THE INFLUENCE OF SPRINT TECHNIQUE ON PERFORMANCE.

# Abstract

# Introduction

The maximal running speeds attained by humans have been recorded across a broad range from 6.2–11.1 m.s-1 (Weyand et al., 2000) with elite sprinters in the Olympic 100 m final reaching speeds over 12 m.s-1 (IAAF report, 2009). This prompts the question of what allows some humans to attain much faster maximal speeds than others.

Running speed is the product of stride length and stride frequency. Therefore, faster speeds could be attained by either taking longer strides or by taking them more frequently. When running at a constant (maximal) speed on level ground, the runner must produce a net vertical force equal to bodyweight. As speeds increase, the portion of the stride in which force can be produced, the contact time, decreases, requiring greater vertical forces to be produced in these briefer contacts. All else being equal, greater vertical forces will result in longer aerial times and stride lengths. Alternatively, a runner could keep the vertical force the same but decrease the stride time so that the vertical force is sufficient to support bodyweight over a shorter period, leading to increased stride frequencies. The maximal attainable speed could therefore be limited by either the ability to produce vertical force in shorter contacts or by the maximum speed in which legs could be cycled. Weyand et al. (2000; 2010) showed that in humans it is vertical force that differentiates faster and slower runners, rather than the time it takes to cycle limb, the swing time, which remains roughly constant regardless of top speed. Further work has shown that it is not just the magnitude of vertical force that is different between faster and slower runners but the shape of the vertical force-time graph, with faster sprinters showing asymmetrical forces, peaking in the early portion of stance (Clark and Weyand, 2014).

As such, much of the research has focused on the stance limb during running (Bezodis et al., 2008) and physical characteristics of faster sprinters which allow them to produce greater forces, such as muscle size (Handsfield et al., 2017, Miller et al., 2020; Weyand and Davis, 2005), architecture (Abe et al., 2000; Kumugai et al., 2000) or musculoskeletal geometry (Lee and Piazza, 2009; Suga et al., 2020). In comparison, there has been a much smaller focus on the technical differences between faster and slower sprinters. This is surprising given clear differences exist between the two, particularly in relation to the swing leg. Trained sprinters show greater amounts flexion at the hip of the swing leg, resulting in the swing leg’s thigh being closer to vertical at contralateral touchdown and reaching a greater amount of hip flexion at contralateral toe-off (Bushnell and Hunter, 2007; Kunz and Kauffman, 1981; Mann and Herman, 1985; Sides, 2010). Further, when running at faster speeds the mechanical demands of the swing leg, mainly at the hip, rapidly increase (Dorn et al., 2012; Schache et al., 2015). These results indicate that although the time taken to reposition the limb does not vary with speed, how the limb moves during this portion of the stride doe. It may therefore be expected that the technique of the swing leg has an important effect on sprinting performance.

Previous work has assumed that the difference in centre of mass (CoM) height between touchdown and toe-off is zero (Weyand et al., 2000). However, this is not strictly true as the CoM rises slightly during stance causing it to be higher at toe-off than at touchdown. An increased difference in CoM height would lead to a longer aerial time (and therefore swing time) for a given vertical velocity at toe-off (Figure 1). Alternatively, this would mean that a runner could have the same swing time but with a smaller vertical velocity at toe-off requiring less vertical impulse during stance – allowing them to run at faster speeds. It is interesting to note that a having the thigh closer to vertical at touchdown, resulting in a smaller angle between the thighs, and a more flexed hip at contralateral toe-off, characteristics of elite sprinters’ technique, would result in a greater difference in whole-body CoM height between touchdown and toe-off (assuming the rest of the body’s motion was unchanged). This may therefore be one mechanism by which technique aids sprinting performance. A larger difference in CoM height between touchdown and toe-off would result in a greater CoM velocity at touchdown however, requiring more vertical impulse to produce the same vertical velocity at toe-off.

Figure 1. Treating a runner as point mass, the effect of the difference in CoM height between touchdown and toe-off (ΔSy) can be determined using the equations of constant acceleration for a given vertical velocity at take-off. The two vertical lines show what the aerial time would be with a ΔSy of 0 cm and -3 cm.



