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Biomechanical determinants of top running speeds in para-athletes with unilateral transfemoral amputation

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Abstract

Background: An increased understanding of biomechanical determinants that influence the sprint performance of para-athletes with a unilateral transfemoral amputation will provide us with a basis for better evaluating athletes' sprint performance and would be expected to aid in the development of more effective training methods and running-specific prosthesis selection guidelines.

Objectives: The aim of this study was to investigate the relative contributions of mechanical determinants to the top running speeds of para-athletes with unilateral transfemoral amputation wearing a running-specific prosthesis.

Study design: Observational study within the subject.

Methods: Nine para-athletes with unilateral transfemoral amputation wearing a running-specific prosthesis were recruited in this study. They were asked to run at their respective constant top speeds on an instrumented treadmill. From the ground reaction force and spatiotemporal parameters, three mechanical variables—step frequency, mass-specific averaged vertical ground-reaction force, and contact length—were determined for both the affected and unaffected limbs.

Results: Stepwise regression analysis showed that the contact length of the affected limb was significant and an independent factor of top running speed ($\beta = 0.760$, $P < 0.05$), with a coefficient of determination (R^2) of 0.577 ($P < 0.05$), whereas the other variables were not associated.

Conclusion: These results suggest that prosthetic components and alignment are crucial to determining the maximal sprinting performance in uTFA.

Keywords

running-specific prosthesis, sprinting, running, amputee locomotion

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Introduction

The development of running-specific prostheses (RSPs) has enabled para-athletes with lower-limb amputations to participate in running events. In fact, the availability of RSPs has resulted in dramatic improvements in the sprint performance of elite para-athletes in the Paralympic Games. Previous studies analyzed the sprinting biomechanics of runners wearing RSPs after unilateral transtibial (below-the-knee) amputations.¹⁻³ These studies reported that the spatiotemporal parameters and force-production capability of athletes demonstrate a fundamentally asymmetric relationship between the affected and unaffected limbs. However, the sprinting

biomechanics of para-athletes with unilateral transfemoral (above-the-knee) amputation (uTFA) are not fully understood yet. An increased understanding of biomechanical determinants that influence the sprint performance of para-athletes with uTFA will provide us with a basis for better evaluating athletes' sprint performance and would be expected to aid in the development of more effective training methods and RSP selection guidelines.

The constant running speed of an able-bodied athlete can be evaluated as the product of the stance average vertical ground reaction force (vGRF) (F_{avg}) relative to the athlete's body weight (BW), step frequency ($Freq_{step}$), and contact length (L_c) (i.e., the distance covered by the athlete's center of mass (COM) during the stance phase). The above calculation is performed assuming the COM height to remain constant at touchdown and takeoff.^{4,5} Considering a within-subject design, a previous study demonstrated the values of these variables to be similar for both limbs at slow speeds in para-athletes with uTFA (between 1.76 ± 0.22 and 2.35 ± 0.3 m/s).⁶ In addition, they demonstrated that the value of $Freq_{step}$ remains nearly identical for both limbs at relatively faster speeds (4.10 ± 0.50 m/s). However, the affected limb was found to exert 11% less F_{avg}/BW while demonstrating 12% longer L_c compared with the unaffected limb. Accordingly, they concluded that para-athletes with uTFA adopt a limb-specific biomechanical strategy to achieve faster running speeds. Despite these findings, there exists a lack of clarity regarding the most major determinants among these variables (F_{avg} , $Freq_{step}$, and L_c in each limb) to the

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interindividual variability in the top speed of para-athletes with uTFA. Therefore, the aim of this study was to investigate the major biomechanical determinants of top running speed in para-athletes with uTFA wearing RSPs.

Methods

Participants

We recruited nine para-athletes with uTFA who were experienced competitors in the 100-m race and long jump (Table 1). Each participant underwent regular training for 1–6 days per week when signing up for this study. All participants wore their RSP (knee + foot) and preferred running shoes on the affected and unaffected limbs, respectively. The protocol was approved by the local ethics committee and was in accordance with the guidelines set out in the Declaration of Helsinki (1983), and informed consent was obtained from all subjects before the experiment.

