A CASE STUDY OF STRIDE FREQUENCY AND SWING TIME IN ELITE ABLE-BODIED SPRINT RUNNING: IMPLICATIONS FOR AMPUTEE DEBATE

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Recent research into trans-tibial double-amputee sprint performance has debated the possible inherent advantages, disadvantages and limitations to sprinting with prosthetic limbs compared to healthy limbs. Biomechanical data gathered throughout a training season from an elite able-bodied sprinter provide a new perspective on this debate. Peak stride frequency was measured at 2.62 Hz, and the corresponding swing time was estimated to be 0.287 s in the able-bodied sprinter. Published swing time and stride frequency values from the double-amputee at maximum velocity, thought to be beyond biological limits, therefore may not be so, although previously published research has provided evidence that some joint kinetic values from the double-amputee have not been shown in elite able-bodied sprinting.

KEY WORDS: athletics, track and field, able-bodied sprinters, double-amputee, limits of maximum performance, kinematics

INTRODUCTION: Current debate on the biomechanical limits, advantages and disadvantages of an elite trans-tibial double-amputee compared to able-bodied maximum performance has reached varying conclusions. A Point: Counterpoint debate by Weyand et al. (in press) highlighted stride frequency and swing time as important limiting factors, but disagreed on the boundaries possible in able-bodied athletes. Stride frequency has previously been identified as an important factor in sprint performance (Bezodis et al., 2008b), although its limits in able-bodied sprinters are currently unknown. The aim of this study was to determine whether double-amputee stride frequency (2.56 Hz) and swing time (0.284 s) values published by Weyand et al. (2009) are within the boundaries possible in able-bodied athletes.

METHODS: One elite able-bodied sprinter (age: 18 years, height: 1.79 m, mass: 81.4 kg, 100 m personal best: 10.20 s) gave written informed consent to participate. The main data were collected in an indoor athletics centre over six months during the 'speed work' phases of indoor and outdoor seasons. Two digital cameras (Sony DCR-TRV 900E) were mounted on the wall 6.40 m apart, 4.25 m above track level and 7.20 m from the centre of the lane in which trials took place. Each camera was set up with a shutter speed of 1/600 s and a field of view of 6.2 m in the lane of interest. There was a 2.5 m overlap of the two cameras' views at the centre of the global field of view. Both cameras were separately calibrated using six control points in the following two orthogonal planes. A calibration area of 6.00 x 1.17 m was set in the transverse plane at track level for the determination of step length. A second calibration area of 5.50 x 2.06 m was set in the sagittal plane at the centre of the lane for the determination of velocity. Data were collected during the course of the subject's normal training sessions, where the athlete was performing 'speed work'. Sessions typically comprised six to eight runs in the early spring and three to four runs by late spring and summer. Video images of the runs were recorded during the maximal velocity phase of a sprint. The start of the combined 9.5 m field of view of the two cameras was at least 40 m from the start of the sprint. The subject was allowed normal training recovery after each run. Video data were imported into Target (Loughborough Innovations Limited, UK) for digitising. The last field before touchdown and the first field after touchdown were digitised for each contact. A 20-point model of the human body was used, with inertia data based on de Leva (1996), apart from the foot segment, for which Winter's data (2005) were used, with an extra 200 g added to account for the mass of the running spike (Hunter *et al.*, 2004). The toe of the

ground foot was independently digitised three times during the first field after touchdown to minimise error in the calculation of step length. Digitised trial sequences were reconstructed using a 2D DLT routine (Walton, 1981). Calculation of variables for each individual step was always carried out with the data gathered from a single camera, ensuring that the respective calibration was used, i.e. no step variables were calculated from mixed views.

Step lengths were calculated by subtracting the mean of the three reconstructed contact foot toe locations from one contact in the direction of the run from the corresponding mean contact foot toe location of the contralateral foot at the next contact. Step velocity (average centre of mass velocity across the whole step) was calculated as the difference between the mean centre of mass displacements from the two digitised fields at two consecutive contacts divided by the time between them. Step frequency was calculated by dividing the step velocity by the step length. Further details of the calculations can be found in Bezodis *et al.* (2008a). Data were collected from three or four steps within the maximum-velocity phase of each maximal sprint, where a stride is defined as two consecutive steps. Thus, the 141 measured steps could not all readily be grouped into separate strides.

