Published in final edited form as:
*Gait Posture*. 2014 January ; 39(1): . doi:10.1016/j.gaitpost.2013.08.010.

# Amputee Locomotion: lower extremity loading using running-specific prostheses

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## Abstract

Carbon fiber running-specific prostheses (RSPs) have allowed individuals with lower extremity amputation (ILEA) to actively participate in sporting activities including competitive sports. In spite of this positive trait, the RSPs have not been thoroughly evaluated regarding potential injury risks due to abnormal loading during running. Vertical impact peak (VIP) and average loading rate (VALR) of the vertical ground reaction force (vGRF) have been associated with running injuries in able-bodied runners but not for ILEA. The purpose of this study was to investigate vGRF loading in ILEA runners using RSPs across a range of running speeds. Eight ILEA with unilateral transtibial amputations and eight control subjects performed overground running at three speeds (2.5, 3.0, and 3.5 m/s). From vGRF, we determined VIP and VALR, which was defined as the change in force divided by the time of the interval between 20 and 80% of the VIP.We observed that VIP and VALR increased in both ILEA and control limbs with an increase in running speed. Further, the VIP and VALR in ILEA intact limbs were significantly greater than ILEA prosthetic limbs and control subject limbs for this range of running speeds. These results suggest that 1) loading variables increase with running speed not only in able-bodied runners, but also in ILEA using RSPs, and 2) the intact limb in ILEA may be exposed to a greater risk of running related injury than the prosthetic limb or able-bodied limbs.

## Keywords

running; impact peak; loading rate; ground reaction forces; amputees

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**Conflict of interest**
None of the authors have any conflicts of interest associated with this study.

## 1. Introduction

Recent development of carbon fiber running-specific prostheses (RSPs) have allowed individuals with lower extremity amputation (ILEA) to regain the functional capability of running [1], which is one of the most difficult everyday motor tasks for ILEA [2]. In spite of this positive trait, the RSPs have not been thoroughly evaluated regarding potential injury risks due to the abnormal loading during running, specifically in unilateral amputees. For example, lower extremity injuries are more common in amputee athletes and typically occur during running activities [3]. Specifically, the most common musculoskeletal injuries among amputee athletes are sprains and strains to the lumbar spine and sacroiliac joint on the uninvolved side [4]. Although these injuries are thought to mainly be attributed to the mechanical stress of the vertical ground reaction forces (vGRF) during running [4, 5], evidence regarding the abnormal loading in ILEA during running has not been reported.

Current running-specific prostheses are made from carbon-fiber, a material known to generate high-frequency vibrations when used [6]. These prostheses have not been systematically evaluated for their appropriateness in running, specifically regarding the mechanical characteristics of the prostheses and the possibility of secondary cumulative injuries that may be caused by the high stiffness and low damping characteristic of chosen materials. The potential problems related to the high natural frequency of these materials have been previously suggested [6], but no follow-up studies on modern carbon-fiber feet have been performed. Frequent running with RSPs may put ILEA at increased risk for physical injuries and degenerative joint diseases [6-9] due to abnormal vGRF loading and potentially harmful impact forces. However, little is known about vGRF loading during running using RSPs.

In order to understand associations between vGRF loading and running-related injury, several researchers have compared the characteristics of the vGRF between healthy runners and runners with a history of running-related injury. Abnormal lower extremity loading may be evaluated by vertical impact peak (VIP; the first peak of vGRF in early contact phase) and vertical average loading rate (VALR), which is an indication of how fast vGRF rises to the VIP [10]. Several studies demonstrated a trend towards higher VIP and VALR in runners with prior stress fractures compared to runners with no injury history [10, 11]. Therefore, abnormal lower extremity loading may be evaluated both by VIP and VALR using vGRF.