Swing leg technique may also improve sprint performance through its effect on the stance leg. As the swinging leg is accelerated upwards it will cause a subsequent acceleration downwards on the rest of the body. This acceleration downwards would put the extensor muscles of the stance leg into a faster eccentric or slower concentric contraction, more favourable for force production. This would allow a runner to generate more vertical force, similar to what is observed with the arm swing in standing (Cheng et al., 2008; Harman et al., 1990) and running jumps (Allen et al., 2010). As different kinematics of the swing leg would cause different accelerations on the rest of the body, one technique may benefit from this whereas another may not. For example, elite sprinters have the swing leg thigh close to vertical at touchdown so that the swing leg’s CoM would mostly accelerate upwards during early phase of contact, causing the stance leg to be put in more favourable contractile conditions. If the swing leg is behind the body at touchdown, as is seen with untrained sprinters, then the hip flexion force will cause a downwards acceleration on the swing leg during the early phase of contact, causing a subsequent upwards acceleration on the rest of the body and putting the stance leg in less favourable contractile conditions.

Despite the strong theoretical rationale there have been limited investigations into what effect technique might have on performance, and those that have were limited to descriptive differences, not able to explain why a certain technique may be better than another. This is probably due to the difficulty in trying to manipulate technique experimentally (Yeadon and Challis, 1994). A computer simulation however does not suffer from these drawbacks, making it a viable approach to investigate this. Therefore, the aim of this study was to explore the ways in which technique affects sprinting performance.

# Methods

## Experimental data

After giving informed consent to participate, one male sprinter (28 years, 91.1 kg, 1.86 m, 100 m pb: 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, to allow identification of joint centres, and their positions recorded (250 Hz) using sixteen infrared cameras (Vicon Vantage, Oxford Metrics, Oxford, UK). A custom Vicon BodyBuilder model, composed of the trunk, thigh, shank, and foot, was written to extract segment and joint angles as well as net joint moments using inverse dynamics and then exported into MATLAB (R2020a, Mathworks, MA, USA) along with the calibrated forces for further analysis.

Kinetic and kinematic data were both 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 legs to give data on one full stride at top speed. Contact was identified using an 80 N threshold in vertical force and the force was set to 0 N during aerial phases.

To determine the effect of differing techniques, a publicly available video of an elite sprinter and a team sport athlete running at their respective top speeds, was used as it illustrated the major differences in technique. The location of the hip, knee, ankle and metatarsophalangeal (MTP) joint centres were digitised along with a point at the base of the neck to represent the top of the trunk, using the open-source package DLTdv7 (Hedrick, 2008). From which, segment and then joint angles were calculated, with quintic smoothing splines fitted to the angle data.

## Computer model

### Model construction

The model was constructed through an iterative process, beginning as simple as possible then progressively adding complexity until it was sufficient for the current purposes (Alexander, 2003; Yeadon and King, 2018). The model was two-dimensional, focusing on the sagittal plane, and composed of seven rigid segments connected by frictionless pin joints. These segments represented the thigh, shank, foot, and toe segment of the stance leg, the thigh and shank for the swing leg, and a combined head, arms and, trunk (HAT) segment, comprising the mass of the rest of the body (Figure 2). Given that the trunk is not completely rigid, and to include the effects of the arm swing, the CoM of the HAT segment was allowed to vary. Its position from the hip joint was calculated from the experimental data and was specified in the model by another quintic spline.

The foot-ground interface was modelled using viscoelastic springs at the end of the MTP joint and the end of the toes. The force at each contact point was calculated as:

Where x,y are the vertical and horizontal spring compressions and ki, bi are the spring stiffness and damping coefficients. The damping component of the vertical force was multiplied by the absolute spring depression to avoid negative force values while the spring was still stretched.

The hip, knee, and ankle joint of the stance leg was actuated by one flexion and one extension mono-articular torque generator, representing the contractile component (CC) of the muscle-tendon unit, in series with a rotational, linear spring, representing the series elastic component (SEC). The MTP joint was actuated by a viscoelastic spring, the equation for which is the same as the vertical force at each contact spring. The hip and knee joint of the swing leg were angle-driven, with the angle specified by either the data from the participant or from the digitised video of the two techniques

The torque produced at each torque generator was calculated as:

Where is the activation of the torque generator, T0 the maximum isometric torque, Tv and Ta are the normalised torque-angular velocity and angle relationships. The torque-angle relationship was taken from Forrester et al. (2011) and the torque-angular velocity relationship was taken from Yeadon et al. (2006), with the exception of differential activation. Differential activation is usually included to represent the lower muscle activity commonly seen in eccentric versus concentric movements (Westing et al., 1991) and was not included for two reasons. Firstly, it was likely much smaller during a movement well accustomed to the participant (e.g. sprinting for a well-trained sprinter) than in an isokinetic dynamometer where the measurements are taken, as increases in muscle activity are seen with training (Hortobagyi et al., 1996). Secondly, by removing the differential activation it allowed a closed-form solution to calculate the angular velocity from the CC torque, which helped when including series elasticity.

