THE REBOUND OF THE BODY USING RUNNING-SPECIFIC PROSTHESES IN UNILATERAL TRANSFEMORAL AMPUTEES

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Although the elastic bounce of the body is considered a prerequisite for running, the rebound strategy in individuals with lower extremity amputation is not well known. This study aims to investigate the rebound strategy at different running speeds in unilateral transfemoral amputees (uTFAs) wearing running-specific prostheses (RSPs). On an instrumented treadmill, eight uTFAs ran at incremental speeds (30%, 40%, 50%, 60%, 70%, and 80% of the average speed of their 100-m personal records). The rebound strategy of the unaffected and affected limbs is evaluated using the ratio of the natural frequency of the spring-mass system (f_{sist}) to the step frequency (f_{step}). At all speeds, f_{sist}/f_{step} in the unaffected limb is considerably greater than that in the affected one. The interlimb differences in f_{sist}/f_{step} tended to increase with the speed. These results suggest that the rebound strategy is not the same for the unaffected and affected limbs in uTFAs across a range of speeds, and that uTFAs wearing RSPs perform bouncing steps using the alternate asymmetric rebound strategy ($f_{step} < f_{sist}$) through different limbs.

KEYWORDS: amputee locomotion, elastic bounce, spring-mass model.

INTRODUCTION: Carbon-fibre running-specific prostheses (RSPs) have enabled individuals with lower extremity amputation to run by partly providing a spring-like leg function in the affected limbs. Human running is fundamentally described as a bouncing movement in which each leg functions like a spring (Farley, Glasheen & McMahon, 1993); hence, a spring-mass model has been extensively applied to describe and predict the dynamics of a bouncing gait (Blickhan, 1989). The elastic bounce of the body is considered a prerequisite for running in individuals with lower extremity amputation; however, the underlying mechanisms remain largely undescribed.

In the bouncing-step during running, the vertical oscillation of the centre-of-mass (COM) of the body can be divided into two parts (Figure 1-A, B, C): the part where the vertical ground reaction force (GRF) is greater than the body weight (lower part of the COM oscillation), called the effective contact time t_{ce}, and the part where it is lesser than the body weight (upper part of the COM oscillation), called the effective aerial time, t_{ae} (Cavagna, Heglund & Willems, 2005). According to the spring-mass model, the duration of the lower part of the oscillation represents the half-period of the bouncing system at the natural frequency f_{sist} (Blickhan, 1989).

A previous study investigated the relationship between f_{sist} and the step frequency (f_{step}) at different running speeds in non-amputees (Cavagna, Franzetti, Heglund & Willems, 1988). The duration of the lower and upper parts of the vertical COM oscillation, which are both either equivalent (symmetric rebound) or non-equivalent (asymmetric rebound), were evaluated. In the study, non-amputees demonstrated symmetric rebound ($f_{step} = f_{sist}$ with $t_{ce} = t_{ae}$) at lower speeds (~11 km/h) and asymmetric rebound ($f_{step} < f_{sist}$ with $t_{ce} < t_{ae}$) at the higher ones. Although the relationship between f_{step} and f_{sist} implies a rebound strategy for vertical COM oscillation, information on the rebound strategy in unilateral transfemoral amputees (uTFAs) wearing RSPs is not well known.

The aim of this study was to investigate the rebound strategy at different running speeds in uTFAs wearing RSPs. According to previous studies, uTFAs exhibit interlimb differences in the mechanical properties as well as running mechanics (Hobara, Sakata, Hashizume & Kobayashi, 2019; Sakata, Hashizume, Takemura & Hobara, 2020). Therefore, we hypothesize that the rebound strategy would not be the same for the unaffected and affected limbs in uTFAs across a range of speeds.