The purpose of this study was to investigate vGRF loading in ILEA runners using RSPs at a range of running speeds. A previous study [12] indicated that the GRF loading rate in able-bodied subjects increased with running speeds from 3.0 to 5.0 m/s. Accordingly, we first hypothesized that loading variables both in ILEA and control subjects would increase with an increase in running speed. Second, given that the loading rate in the intact limb was greater than in the prosthetic limb during running in one transtibial amputee at 2.8 to 3.0 m/s [13], we hypothesized that the loading variables in the intact limb would be greater than the prosthetic limb. Third, given that the average loading rate (the linear gradient to the maximum vGRF) was significantly higher in able-bodied athletes than in a bilateral amputee sprinter [14], we hypothesized that loading variables of both intact and prosthetic limbs in ILEA would not exceed those of an able-bodied control group.

## 2. Materials and Methods

### 2.1 Participants

Eight male subjects with unilateral transtibial amputations (ILEA; mean age = 32.0 ± 10.2 years, height = 1.80 ± 0.07 m, mass = 82.3 ± 13.0 kg; Table 1) and eight healthy male able-bodied control subjects (AB; mean age = 29.0 ± 6.9 years, height = 1.84 ± 0.05 m, mass =

79.3 ± 7.9 kg) between 18 and 50 years of age volunteered to participate in the experiment. Each ILEA used his own RSP. The study was approved by the local ethics committee of the University of Maryland, College Park Institutional Review Board and prior to testing, written informed consent was obtained.

### 2.2 Task and procedure

We instructed the participants to run overground on a 100-m long track at 2.5, 3.0 and 3.5 m/s. Each subject ran continuously around the track for up to ten minutes at the prescribed running speeds in a randomized order (Figure 1). In order to monitor and concurrently provide subjects with feedback of the desired running speeds, we used six sets of laser sensors around the track. The average speeds over different sections of the track were instantaneously calculated when the subject passed through two consecutive sensors. A previous study demonstrated that fatigue induced by the exhaustive running resulted in decreased loading rates in runners [15]. Therefore, we instructed participants to have at least 10-min rest between running trials to reduce the effects of fatigue.

### 2.3 Data collection and analysis

Ten six-degree-of-freedom piezoelectric force platforms (9260AA6, Kistler, Amherst, NY) embedded in the running track in series were used to collect vGRFs sampled at 1000 Hz. The vGRF data were filtered using a fourth order, zero lag low pass Butterworth filter with a cut-off set at 30 Hz. Five successful trials for intact and prosthetic limb at each of the three running speeds were taken and averaged for the further analysis. A successful trial was defined as the subject running within ±0.2 m/s of the prescribed running speed within the track section containing the force platforms and stepping within the boundaries of the force platforms during the trial.

Following previous studies [10, 11, 16, 17], VIP was identified from the first peak of the vGRF. VALR were calculated for the vGRF as the change in the force divided by the time interval between 20% and 80% of the VIP (Figure 2). When no distinct impact peak existed, the VIP and VALR were measured at the same percentage of stance as determined for each condition in the trials with an impact transient [18].

### 2.4 Statistics

A 2×2×3 three-factor repeated-measures ANOVA using Group (ILEA and AB), Limb (prosthetic/intact in ILEA and left/right in AB subjects), and Speed (2.5 m/s, 3.0 m/s, 3.5 m/s) was performed. Group was treated as a between-subject factor while Limb and Speed were treated as within-subject factors. Bonferroni post-hoc multiple comparison tests were performed if a significant main effect was observed. Statistical significance was set at $p < 0.05$. Statistical analysis was executed using SPSS (IBM SPSS Statistics Version 19, SPSS Inc., Chicago, IL).

## 3. Results

Statistical analyses revealed that there were no differences in VIP ($p = 0.945$) between the left (1.34 ± 0.19 BW at 2.5 m/s, 1.49 ± 0.17 BW at 3.0 m/s, 1.62 ± 0.25 BW at 3.5 m/s) and right leg (1.34 ± 0.19 BW at 2.5 m/s, 1.49 ± 0.19 BW at 3.0 m/s, 1.65 ± 0.24 BW at 3.5 m/s) in control subjects. Similarly, there were no differences in VALR ($p = 0.947$) between the left (38.96 ± 10.14 BW/s at 2.5 m/s, 46.34 ± 12.51 BW/s at 3.0 m/s, 51.67 ± 14.91 BW/s at 3.5 m/s) and right leg (36.79 ± 7.10 BW/s at 2.5 m/s, 44.75 ± 8.62 BW/s at 3.0 m/s, 53.59 ± 11.93 BW/s at 3.5 m/s) in control subjects. Consequently, the data were averaged to generate a representative control limb for clearer presentation in figures. However, all statistical outcomes were based on the balanced statistical design that included both left/ right limbs.