At each timestep the CC angle was calculated via numerical integration from the CC angular velocity. This then allowed the SEC angle to be calculated, from which the torque could be found by multiplying the SEC angle by the angular stiffness. By assuming the torque in the SEC was equal to the torque in the CC, the CC angular velocity could then be found, and the process repeated. This left just the initial CC angle to be determined which was done by assuming, initially, that the CC angular velocity equalled the joint angular velocity and numerically solving for the CC angle using the binary split method.

Activations of the torque generators were specified using the quintic function from Yeadon and Hiley (2000) with a slight modification. Each quintic function specified a ramp from one activation level to another, and so given an initial activation level, three parameters were required to define the function to the new activation level, the ramp onset time, the ramp time and the new activation level. The functions were pieced together such that the next ramp began at a specified time from the end of the previous ramp. In preliminary tests it was found that two ramps allowed the torque generators sufficient freedom, while keeping computing time low.

Input to the model was the initial segment angles and angular velocities, the initial position and velocity of the end of the foot segment and the parameters defining the activations for each torque generator. As CoM velocity was a more useful input this was specified and then the position and velocity of the end of the foot calculated. Given the participant was running on a treadmill and so would have small horizontal velocities in the laboratory frame, input was the measured CoM velocity plus the belt speed. Simulations began at touchdown of the stance leg and finished at take-off when the vertical force dropped to zero.

The equations of motion for the model were generated in Autolev (Kane and Levinson, 1985) and the Fortran code generated was then modified to include additional features of the model e.g. torque generator profiles. The equations of motion were integrated forwards using fourth order Runge-Kutta integration with a variable timestep.

### Parameter determination

Segments’ inertial properties were calculated using the geometric model of Yeadon (1990) for a previous study on the same participant and were left unchanged as there was only a small difference in the participant’s body mass on the two occasions. As torque generator parameters were unavailable, they were taken from a triple jumper with a similar performance level to the participant used here (Allen, 2009), and scaled by body mass. Parameters for the viscoelastic springs were determined during the model evaluations (see Section 2.3).

## Model Evaluation

The model was evaluated against the experimental data collected on the participant to assess how well it could match the contact phase. A simulated annealing algorithm, set to run in parallel (Higginson and Anderson, 2005), minimised a cost function by varying 42 activation parameters, 2 MTP spring and 8 contact spring parameters. The cost function to be minimised is shown below:

Where θtrunk is the global orientation of the model, θjoint the sum of the mean squared errors in hip, knee, ankle and MTP joint angles, taer, tcon the absolute difference in aerial and contact times and, vcmx the absolute difference in horizontal CoM velocity. Aerial time was calculated, using the equations of constant acceleration, from the CoM vertical velocity at the end of a simulation and the difference in height of the CoM between take-off and touchdown. Horizontal CoM velocity was calculated from the difference in the horizontal CoM position at the start and end of a simulation divided by the contact time.

The initial temperature for Simulated Annealing was chosen to give an appropriate step length so that roughly 50% of all function evaluations were accepted (Goffe et al., 1994) and NT, 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. Upper bounds on the activation level were 1.0. Ramp times for the activation profiles were given a lower bound of 100 ms (Tillin et al., 2012). The upper bound for the stiffness of spring at the MTP joint was 300 N.m and the contact spring parameters were not constrained in anyway. While this may lead to unrealistic spring compression during contact, it would account for the lack of compliance elsewhere in the model (Allen et al., 2012).

## Optimisation

Optimisations were carried out to assess how fast the model could run while still producing the necessary swing time. With the spring parameters kept the same as in the evaluation, the 42 activation parameters were again varied. The cost function to be minimised is shown below:

Where tsw is the absolute difference in swing time, between the performance and the simulation and vcmx the absolute difference in horizontal CoM velocity. If the model could match the swing time to within 0.001 s and there was not a drop in horizontal velocity of more than 0.01 m.s-1 between the start and end of the simulation, bounds picked from the variation in the experimental data, then the model was said to be able to run at that speed. The speed was then increased, and the optimisation repeated until the model could not meet those conditions. Bounds on the activation parameters were kept the same as in the evaluation. To further evaluate the model, an optimisation was first performed using the function specifying the swinging limb movement from the matching data. Optimisations were then performed to compare the two techniques; everything was kept the same between optimisations except the spline coefficients used to drive the swing leg.

# Results

# Discussion

# References