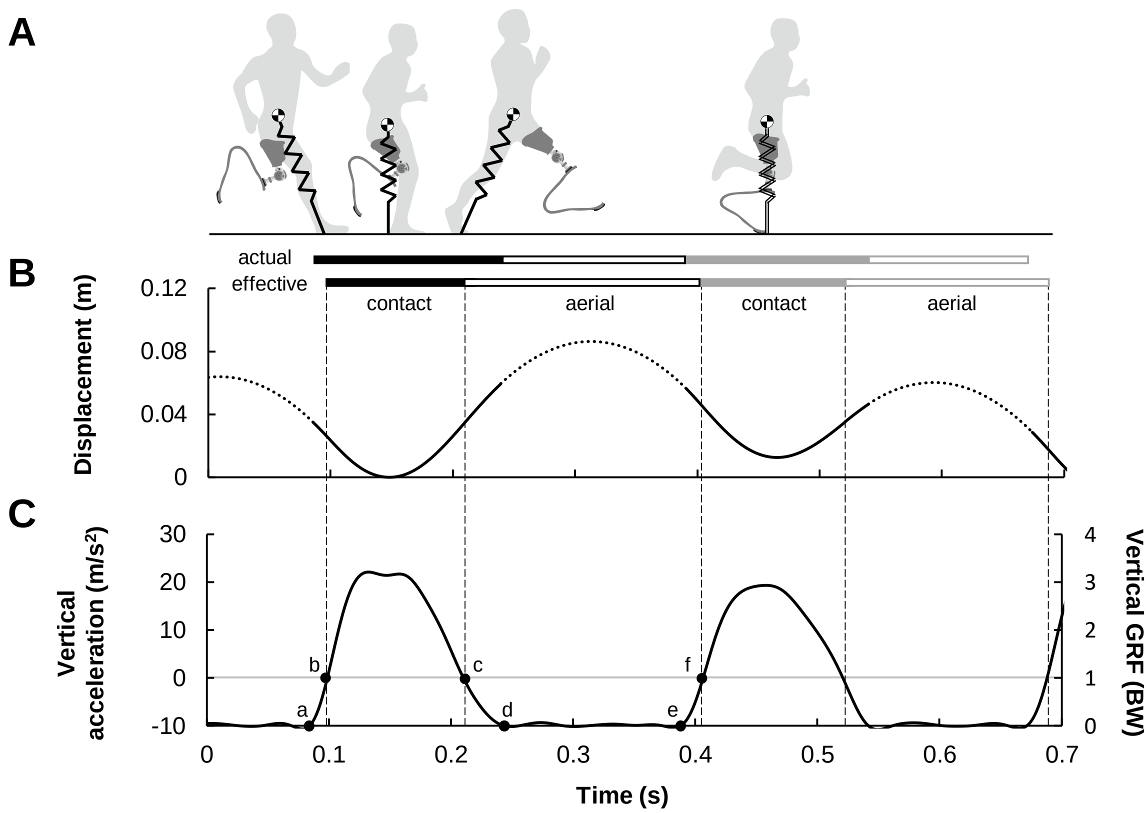

Figure 1: Running phases and centre-of-mass (COM) movement: (A) Illustration of an uTFA wearing RSP in the sagittal plane during the contact phases. The elastic bounce of the body is expressed by the spring-mass model. (B) Recorded COM displacement for an uTFA, while running at 17.3 km/h. (C) Corresponding vertical acceleration of the COM. (a, b, c, d, e, and f represent the following timing: foot strike (a, e), landing (b, f), take-off (c), and toe-off (d)). Duration (b–c) indicates the lower part of the COM oscillation, called the effective contact time, t_{ce}; duration (c–f) indicates the upper part of the COM oscillation, called effective aerial time, t_{ae}.

METHODS: Eight uTFAs participated in this study (six males and two females, age: 27 ± 11 years, body height: 1.68 ± 0.07 m, body mass: 64.5 ± 8.1 kg, 100-m personal records: 15.65 ± 1.03 s, mean ± SD). The protocol was approved by the local ethical committee and was in accordance with the guidelines set out in the Declaration of Helsinki (1983). All participants gave informed written consent before participating. Each participant used their own recommended RSP and prosthetic knee joint. Three participants used the Sprinter 1E90 and Runner 1E91 (Ottobock, category 3 or 4, Duderstadt, Germany), whereas two participants used the KATANA-β (IMASEN & MIZUNO, hard and medium, Gifu, Japan). All the participants used 3S80 for the knee joint (Ottobock, Duderstadt, Germany).
The participants ran on an instrumented treadmill (FTMH-1244WA, Tec Gihan, Kyoto, Japan) at incremental speeds of 30%, 40%, 50%, 60%, 70%, and 80% of their average speed. In our study, the (100%) speed of an individual was defined as the average speed of their 100-m personal records in official competitions. The participants started a series of trials at 30% speed, and the speed for each subsequent trial was increased by 10%, until the participants reached 80% speed. The average running speed for each trial were as follows: 1.92 ± 0.13 m/s for 30%, 2.56 ± 0.19 m/s for 40%, 3.19 ± 0.23 m/s for 50%, 3.83 ± 0.26 m/s for 60%, 4.47 ± 0.31 m/s for 70%, and 5.10 ± 0.36 m/s for 80%, respectively. GRF data were collected at 1000 Hz using treadmill-mounted force plates and filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 25 Hz (Clark & Weyand, 2014).
In this study, f_{step} was calculated as the inverse of the time from landing to contralateral landing (duration of t_{ce} and t_{ae}), as $f_{step} = 1 / (t_{ce} + t_{ae})$. According to the spring-mass model, t_{ce} represents the half-period of the bouncing system; hence, f_{sist} was calculated as the inverse of twice of t_{ce}, as $f_{sist} = 1 / (2t_{ce})$.