Experimental procedures

Figure 1(a) presents the sprinting experiments performed by the para-athletes with uTFA on an instrumented treadmill (FTMH-1244WA, Tec Gihan, Kyoto, Japan). After 5-min walking to familiarize the instrumented treadmill,⁷ all participants were asked to perform running trials on the treadmill at submaximal speeds increasing from 30% to 80% of their respective maximum speed in 10% steps. In this study, the maximum (100%) speed of each participant was defined as the average of their respective best 100-m times recorded in actual competitions (Table 1). For all trials, the treadmill belt speed was subjected to a constant acceleration of 0.84 m/s² up to the target speed. To avoid the effects of fatigue, all participants were instructed to take as much rest between trials as they deemed appropriate.

After reaching the 80% speed, all participants attempted to attain their maximum running speed on the treadmill. In accordance with the participants' feedback regarding the difficulty encountered, the running speed was gradually increased with sufficient rest intervals between successive trials. On average, each participant preferred a 0.28–0.56 m/s increase in treadmill speed between successive trials. In this study, the maximum running speed of participants corresponds to the last speed successfully attained by them during trials (Table 1). Multiple attempts were made to attain the fastest speed on the treadmill. However, when the participants failed to attain a faster speed in two consecutive attempts, the speed recorded in their last trial was considered their top speed. The trials were considered successful if each participant ran more than 8 steps of both limbs at a given speed without notable forward or backward movement.

Data collections and analyses

The vGRF was measured using two six-degrees-of-freedom piezoelectric force plates (TF-40120-CL and TF-40120-CR; Tec Gihan) with a sampling frequency of 1000 Hz embedded in the instrumented treadmill. Based on previous studies, a fourth-order zero-lag low-pass Butterworth filter with a cutoff frequency of 25 Hz and a threshold of 40 N was used for further vGRF analysis.^{6,8}

Table 1. Participant characteristics, including body mass, which accounts for prosthesis weight, best 100-m personal time (s) during preceding year, and maximum speed during experiment performed in this study.

| Subject number | Sex (M/F) | Age (years) | Height (m) | Mass (kg) | Unaffected limb length (m) | Affected limb length (m) | Amputated side | RSP model (category of stiffness) | Prosthetic knee | 100-m personal record (s) | Maximal speed (m/s) |
|----------------|-----------|-------------|------------|-----------|----------------------------|--------------------------|----------------|-----------------------------------|-----------------|---------------------------|---------------------|
| UTFA1 | M | 24 | 1.68 | 57.6 | 0.84 | 0.89 | Left | Sprinter 1E90 (cat.3) | 3S80 | 16.81 | 5.50 |
| UTFA2 | M | 34 | 1.61 | 58.7 | 0.82 | 0.85 | Left | Runner 1E91 (cat.5) | 3S80 | 17.82 | 4.81 |
| UTFA3 | M | 18 | 1.77 | 86.0 | 0.89 | 0.93 | Right | Sprinter 1E90 (cat.4) | 3S80 | 14.45 | 7.08 |
| UTFA4 | M | 54 | 1.70 | 65.8 | 0.89 | 0.95 | Left | KATANA-β (medium) | 3S80 | 16.25 | 4.89 |
| UTFA5 | M | 26 | 1.71 | 63.3 | 0.89 | 0.95 | Left | Runner 1E91 (cat.3) | 3S80 | 16.02 | 5.97 |
| UTFA6 | F | 20 | 1.56 | 57.9 | 0.80 | 0.83 | Right | Runner 1E91 (cat.3) | 3S80 | 16.86 | 6.31 |
| UTFA7 | F | 29 | 1.64 | 63.2 | 0.86 | 0.94 | Left | Runner 1E91 (cat.4) | 3S80 | 14.61 | 5.83 |
| UTFA8 | M | 24 | 1.60 | 61.1 | 0.77 | 0.82 | Right | KATANA-β (hard) | 3S80 | 16.13 | 6.39 |
| UTFA9 | M | 37 | 1.61 | 62.3 | 0.83 | 0.89 | Right | Runner 1E91 (cat.3) | 3S80 | 20.00 | 4.11 |
| Mean | | 30 | 1.65 | 64.0 | 0.84 | 0.89 | | | | 16.55 | 5.65 |
| SD | | 10 | 0.06 | 8.2 | 0.04 | 0.05 | | | | 1.58 | 0.87 |

Abbreviation: RSP, running-specific prosthesis.