A significant main effect of running speed on VIP ($p < 0.01$) was identified where VIP increased with running speed in all limbs (Figure 3-A). Further, significant main effects of limb were observed for VIP ($p < 0.01$). The ILEA intact limb had a significantly greater VIP than the prosthetic limb and AB subject limbs at each speed (Figure 3-A). However, there were no significant differences in VIP between the prosthetic limb and the AB subject limbs at each speed.

We also identified a significant main effect of running speed on VALR ($p < 0.01$), where the VALR increased with running speed in all limbs. Further, significant main effects of limb were observed for the VALR ($p < 0.01$). The ILEA intact limb had a significantly greater VALR than the prosthetic limb at each speed (Figure 3-B). The ILEA intact limb also had significantly greater VALR than AB limbs at 2.5 m/s ($p < 0.05$) and 3.0 m/s ($p < 0.05$) but not at 3.5 m/s ($p = 0.07$). The VALR for the prosthetic limb and the AB limbs did not significantly differ at any speeds. It was also identified that the Limb*Group interaction was significant both in VIP and VALR (Figure 4-A and B; $p < 0.01$).

## 4. Discussion

The purpose of this study was to investigate vGRF loading in ILEA runners using RSPs at a range of running speeds. We identified significant main effects of running speed on VIP and VALR, where both variables increased with speed in all limbs (Figure 3-A and B). These results support our first hypothesis that loading variables both in ILEA and AB subjects would increase with an increase in running speed. To our knowledge, this is the first study demonstrating that these loading variables increase with running speed in ILEA running. Several studies demonstrated that the VIP and VALR increased with running speeds from 1.5 to 8.0 m/s in able-bodied runners [12, 19]. Therefore, the results of the present study suggest that loading variables increase with running speed not only in able-bodied runners, but also in ILEA using RSPs.

In the present study, we also observed that both VIP and VALR in the ILEA intact limb were significantly greater than the prosthetic limb (Figure 3-A and B), supporting our second hypothesis. Furthermore, current results corroborate a recent finding which demonstrated that the loading rate in the intact limb was greater than that in the prosthetic limb during running in one transtibial amputee [13]. One potential explanation for the results might be compensatory strategies to prevent skin discomfort and possible pain in residual limb-socket interface. According to previous studies, high impact forces of short duration associated with running can result in a reticence to participate in exercise due to skin discomfort and possible pain in the residual limb-socket interface [13, 20, 21]. Therefore, ILEA in our study might attenuate the vGRF to prevent possible soft tissue injury in their residual limb-socket interface. Although joint kinematics were not collected in the present study, it has been reported that running with the knees bent more than usual can reduce VIP during running [22]. Since the touchdown joint angle changes the distance of the moment arm of GRF at each joint [23], ILEA in our study might attenuate the vGRF by changing touchdown joint angle in the prosthetic limb. The mechanisms of lower loading variables in prosthetic limb should be the subject of future investigations. A second possible explanation for the results might be that the RSP or muscle weakness/impairment due to the prosthesis limits force production. A recent finding [24] suggested that the RSPs limit the ability to generate GRFs equivalent to intact limbs. This limitation may stem from the RSP's spring-like function that attenuates shock more than an intact limb, thus reducing VALR combined with loss of overall limb muscle function to push against the ground and generate greater GRFs.