The rebound strategy was then evaluated as the ratio of f_{sist} to f_{step} (f_{sist}/f_{step}) in the unaffected and affected limbs. We analysed 10 consecutive steps and averaged five steps of each limb to determine the representative values for each speed.
Two-way repeated-measures ANOVA with two factors, limb (two levels) and speed (six levels), was performed to compare the variables between the unaffected and affected limbs at six different speeds. If a significant main effect was observed, a Bonferroni post-hoc multiple comparison was performed. The statistical significance was set to $P < 0.05$. All the statistical calculations were performed using SPSS for Windows, Version 22 (IBM, Armonk, NY, USA).

RESULTS: As shown in Figure 2-A, there were significant main effects in the limb ($P < 0.05$) and speed ($P < 0.01$), and interaction effects between the limb and speed ($P < 0.05$). f_{sist}/f_{step} was considerably greater in the unaffected limb compared to the affected one at 40–80% speeds. For the unaffected limb, f_{sist}/f_{step} increased with the speed, whereas no changes were observed in the affected limb. f_{step} did not exhibit any significant main effect in the limb and interaction (Figure 2-B). However, there was a significant main effect in the speed ($P < 0.01$), and f_{step} increased with the running speed in both limbs. Moreover, statistical analysis revealed significant main effects in the limb ($P < 0.05$), speed ($P < 0.01$), and interaction effects ($P < 0.05$) in f_{sist} (Figure 2-C). In the unaffected limb, f_{sist} was considerably greater than in the affected limb at all speeds, and the interlimb differences in f_{sist} between limbs tended to increase with the speed.

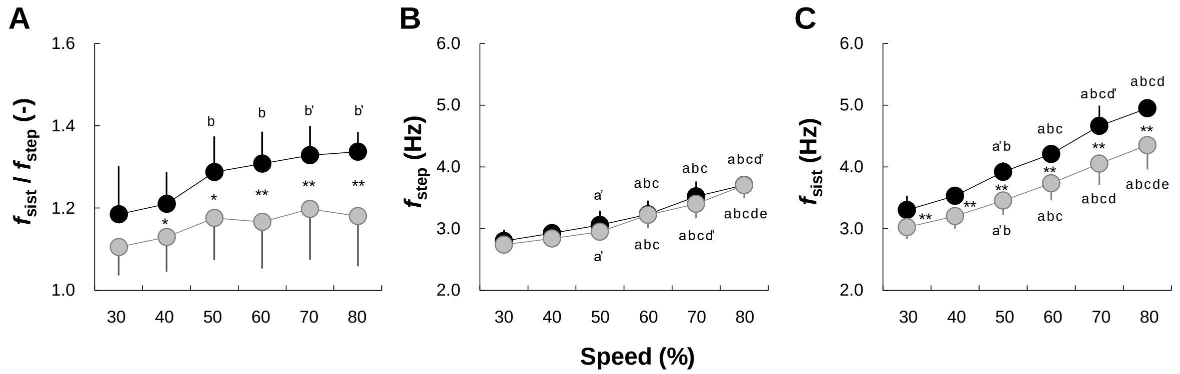

Figure 2: (A) Ratio of the natural frequency to step frequency (f_{sist}/f_{step}). (B) Step frequency (f_{step}). (C) Natural frequency (f_{sist}) of the unaffected (black circles) and affected (grey circles) limbs across six running speeds. The error bars represent 1 SD. The asterisks (*, **) indicate significant differences between the limbs at each speed, at $P < 0.05$ and $P < 0.01$, respectively. (a', b', c', d', e') and (a, b, c, d, e) indicate significant differences at 30%, 40%, 50%, 60% and 70% speed, at $P < 0.05$ and $P < 0.01$, respectively.

