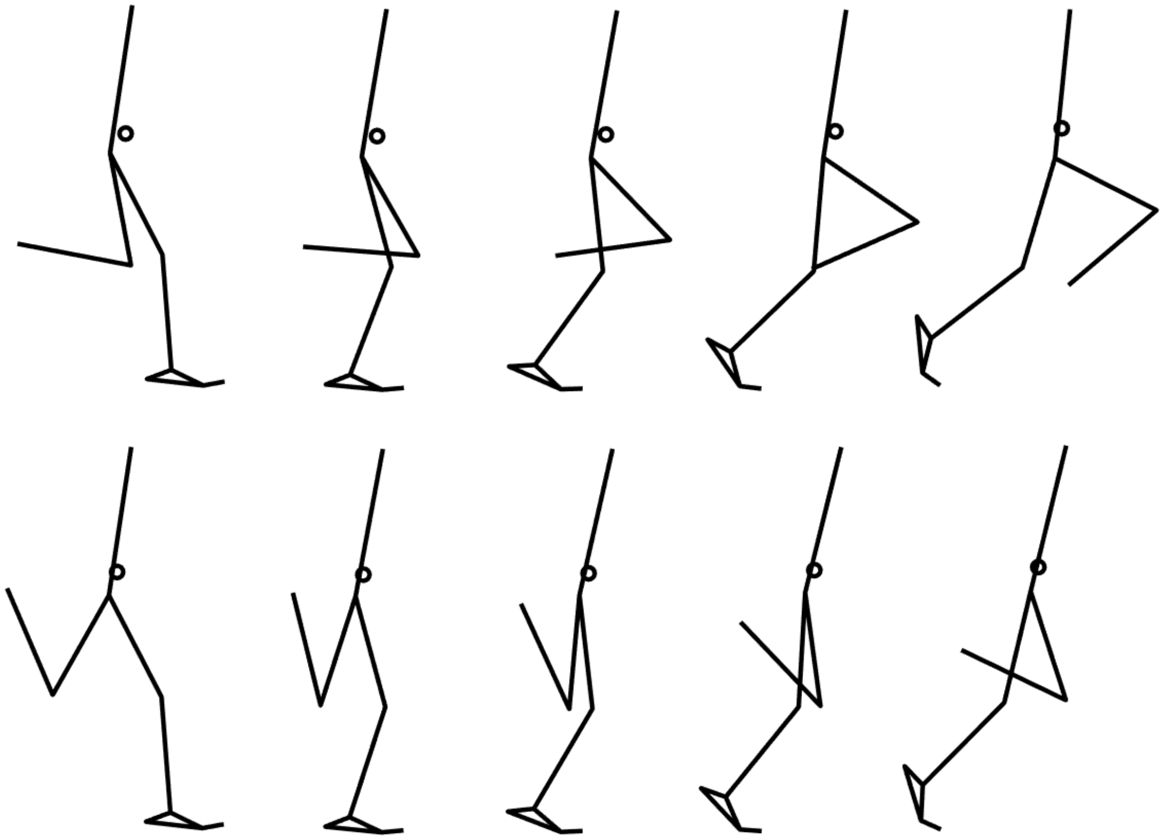

Figure 4

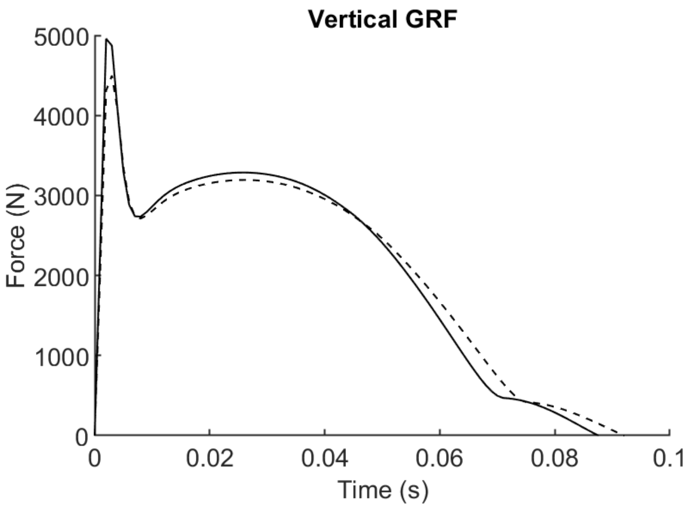
Vertical GRF
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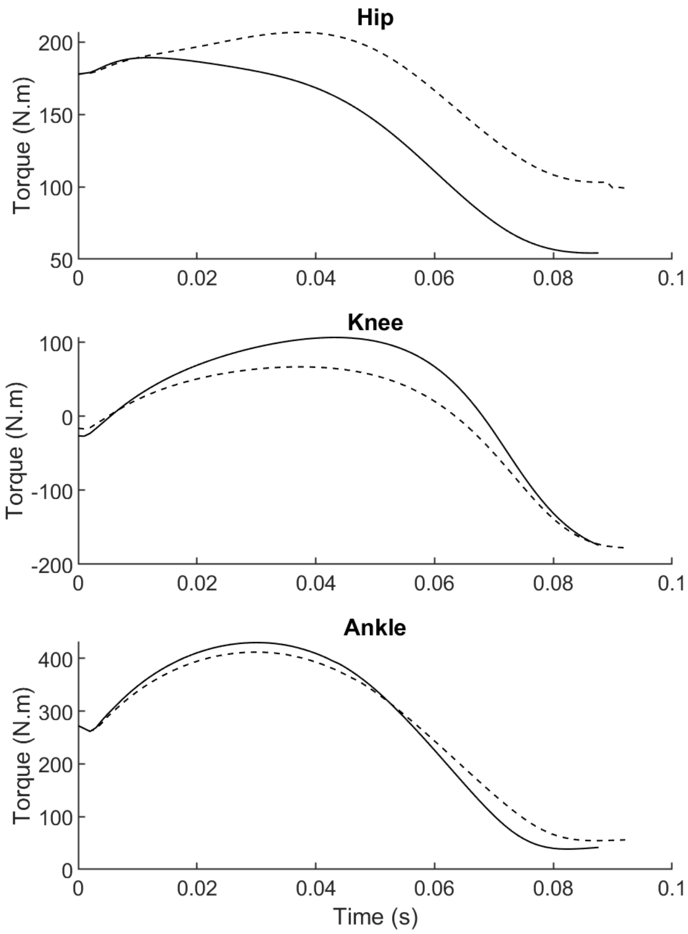
Figure 5



