First and Second Step characteristics of Amputee and Able-Bodied Sprinters

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Abstract

Purpose: In the sprint events, the first two steps are used to accelerate the center of mass horizontally and vertically. Amputee athletes cannot actively generate energy with their running specific prosthesis. It is likely that sprint acceleration mechanics, including step asymmetry, are altered compared to able-bodied athletes. Therefore, the aim of this study was to investigate spatio-temporal and kinetic variables of amputee compared to able-bodied sprinters.

Methods: Kinematic and kinetic data of the first and second stance were collected from 15 able-bodied and 7 amputee sprinters (2 unilateral-transfemoral, 4 unilateral-transtibial, 1 bilateral-transtibial) with a motion-capture system (250 Hz) and two force plates (1000 Hz), additionally bilateral asymmetry was quantified and compared between groups.

Results: Compared to able-bodied athletes, amputee athletes demonstrated significantly lower performance values for 5 m and 10 m times. Step length, step velocity, step frequency were decreased and contact times increased. Peak horizontal force and relative change of horizontal velocity were decreased in both stances. Peak vertical force and relative change of vertical velocity were lower for the amputee than able-bodied group during first stance, but significantly higher during second stance. During the first stance able-bodied and amputee sprinters displayed a similar orientation of the ground reaction force vector, which became more vertically orientated in the amputee group during second stance. Amputee sprinters showed significantly greater asymmetry magnitudes for vertical force kinetics compared to able-bodied athletes.

Conclusion: The running specific prosthesis does not replicate the function of the biological limb well in the early acceleration phase.

Keywords: running specific prosthesis, transfemoral amputee, transtibial amputee, athletics, ground reaction force

Introduction

In sprint events, the early acceleration phase (defined here as first and second steps from the blocks) is used to accelerate the center of mass (COM) horizontally and vertically.[1,2] In able-bodied (AB) elite athletes, the first and second steps comprise approximately 5% of total 100 m race time.[3] After block clearance the highest gain of horizontal velocity occurs during the first step[4], followed by the second step, after which approximately half of the maximum horizontal velocity is achieved,[3] while vertical acceleration of the COM occurs similarly during both stance phases.[2] The capability of an athlete to generate forward COM acceleration mainly depends on (a) the neuromuscular characteristics and musculoskeletal mechanical properties of the sprinter and (b) the technical ability to move the body mass forward.[5,6]

With respect to (a), during the start and early acceleration, the positive power to generate acceleration in AB originates from the contractile components of the extensor muscle-tendon units.[7] The role of passive elastic structures like tendons and ligaments is less clear. While earlier studies report an increase of work performed by passive elastic structures with increasing sprint velocity,[8] recent findings suggest storage of tendon elastic strain energy in the plantar flexors is just as vital at the start as it is at the end of a race.[9]

The technical ability (b) can be summarized by athletes' ability to increase the horizontal component of the ground reaction force (GRF) and can be expressed as the ratio of force (RoF), i.e. the ratio of mean horizontal to resultant force.[5,6] Over a sprint acceleration phase of able-bodied athletes, the orientation of force onto the ground and as such the RoF decreases with increasing running speed.[5,6]

In AB sprinting, acceleration during the first stance is mainly due to ankle and hip joint work.[2,10] Brazil et al. [10] reported the ankle (42 ± 6%) as the most dominant contributor to leg extension energy generation followed by the hip (32 ± 9%) and knee joints (26 ± 8%). This finding agrees with previous work of able-bodied sprinting, citing the ankle as the main relative contributor to horizontal (first and second stance: 67%, 93%) and vertical (first and second stance: 50%, 76%) COM acceleration.[2] Additionally research of able-bodied sprinting highlights the importance of the m. soleus and m. gastrocnemius for the first contact.[9] Of the three lower limb joints, the knee contributes with approx. 25% the least amount towards acceleration. Amputee athletes (AMP) miss the contractile elements of the musculature of the amputated limb (e.g. m. gastrocnemius and m. soleus) and even though running specific prostheses (RSP) utilize elastic components, they can only store and return energy, not generate it for the sprinter,[11] as the biological ankle can.[12] When exiting the blocks, preloading the RSP might be possible to allow for some compression and recoil of energy in the following steps; however, no data on a possible recoil of energy was found by the authors for the first steps and it is assumed that, due to the lower input velocity, these forces are minor in comparison to those reported at maximum velocity. Additionally, the ability of AMP to generate a powerful block start is shown to be less than of AB athletes.[11,13] The prosthetic limb with the RSP is often longer than the biological limb, to replicate the functional on-toe leg length during the maximum velocity phase.[14] During early acceleration, this necessitates specific movement strategies, to bring the leg forward whilst the athlete is in a crouched position and lacks space for toe-clearance. Transfemoral amputees (TF) additionally need to place the prosthetic limb in an extended position with the rotational center being posterior to the force vector to avoid collapsing of the prosthetic knee joint. Furthermore, TF cannot flex or extend their knee with muscular activation, due to the missing function of hamstring and gastrocnemius muscles which has implications for swing and stance phases.