Following the results of the main study, a brief follow-up study was set up outdoors after the competition season had finished. Three-dimensional kinematic data was collected with two high speed cameras (Motion Pro®, HS-1, Redlake, USA) at 200 Hz. Camera 1 was set perpendicularly at 38.30 m away from the midline of the running lane and camera 2 was located at 30.00 m in front of the central point with 1.50 m offset to the right of the running lane in order to let the athlete pass the camera. Both cameras were set at the height of 1.00 m with 1/1000 s shutter speed. The camera views were calibrated with 18 points creating a volume with maximum dimensions of 6.50 m (length), 1.20 m (width) and 2.07 m (height), thus allowing a full running stride to be analysed. The athlete performed three maximum effort sprints with 40 m run-in before the camera views and normal training recovery between the runs. Contact time, swing time and stride frequency data were analysed directly from the camera clips. The stride velocity was analysed in exactly the same way as the step velocity above by digitising the relevant fields from both camera views in Peak Motus® (v. 8.5, Vicon, USA) with centre of mass positional data extracted after DLT reconstruction (Abdel-Aziz and Karara, 1971).

RESULTS: In the main study, the maximum step frequency measured was 5.28 Hz at a velocity of 10.84 $m \cdot s^{-1}$ (Figure 1), equivalent to a stride frequency of 2.64 Hz. When considering pairs of consecutive steps the highest stride frequency was 2.62 Hz, at 10.87 $m \cdot s^{-1}$. A total of 20 measured steps for this athlete displayed a frequency of at least 5.12 Hz (equivalent to a stride frequency of 2.56 Hz). Comparisons against known locations on the track surface and repeat digitisations in the horizontal plane revealed step length errors of ± 0.01 m. Comparisons of sagittal plane results to sequences in which all fields were digitised revealed velocity errors of ± 0.01 $m \cdot s^{-1}$, and errors in step frequency of ± 0.01 Hz. In the follow-up study, the highest stride frequency was 2.53 Hz at 10.60 $m \cdot s^{-1}$ (Table 1). The shortest measured swing time was 0.295 s and contact times varied between 0.095 and 0.105 s.

Table 1. Velocity, stride frequency and swing and contact times for three follow-up runs.

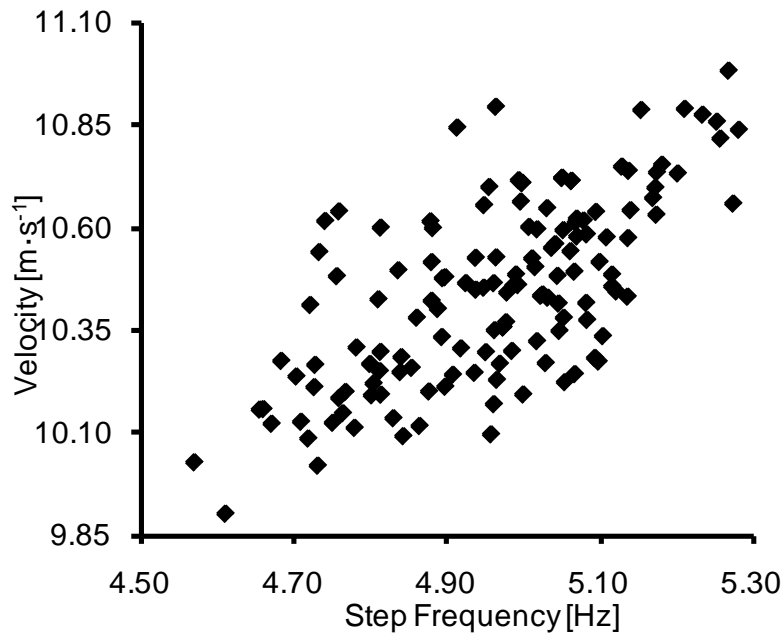|		Run 1	Run 2	Run 3
Velocity	[$m \cdot s^{-1}$]	10.34	10.61	10.60
Stride frequency	[Hz]	2.44	2.47	2.53
Swing time	[s]	0.305	0.300	0.295
Left contact time	[s]	0.105	0.105	0.105
Right contact time	[s]	0.100	0.095	0.095

Figure 1. Step frequency against velocity for all measured steps in the main study.