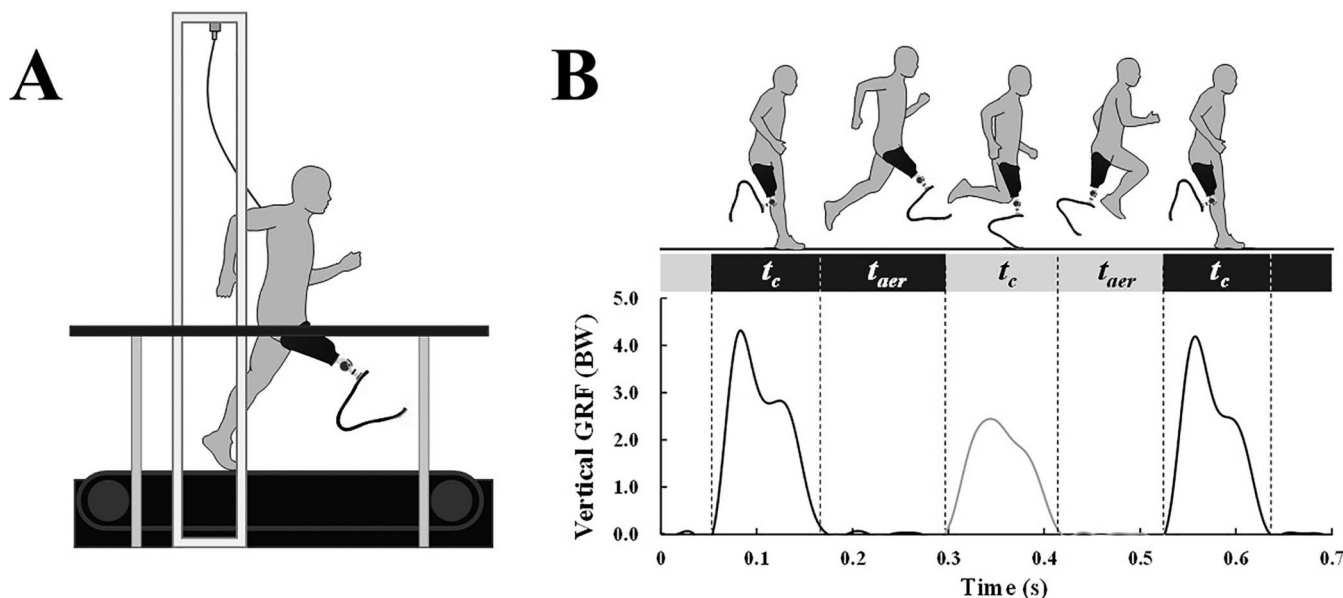


Figure 1. (a) Schematic of the experimental setup. A safety harness was used to support the participants in the event of a fall. In its default setting, the harness was sufficiently slack to ensure that it does not impede the participants' natural running mechanics; (b) typical time series data for ground reaction force (normalized with respect to participant body weight [BW]) recorded from one participant. Gray and black and gray lines indicate affected and unaffected limbs, respectively.

AU2

In this study, we analyzed 5 steps each performed by both affected and unaffected limbs at their respective top running speeds. The corresponding contact and aerial times (t_c and t_{aer} , respectively) were determined based on the vGRF data. As previously reported,^{4,5} the running speed of able-bodied athletes can be represented using three variables, as described hereunder,

$$Speed = Freq_{step} \left(\frac{F_{avg}}{BW} \right) L_c \quad (1)$$

and

$$Freq_{step} = 1 / (t_c + t_{aer}). \quad (2)$$

In the above equations, $Freq_{step}$ denotes the step frequency (inverse of the time elapsed between touchdown and contralateral touchdown). Similarly, F_{avg}/BW denotes the stance-average vGRF normalized with respect to the participant BW. Finally, L_c denotes the contact length (forward distance covered by the participants' COM during the contact period). It is calculated by multiplying t_c with the treadmill belt speed (Figure 1(b)). The participant BW for vGRF normalization was determined during a static standing trial performed on the instrumented treadmill. As already mentioned, these variables were evaluated for both limbs of all participants (Figure 2).