Finally, the first two steps in the early acceleration phase differ from each other in their initial position and joint contribution to COM acceleration.[2] Therefore, asymmetry between the right and left limb during first and second stance phases may be functionally useful in able-bodied athletes,[4] but the asymmetry characteristics in able-bodied and amputee athlete sprint acceleration are still unclear. Unilateral amputee athletes may display increased asymmetry between first and second stance due to structural differences between the limbs and the possible need to compensate for the functional deficits of the prosthetic limb. However, as the purpose of the RSP is to replicate the function of the biological limb, asymmetry may be similar to that of able-bodied athletes due to the differing demands of each limb during early acceleration. Comparing asymmetry between able-bodied and amputee athletes during early acceleration would further increase the understanding of the differences between the athletes and the effectiveness of RSP in replicating able-bodied performance. Overall, given the mechanical and anatomical constraints, it remains unclear how AMP athletes of various amputation levels perform during early acceleration compared with AB. It is hypothesized, that AMP will demonstrate altered spatio-temporal and kinetic performance variables in both the affected and biological limbs compared to AB sprinters. Therefore, the main aims of this research were to compare 1) spatio-temporal characteristics and 2) ground reaction forces between AB and AMP sprinters during early acceleration. In addition, between-limb differences in spatio-temporal and ground reaction force data may further inform the influence of RSP on the sprint start; therefore, the final aim was 3) to gain knowledge of step asymmetry during the sprint start and the influence of structural differences between RSP and the biological limb on this. The knowledge gained from this study enhances current understanding of how AMP athletes apply force to the ground in early acceleration and can inform coaching practice.

Methods

Participants

Fifteen male AB sprinters (Mean ± SD: 23.5 ± 4.5 yrs, 1.78 ± 0.04 m, 75.0 ± 3.6 kg,) with 100 m personal best (PB) times ranging from 10.10-11.20 s and seven male AMP sprinters (Table 1) participated in this study.

---Table 1----

Hence, the mean performance of the AB and AMP group was 11.4 ± 3.4% and 11.2 ± 5.7% slower than the current 100 m sprint world record of each group, respectively. Informed consent was obtained from all participants and experimental procedures followed ethical standards in the spirit of the Helsinki Declaration. No potential conflicts of interest occurred for the participants of this study.

Design

Observational research

Methodology

Data collection took place at indoor tracks based in Cardiff, UK (n= 15 AB, 3 AMP) and Cologne, Germany (n= 4 AMP). Data were collected using a 3D motion capture system (VICON, Nexus 1.8.x Oxford Metrics Ltd, UK, using 12 MX 13 (UK) and 15 MX F 40 (Germany) cameras) and two force plates (Kistler Instruments Corporation, Winterthur, Switzerland, 9287) embedded in the track and covered with the original runway surface. The same custom made start block system including speed gates (type: 7280, Weitmann & Konrad GmbH & Co.KG, Leinfeld-Echterdingen, Germany) at 5 m and 10 m was used. Participants wore their own spiked shoes and RSP (AMP). A reflective toe marker was placed at the second metatarsal joint on each biological limb and at the medial and lateral distal part of the RSP. Marker data were collected at 250 Hz and kinetic data at 1000 Hz synchronously. After individual warm-ups, all athletes performed up to 6 maximum effort 10 m acceleration runs from the blocks, contacting the force plates with first and second steps.