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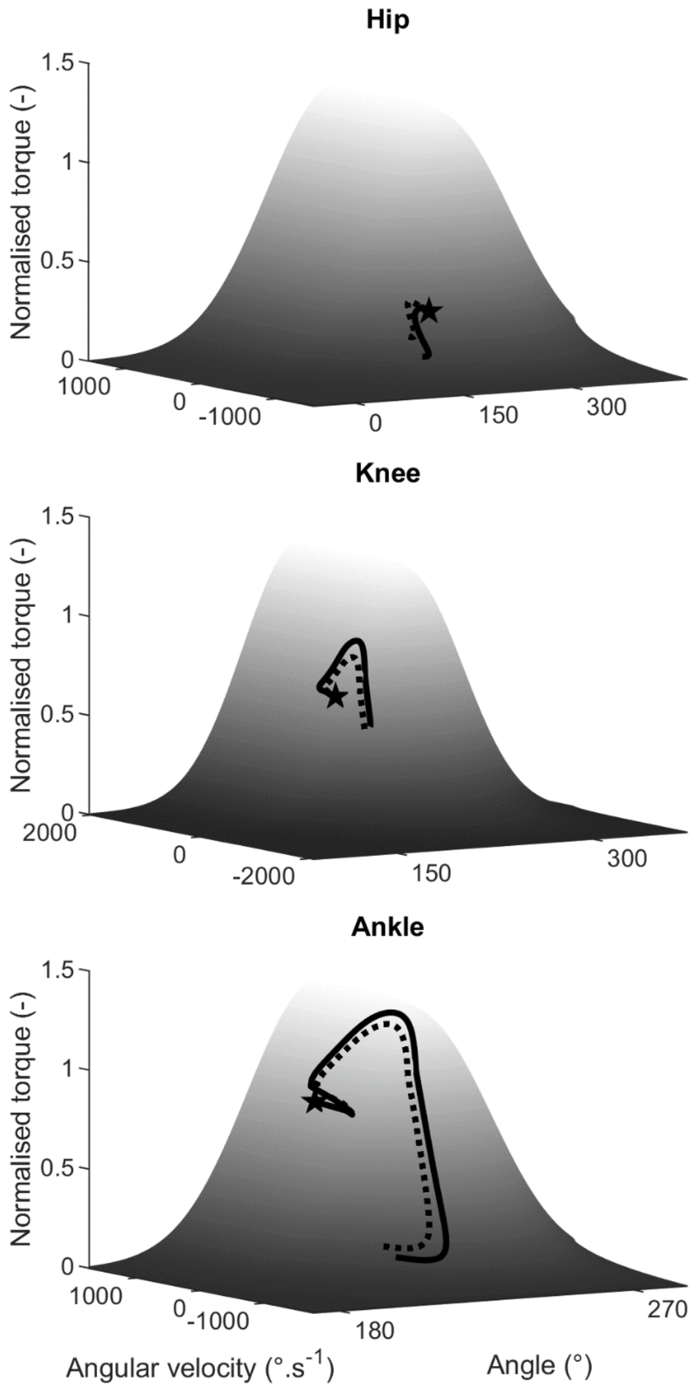
479 Figure 6


Hip
Normalised torque (-)
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Knee
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0
2000
0
-2000
150
300
Ankle
Normalised torque (-)
1.5
1
0.5
0
1000
0
-1000
180
270
Angular velocity (°.s-1)
Angle (°)

Figure 7

Table 1. Comparison between the two swing leg techniques for selected variables.

	Elite athlete	**Sub-elite athlete**
Horizontal velocity ($m.s^{-1}$)	10.0	9.2
Swing time (s)	0.374	0.374
Stance time (s)	0.088	0.092
Flight time (s)	0.143	0.141
Horizontal CoM displacement (m)	0.866	0.837
Vertical CoM displacement (m)	0.021	0.022
Vertical impulse (N.s)	111.7	109.8
Mean vertical force (N)	2123	2033
Mean hip extensor torque (N.m)	138.2	168.6
Mean knee extensor torque (N.m)	208.8	186.3
Mean ankle extensor torque (N.m)	277.2	267.8

Matched simulation animation

Sub-elite athlete optimised simulation animation

Click here to access/download
Supplementary Material
SLTse_optimisation.gif

Elite athlete optimised simulation animation

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Conflict of interest statement:

In the manuscript entitled “The influence of swing leg motion on maximum running speed” submitted for publication in the Journal of Biomechanics there are no issues of conflict of interest arising from the personal or professional associations of any of the authors.

Yours sincerely,

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