It is worthwhile to note that although loading variables for the prosthetic limb and AB limbs did not significantly differ at any running speeds, ILEA intact limbs had significantly greater VIP and VALR than those in AB subjects (Figure 3-A and B ). These results do not support our third hypothesis that loading variables of both intact and prosthetic limb in ILEA would not exceed those of control group. Furthermore, current results contrast with a previous finding which stated that the rates of loading (the linear gradient to the maximum vGRF) were significantly higher in able-bodied athletes than in a double amputee sprinter [14]. The differences in the results between the two investigations may be explained by the differences in running speeds (submaximal vs. maximal), computation of the loading rate (20% and 80% time interval of the first impact peak vs. the linear gradient to the maximum vGRF), level of amputation (unilateral vs. bilateral), and type of RSP, or any combination of these variables utilized in the experimental protocols.

It has been implicated that abnormal mechanical stress of the ground reaction forces during running may put ILEA wearing RSPs at increased risk for musculoskeletal injuries (e.g. sprains and strains to the lumbar spine and sacroiliac joint) [3-5], and degenerative joint diseases [6-9]. The current results suggest that the intact limb in ILEA runners may be exposed to a greater risk of running related injury as loading rates have been indicated as a possible risk factor in developing running injuries for able bodied runners [6, 7]. Further, the observed significant Limb*Group interaction for both VIP and VALR indicated a greater difference between the ILEA limb loading rates as compared to those of the AB limbs (Figure 4-A and B). Several studies have suggested that asymmetrical loading between limbs may be an injury risk factor for musculoskeletal injury [25, 26]. Thus, modifying these loading mechanics may decrease a risk for such injuries in ILEA runners.

Gait retraining protocols using a real-time visual feedback have successfully reduced axial shank accelerations and VALR in non-amputee runners, both immediately and after a one-month follow-up [16], although it is still unknown if these adjustments result in a reduced incidence of injuries in the long term. Reduction in impact loading could also be achieved by wearing shoes with cushioning functions [27, 28] and/or orthotic intervention [29]; however, there is no agreement in the literature on whether or not the loading of the musculoskeletal system is reduced by wearing the shoes [30-32]. Recently, Waetjen et al. [13] demonstrated that a forefoot strike pattern in the intact limb could decrease loading rate compared to a rearfoot strike. Therefore, as reported in past findings [18, 29, 33], changes in footstrike pattern may be effective to reduce a risk for running related injury not only in ABS, but also in ILEA runners.

There are certain considerations that must be acknowledged when interpreting the results of the current study. First, in the present study, we recruited eight ILEA, but there is a great variation in the running experience of the participants (3-256 months). Running with prostheses can take some time to adjust to, and this may affect the current results by introducing greater variability in the ILEA group regarding their running patterns. Second, current participants used their own RSP (2 in Cheetah, 4 in Flex-Run, 2 in Catapult) during the experiment. It has been implicated that running mechanics using RSPs may be influenced by type of RSPs [1, 34, 35]. Therefore, caution needs to be taken regarding the interpretation and generalization of these findings.

In summary, the results of the present study suggest that the loading variables (VIP and VALR) in both ILEA and AB runners increase with increasing running speed. Loading variables in the ILEA intact limb were greater than the prosthetic limb and the limbs of AB subjects for a range of running speeds. Additional work is needed to identify effective methods that can reduce the elevated loading rates in the intact limbs of ILEA using RSPs during running.

## Acknowledgments

This project was supported in part by NIH 1R03AR062321, Grant-in-Aid of Japan Society for the Promotion of Science, and Kyung Hee University International Scholars Program.

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**Research Highlights**

- Vertical loading rates using running-specific prostheses were examined.
- Eight amputee runners performed overground running at a range of running speeds.
- Loading rates in intact limbs were greater than prosthetic limbs and control subjects.
- Amputee runners may be exposed to a greater risk of injury than able-bodied runners.