DISCUSSION: The aim of this study was to investigate the rebound strategy at different running speeds in uTFAs wearing RSPs. As depicted in Figure 2-A, f_{sist}/f_{step} was considerably greater in the unaffected limb compared to the affected one. Furthermore, the magnitude of the differences in f_{sist}/f_{step} tended to be greater at higher speeds (Figure 2-A). The obtained results demonstrate that the rebound of the unaffected limb is more asymmetric than that of the affected limb at all speeds. These results support our hypothesis that the rebound strategy would not be the same for the unaffected and affected limbs in uTFAs across a range of speeds.
At all speeds, f_{sist}/f_{step} of the unaffected as well as affected limb was greater than unity (Figure 2-A). When $f_{sist}/f_{step} = 1$, the rebound is perfectly symmetric; hence, the rebound of both unaffected and affected limbs was determined to be asymmetric ($f_{step} < f_{sist}$, with $t_{ce} < t_{ae}$), which is the same as the rebound strategy of non-amputees at higher speeds.
According to a previous study, non-amputees exhibit increased asymmetric rebound ($f_{sist}/f_{step} > 1$) at higher running speeds than at the lower ones (Cavagna, Legramandi & Peyré-Tartaruga, 2008). Asymmetric rebound was a consequence of the increase in the vertical GRF during the lower part of the oscillation (t_{ce}). In our study, f_{sist}/f_{step} of the unaffected limbs increased with the increase in speed (Figure 2-A), whereas that of the affected limbs remained constant. These

results indicate that the vertical GRF is greater in the unaffected limb than in the affected one during t_{ce}. A recent study demonstrated that the vertical GRF of the unaffected limb was greater than that of the affected one across a range of running speeds in uTFAs because the thigh muscle atrophy after transfemoral amputation deteriorates the force production capability in the affected limbs (Sakata, Hashizume, Takemura & Hobara, 2020). Therefore, our results indicate that uTFAs wearing RSPs perform bouncing steps using the alternate asymmetric rebound strategy ($f_{step} < f_{sist}$) through different limbs.
In addition, we determined that there were no obvious differences in f_{step} between the limbs (Figure 2-B). The results of this study agree with recent findings which suggest that the step frequency is symmetric for the unaffected as well as affected limbs in uTFAs across a range of speeds (Hobara, Sakata, Hashizume & Kobayashi, 2019; Sakata, Hashizume, Takemura & Hobara, 2020). A possible explanation for the similar step frequency in both limbs may be the minimisation of the expended metabolic energy. Running at an asymmetric step frequency increases the metabolic energy expenditure rate in non-amputees (Beck, Azua & Grabowski, 2018). Hence, uTFAs would maintain a symmetric f_{step} in order to reduce metabolic energy expenditure during running.
It is noteworthy that f_{sist} was considerably greater in the unaffected limb than in the affected one at all speeds (Figure 2-C). As there were no significant differences in f_{step} between the limbs (Figure 2-B), the interlimb differences in f_{sist}/f_{step} were mainly caused by differences in f_{sist}. f_{sist} is predominantly characterized by the mass-specific vertical stiffness of the spring-mass system during t_{ce}. Past finding demonstrates that the vertical stiffness of uTFAs is greater in the unaffected limbs compared to the affected ones during running (Hobara, Sakata, Hashizume & Kobayashi, 2019). As greater vertical stiffness induces greater f_{sist}, the interlimb differences in f_{sist} may be due to the differences in the vertical stiffness of the spring-mass system between limbs.

CONCLUSION: This study investigated the rebound strategy at different running speeds in uTFAs wearing RSPs. The obtained results suggest that (1) the rebound strategy differs in the unaffected and affected limbs in uTFAs across a range of speeds, and (2) uTFAs wearing RSPs performed bouncing steps using the alternate asymmetric rebound strategy ($f_{step} < f_{sist}$) through different limbs. Therefore, coaches and practitioners should take into account any potential biomechanical difference between limbs during running in uTFAs for implementations of running gait rehabilitation programmes.

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