Data were analyzed for the first and second stance phase and the respective flight phase in between using Visual3D software (C-motion, Rockville, MD, USA). Marker trajectories were low pass filtered using a 12 Hz recursive 4th order Butterworth filter. Touchdown and take-off were identified via the kinetic data as the first frame in which the raw signal of vertical force exceeded and fell below a threshold of 20 N, respectively. For the RSP a virtual toe marker was created half-way between the two RSP markers. Step length and width were identified using the toe markers. Step frequency of the first step was calculated as 1/(first stance contact time + flight time) and step velocity as the product of step frequency and step length. Kinetic data were filtered using a recursive, low-pass 4th order butterworth filter of 35 Hz and normalized to body weight. Peak and mean horizontal (anterior-posterior) and vertical forces (peak F_h, peak F_v) were identified. To calculate relative change in horizontal and vertical velocity (Δv_h, Δv_v), the horizontal and vertical impulse, obtained by trapezium integration of the respective force-time signal (with body weight subtracted from the vertical force signal) was divided by body mass. As an indicator for the orientation of the resultant force vector, the ratio of force (RoF) was calculated for each step by:[6,11]

$$RoF = \frac{mean\ F_h}{mean\ F_{resultant}} = \frac{mean\ F_h}{\sqrt{mean\ {F_h}^2 + mean {F_v}^2}}$$

Asymmetry between first and second contact was calculated for each group for contact time, peak $F_{h/v}$, $\Delta v_{h/v}$ and RoF via the symmetry angle:[15]

$$symmetry\ angle = \frac{\left(45° - arctan\left(x_{second\ stance}/x_{first\ stance}\right)\right)}{90°} \times 100\% \qquad (1)$$

Where $x_{first\ stance/\ second\ stance}$ is the value for the variable of the first/second stance, respectively. A value of 0% indicates perfect symmetry, a positive value indicates a higher first stance and a negative value indicates a higher second stance value.

For each parameter the mean of each participant's three fastest trials was taken for further analysis.

Statistical Analysis

Statistical analysis was calculated using SPSS software (v.23, IBM, Armonk, NY, USA). Due to the low sample size of the individual amputation levels, all amputee athletes were pooled together. Not all parameters were normally distributed (Shapiro-Wilk test); therefore, nonparametric statistics were calculated. The main effect of the stances (first vs second contact) was analyzed using the Wilcoxon test, and the main effect of the groups (AB-AMP) was analyzed using the Mann-Whitney U-test for independent samples. The interaction effect between steps and group was identified using the difference between first and second stance values and calculated via a Mann-Whitney U-test for independent samples (AB, AMP). For all tests the significance level was set to 5%. To identify meaningful asymmetry relative to intra-limb variability the difference between the first and second contact for each group was tested for significance.[16] Effect-sizes were calculated for nonparametric data using *r* with the boundaries of 0.1, 0.3 and 0.5 for small, medium and large effect-size.[17] The inferential statistical analysis identifies differences between the able-bodied and all AMP athletes. However, due to the influence of the different amputation levels on the athlete, it was also of interest to investigate step characteristics between different amputation levels. Therefore, a descriptive approach was also taken to identify whether there was overlap in the 95% confidence interval of the median for unilateral transtibial (UTT), unilateral transfemoral (UTF) and bilateral transtibial (BTT) groups. This approach allowed the authors to also consider the homogeneity within the amputee group.

Results

All unilateral AMPs chose their affected leg as the rear leg in the starting blocks and consequently the first stance contact was made with the RSP and second stance with the biological limb. For the spatio-temporal parameters the AMP athletes demonstrated significantly decreased step length, frequency and velocity and significantly increased 5 m times, 10 m times and first and second contact times with large effect-sizes (Table 2). The interaction between group (AB/AMP) and stance (first/second) identified a significant interaction effect for contact time (P=0.032, r=0.46), supported by a lower symmetry angle for AB (Median (IQR) 3.8 (3.8)%) compared to AMP (6.2 (7.2)%) (Figure 1).

---Table 2 ---

---Figure 1---

The time series of the horizontal and vertical GRF demonstrate differences between the AB and AMP group for the first and second stance (Figure 2).

--- Figure 2---

Peak F_h and Δv_h for both the first and second stance were significantly decreased in the AMP athletes compared to the AB with large effect-sizes (Figure 3). A significant interaction (P=0.012, r=0.53) identified that AB athletes had a higher peak F_h at the first stance compared to the second stance while AMP athletes had similar peak F_h during first and second stance. Additionally, the AMP group demonstrated significantly lower performance values for Δv_h in both stances compared to the AB athletes, with large effect-sizes. Both groups produced a higher Δv_h at first stance with no interaction effect (Figure 3). The symmetry angle values corroborate these findings for F_h with a meaningful symmetry angle of 5.14 (3.87)% for AB and -1.15 (18.54)% for AMP and for Δv_h with similar meaningful symmetry angle values of 10.52 (4.62)% (AB) and 8.61 (15.35)% (AMP) (Figure 1).