F2

Statistical analysis

Stepwise multiple linear regression analyses were used to investigate the major determinant of sprint performance by considering the top running speed as the dependent variable and $Freq_{step}$, F_{avg}/BW , and L_c for both limbs as independent variables. A standardized partial regression coefficient (β) was used to determine the relative influence of each mechanical variable on the top speed. In this study, all statistical tests were performed at

the 5% significance level using IBM SPSS Statistics Version 19 (IBM, Armonk, NY).

Results

Stepwise regression analysis showed that the L_c of the affected limb was significant and an independent factor of top running speed ($\beta = 0.760$, $P < 0.05$), with a coefficient of determination (R^2) of 0.577 ($P < 0.05$), whereas the other variables were not associated.

Discussion

The aim of this study was to investigate the major biomechanical determinant of top running speed in para-athletes with uTFA wearing RSPs. The statistical analysis revealed that the L_c of the affected limb was selected as a sole variable significantly associated with the top speed. The results of this study suggest that the L_c is a major biomechanical determinant of the top running speeds in para-athletes with uTFA during maximal effort sprinting.

Regarding nonamputee sprinting, a previous study reported that L_c (considered the "stance distance" in their study) is determined by the touchdown distance (horizontal distance from the second stance-foot metatarsal head to COM at the instant of touchdown), foot-movement distance (horizontal distance covered by the second stance-foot metatarsal head during the stance phase), and takeoff distance (horizontal distance from the second stance-foot metatarsal head to COM at the instant of takeoff).¹⁰ Furthermore, the authors identified these variables to be determined using the segment positions during landing and takeoff and segment inertial parameters. Consequently, L_c values corresponding to the top speed of para-athletes with uTFA mainly depend on the touchdown and takeoff techniques used and mechanical properties (i.e. shape and length) of the prosthetics used. Previous studies