DISCUSSION: Results of the main study showed that 20 of the 141 measured steps in the study were at a greater frequency than the double-amputee strides measured by Weyand et al. (2009). The debate in Weyand et al. (in press) also focused on swing time, which although not directly measured in the main study, can be estimated. The minimum stride time was 0.381 s (reciprocates as 2.62 Hz). An individual stride time comprises ground contact and recovery swing of the same limb. Since contact times were not measured in the main study, they must be inferred from other data. The top speed of the able-bodied athletes in Weyand et al. (2009) was 10.8 ± 0.6 m·s^{-1}, equivalent to the 10.87 m·s^{-1} measured in this study. The subjects in Weyand et al. (2009) had a mean contact time of 0.094 s which corresponds well with the elite athlete (Bezodis et al., 2008b) contact time of 0.097 s measured via force plate in another study (Bezodis et al., 2008a), although the velocity for this athlete on that occasion was slightly lower at 10.37 m·s^{-1}. These values also match with the shortest contact times of 0.095 s measured from our elite athlete in the follow-up study running at 10.60 m·s^{-1}. Subtracting 0.094 s from the 0.381 s stride time leaves a 0.287 s swing time for the elite athlete in this study, just longer than 0.284 s recorded for the double-amputee at the same speed (Weyand et al., 2009). Considering that generally able-bodied athletes have slightly longer aerial than contact times (Weyand et al. 2000; 2009), it could be possible that the elite athlete's contact time in this study was slightly shorter than the values presented above. Even if the contact time was 10% less than above, i.e. 0.085 s (which would be extraordinarily short), the swing time would still have been 0.296 s. In the follow-up study during the off-season, the shortest measured swing time was 0.295 s. This occurred with a stride time of 0.395 s (stride frequency of 2.53Hz), i.e. the contact time was 0.100 s at the start of this stride. Overall, it is clear that the contact time as short as 0.085 s in the above example is not realistic for this athlete, and consequently the upper limit estimation for the swing time at 0.296 s is over conservative when the athlete was running with the stride frequency of 2.62 Hz. In any case, these values are substantially shorter than able-bodied athletes' swing times of 0.359 ± 0.019 s in Weyand et al. (2009) and clearly shorter than 0.320 s reported for the fastest 100 m sprinter in the world at the time (Weyand et al., 2000). While the double-amputee's swing time of 0.284 s (Weyand et al. 2009) may still be shorter than any able-bodied sprinter's data, this study shows that swing times under 0.300 s are possible at high speeds for able-bodied athletes and challenge a conclusion in the debate by Weyand et al. (in press) that 0.284 s is beyond biological limits. Moreover, 14% of all steps

measured in this study were greater in frequency than the 5.12 Hz measured in the double-amputee sprinter by Weyand et al. (2009), suggesting that a step frequency of 5.12 Hz is clearly possible in an able-bodied sprinter and thus not artificial nor attributable to non-biological factors as claimed in Weyand et al. (in press).

Determining whether an individual biomechanically fits into a population when sample sizes of elite athletes are inevitably small makes consideration of mean and standard deviation prone to incorrect assumptions of normal distribution of data. Presentation of individual able-bodied values for specific variables shows whether the double-amputee produces similar magnitudes to controls. Data presented here suggests the perceived amputee temporal advantages over able-bodied athletes may not exist. However, previous studies of joint kinetics suggest that the double-amputee does clearly get an advantage over able-bodied athletes during the maximum-velocity phase (Bezodis et al., 2008a; Brüggemann et al., 2008). There are so many ways of looking at sprint biomechanics without even considering physiological and psychological factors, as well as ethical and philosophical issues, that it may never be possible to say if there's a definitive overall advantage inherent to amputee performance.

CONCLUSION: Kinematic data presented here show the example of an elite able-bodied athlete with stride frequencies and swing times similar to those recorded in the double-amputee. Data presented elsewhere, however, suggest that some of the joint kinetic variables in the double amputee have not been matched by elite able-bodied sprinters.

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