---Figure 3---

During first stance, the AMP athletes produced a significantly decreased peak F_v and Δv_v (effect-size: large) with their RSP compared to the biological limbs of the AB athletes. The second stance showed opposite characteristics, as the AMPs produced a significantly increased peak F_v (effect-size: large) and Δv_v (effect-size: medium) than the AB athletes (Figure 4). This is supported by the symmetry angle results where AB athletes had positive meaningful symmetry angle for F_v (1.72 (1.68)%) and Δv_v (2.79 (11.86)%), whereas AMP athletes displayed meaningful negative symmetry angles for F_v (-9.43 (7.42)%) and Δv_v (-22.99 (36.89)%). Additionally, the symmetry angles for both, F_v and Δv_v differed significantly between the AB and AMP group with large effect-sizes. (Figure 1).

--- Figure 4---

The analysis of the RoF showed a significant increase of the vertical orientation of the GRF from first contact to second contact in the AB group only ($P=0.00$, $r=0.88$). Further, during the second contact, the RoF was significantly more vertically orientated ($P<0.001$, $r=0.79$) in the AMP group compared to the AB group (Figure 5). Within the AMP group, both UTF athletes showed different trends in RoF than all other participants, with the horizontal orientation of the force to the ground increasing from first to second ground contact. The symmetry angle results supported these findings, and showed a meaningful symmetry angle between first and second stance only for the AB group (3.9 (3.2)%) (Figure 1).

---Figure 5 ----

With respect to effects of the RSP on different amputation levels, some parameters showed a difference based on the 95%-CI of the median between the unilateral TF and TT (UTF and UTT) amputees. The UTF athletes displayed higher peak F_v (Figure 4) and generally higher contact times (265-288 ms UTFs vs. 204-304 ms UTTs and 212 ms BTT) during first stance and an increase in step width (0.63-0.35 m UTFs versus 0.18-0.32 m UTTs), accompanied with an overall decrease in step velocity (2.4-2.5 m/s UTFs vs 2.7-4.1 m/s UTTs). The values for the bilateral TT athlete were within the 95%-CI of the median of either the UTF or UTT group for all parameters..

Discussion

The primary aim of this study was to investigate biomechanical performance characteristics of the first and second stance phase of AMP compared to AB sprinters.

After block clearance, athletes develop forward and upward propulsion in the first and second stance to transition effectively into sprint running.[1,2] During these stance phases, the ankle and hip have been identified as the main joints contributing to acceleration.[2,10] The current study showed generally significantly lower performance values for AMP compared to AB athletes for both the first and second stance, excluding step width and flight time (equal performance values). Additionally, the vertical force data showed a compensation mechanism, indicating that the biological limb of the unilateral AMPs compensated for the low peak F_v during first stance by significantly increasing second stance peak F_v and Δv_v compared with AB. Further, it was noticeable, that the AMP group displayed higher IQR than the AB group in most parameters, indicating that the AMP group was more heterogeneous and showed more individual solutions within their movement execution than the AB group.

Current research suggests that the orientation of the resultant force vector is more important to sprint performance than the magnitudes of individual force components.[6,18] The RoF values of the able-bodied participants in the current study decreased from first to second stance by approx. 5%, demonstrating that the force during the second step was more vertically oriented. Whilst the orientation of the force vector indicated by the RoF of the AMP is comparable to the AB during first stance, the amputee's RoF was decreased by approximately 10% during second stance, showing a significantly increased vertical orientation of the GRF compared to AB. Previous research showed, that RoF was able to differentiate between elite and sub-elite athletes,[5] therefore this is further evidence that the RSP limits the sprint acceleration phase of unilateral AMP sprinters. The data suggests that the biological limb needed to compensate for the RSP in the second stance by generating an increased vertical force compared to the AB group. When considering individual amputation levels, the bilateral athlete decreased horizontal orientation of the GRF from first to second contact by 4%, showing similar values to the AB athletes. The UTT athletes appeared to use their biological limb rather than their affected limb to lift their CoM upwards. The RoF for the UTF athletes showed a decreased horizontal orientation of the GRF (and as such an increased vertical orientation) compared to AB during both stances. We speculate based on previously published data from Willwacher et al (2016)[11], where the authors observed that UTF athletes tend to raise more vertically out of the starting blocks compared to UTTs and AB,[11] that the participants of this study were likely to show similar starting block performances. If so, this partly could explain the more vertically orientated GRFs during the first and second stance. Additionally, and even though the horizontal force was generally decreased in UTFs, they increased or kept the horizontal orientation constant with the second step, which is different to all other participants. These characteristics indicate a specific compensatory technique due to the artificial knee. When exiting the starting blocks, the UTF athlete cannot actively flex the knee to clear the ground and therefore brings the artificial limb laterally forward by external rotation of the hip.[11] The step width is often increased due to this technique, as the RSP contacts the ground laterally to the COM. During the following stance, the knee joint additionally has to be positioned in an extended position with the mechanical knee joint center being positioned posterior to the GRF vector to avoid collapsing. This is achieved by the UTF athlete actively swinging the leg in a whip-like movement pattern prior to ground contact, which likely increases the horizontal component of the force.