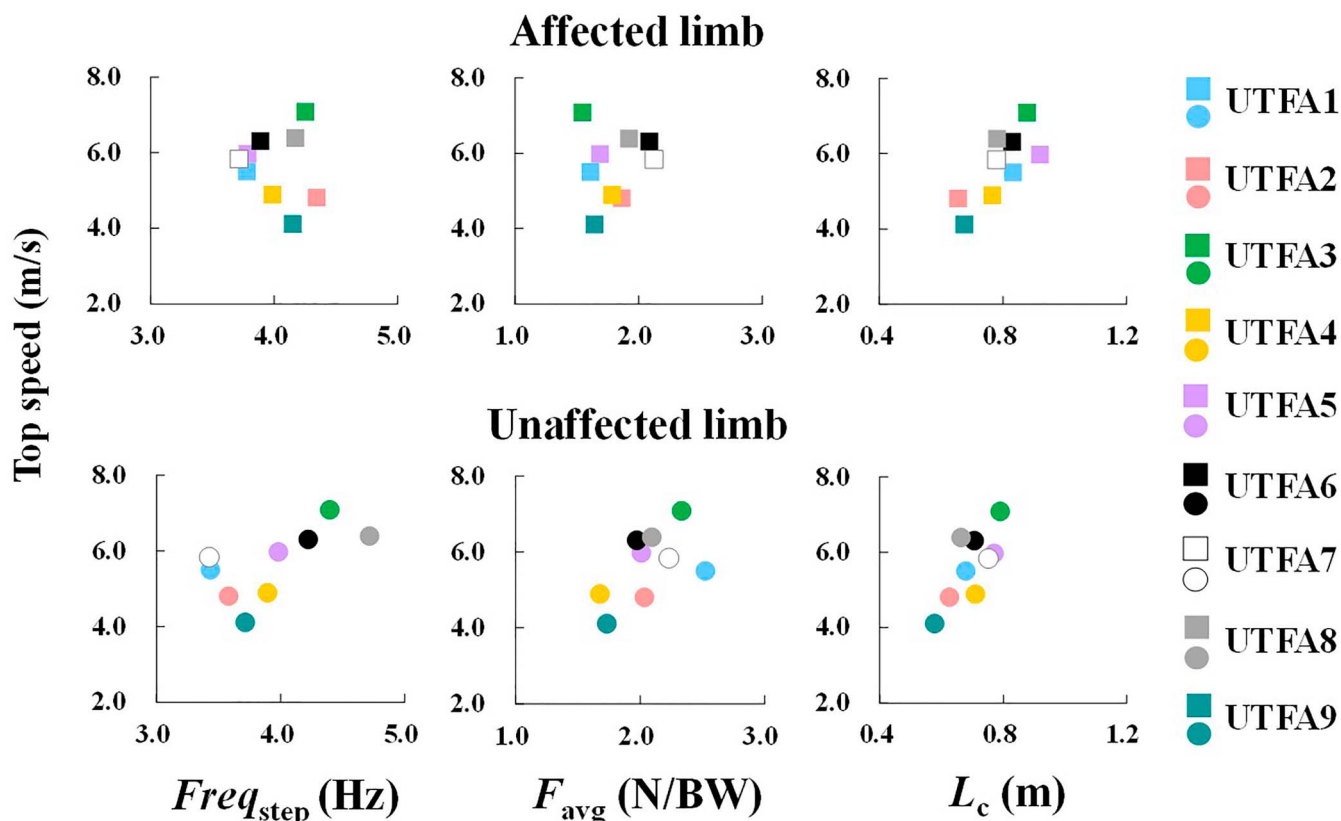


Figure 2. Interindividual relationships between top running speed and $Freq_{step}$, F_{avg}/BW , and L_c , with squares and circles indicating affected and unaffected limbs, respectively.

revealed that the affected limbs of para-athletes with uTFA wearing RSPs tend to perform flatter landings and takeoffs (determined by the angle of attack of a spring–mass model) at a faster running speed and a higher step frequency at a given running speed.^{8,11} This increases the stance distance of the affected limb compared with its unaffected counterpart. Furthermore, considering that the affected limb length of the participants involved in this study, on average, exceeded that of the unaffected limb by 5.9% (Table 1), the adjustment and optimization of the prosthetic alignment for para-athletes with uTFA may be considered important to help them achieve their top speeds.¹²

It is worthwhile to note that a coefficient of determination (R^2) of the regression model was 0.577, indicating that L_c of the affected limb could explain 57.7% of the interindividual variation of top running speed in uTFA. In other words, although L_c of the affected limb may be a major determinant, other variables could be related to the top running speed in uTFA wearing RSPs. Therefore, the relative importance of $Freq_{step}$ and F_{avg}/BW of both limbs and L_c of the unaffected limb is not negligibly small. Athletes, coaches, and practitioners should carefully consider and monitor an individual's force production capability and spatiotemporal parameters during maximal sprinting in uTFA wearing RSPs.

In summary, we investigated the relative contribution of mechanical determinants to enable para-athletes with uTFA wearing RSPs to achieve faster top speeds. We found that the L_c of the affected limb was significant and an independent factor of top running speed in this population. The results of this study suggest that prosthetic components and alignment are crucial to determining the maximal

sprinting performance in uTFA. Current results are useful to aid in developing ideal coaching and training regimes by identifying the underlying mechanisms for obtaining top running speed.

Author contributions

The authors disclosed the following roles as contributors to this article: This project was conceived by H.H. and A.C. Data collection was conducted by H.M., G.H., S.H., and N.P. Data analyses were conducted by H.H., H.M., and S.H. The manuscript was drafted by H.H., S.H., D.I., A.C., and N.P. H.H., A.C., and N.P. supervised the study. All the authors read and approved the final manuscript.

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Declaration of conflicting interest


The authors disclosed no potential conflicts of interest for the research, authorship, and/or publication of this article.

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Supplemental material

No supplemental digital content is available in this article.

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