The compensatory role of the AMP biological limb during second stance may be to effectively prepare for the 3rd stance which again occurs on the RSP. In addition, the AMP group demonstrated significantly shorter step lengths led to slower 5m and 10 m sprint times for the AMP group. It can be concluded that the RSP does not perform well in the early acceleration phase of the sprint compared to the biological limb. The significantly greater asymmetry for vertical kinetics parameters, which further showed a reversed asymmetry (higher values on the second stance (AMP) versus higher values on the first stance (AB)) indicates that accelerative step asymmetries were increased by the RSP, suggesting that the RSP does not fully replicate the function of the biological limb. This finding also indicates that the lower AMP performance is due to the lower performance of the RSP rather than just being a result of lower block phase performance.[11] From a performance perspective, step velocity could be improved by either increasing step length, step frequency, or both. However, given the constraints of the RSP to generate vertical propulsion (Figure 4) which influences flight time, it may be beneficial for AMP sprinters to focus on technical strategies to increase step frequency during the first step.

All unilateral athletes placed their affected limb in the rear position at the start and consequently the first stance involved their RSP. This pattern of leg positioning seems to be common; however, for transtibial amputees, block performance appears to be independent of the biological or affected limb being placed in the rear block.[13] As the opportunity to generate high Δv_h is higher during the first than second stance (demonstrated by AB athletes), unilateral transtibial AMP athletes may benefit from positioning the biological limb in the rear block so that it is used for first stance contact, allowing the biological ankle joint to have maximal contribution to forwards and upwards propulsion.[2] This strategy may also increase the vertical position of the athlete at second stance contact, increasing preloading of the RSP and potentially performance. Currently, the suggestion of potential performance gains through altered foot placement in the blocks remains speculative.

Practical Application

These findings demonstrate the different movement strategies required by a range of athletes with different amputation levels for the first time and lead the way for further research to better inform RSP development and training practice. Step asymmetries are imposed by the RSP and are more pronounced in UTF than UTT athletes. For vertical force development, asymmetry direction is reversed compared with AB, indicating that the biological limb can partly compensate for the vertical rise of the COM.

From a performance perspective, training for AMP sprinters could focus on increasing step length and/or reducing contact times to increase step frequency. Improving e.g. hip extensor strength to increase the ability for load application onto the prostheses, or technical changes to the point of contact may have an effect on both step length and contact times. However at present the exact performance implications of changes to either of those step characteristics are unknown. Additionally, further research should investigate whether switching the leg position in the starting block could improve performance in the first steps.

Conclusions

In addition to poorer block performance, the mechanical characteristics and inability of the RSP to increase energy of the athlete, make the RSP less favorable compared to able bodied athletes' limbs for the development of horizontal and vertical acceleration in the first and second stance. Further insights into the effect of amputation levels and RSP designs on joint kinematics and kinetics is necessary to develop effective training strategies for AMP sprinters

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Figure Captions

Figure 1: Mean symmetry angle for first and second stance for able-bodied and amputee athletes. #: indicates a meaningful asymmetry between first and second stance, *: indicates a significant difference in symmetry angle between groups

Figure 2: Mean horizontal (a) and vertical (b) force time curves for the first and second contact for able bodied (AB) and amputee sprinters divided in unilateral transfemoral (UTF), unilateral transtibial (UTT) and bilateral transtibial (BTT). Unilateral amputee athletes realized the first contact with their RSP.

Figure 3: Peak horizontal force (a) and relative change in horizontal velocity (b): Boxplots for the able-bodied (AB) and amputee (AMP) group including individual data for the amputee athletes for the first and second contact.

Figure 4: Peak vertical force (a) and relative change in vertical velocity (b): Boxplots for the able-bodied (AB) and amputee (AMP) group including individual data for the amputee athletes for the first and second contact.

Figure 5: Ratio of force (RoF) for the first and second contact for the able-bodied (AB) and amputee (AMP) group including individual data for the amputee athletes.

Tables:

Table 1: Amputee athlete characteristics

Table 2: Median and interquartile range of spatio-temporal parameters of the able-bodied (AB) and amputee (AMP) group.