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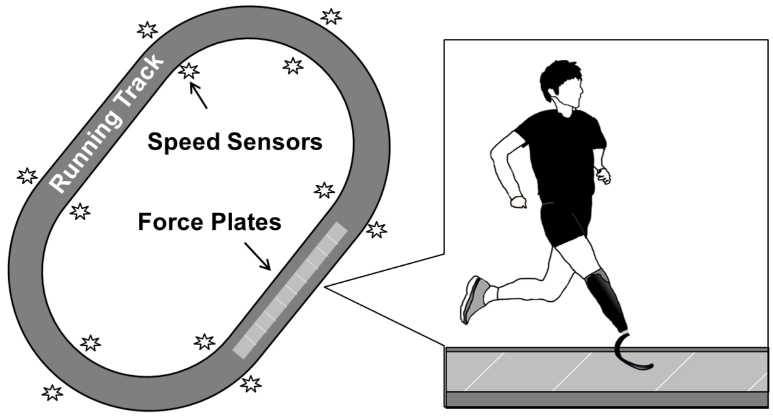


**Figure 1.**

Schematic of experiment setup. Each subject ran around a 100m track containing 10 force plates that recorded ground reaction force data. Six sets of sensors around the track monitored running speed in real-time.

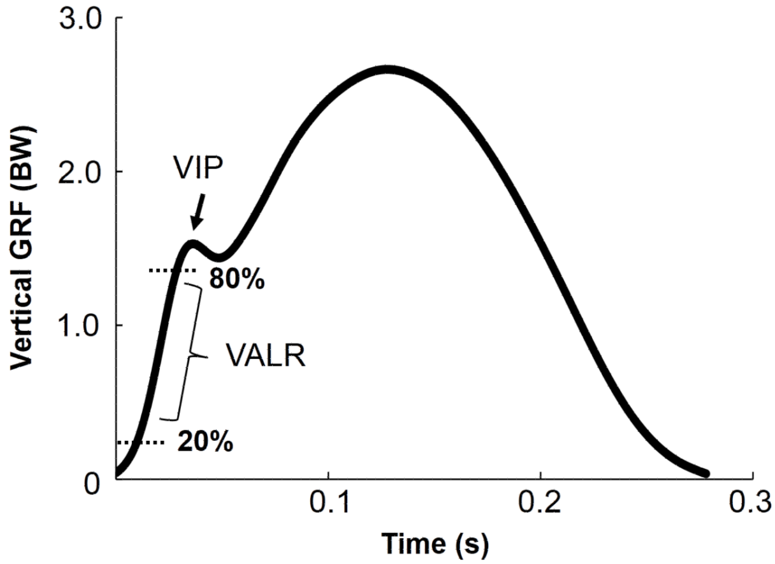


**Figure 2.**

Vertical ground reaction force (vGRF) during the stance phase, recorded from the intact limb of a single ILEA at 2.5 m/s. Vertical average loading rate (VALR) was determined at early stance phase between 20% and 80% before the first GRF peak (vertical impact peak; VIP).

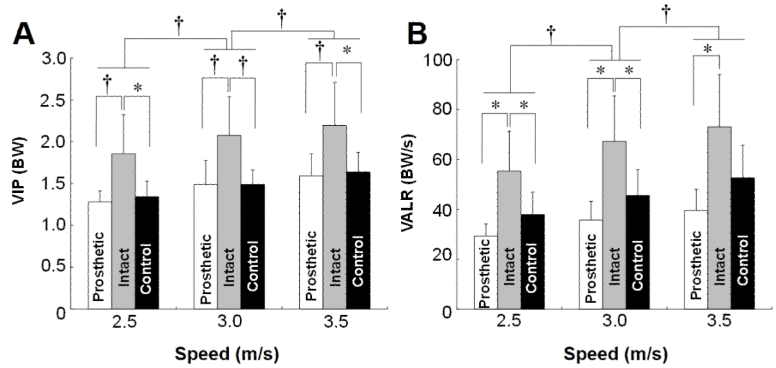


**Figure 3.**
(A) Vertical impact peak (VIP) and (B) vertical average loading rates (VALR) for the prosthetic and intact limbs of ILEA as well as for the limbs of the control group at three running speeds, 2.5m/s, 3.0m/s, and 3.5ms. An asterisk (*) indicates statistically significant differences between limbs at $p$ <0.05. A dagger (†) indicates statistically significant differences between running speeds at $p$ <0.01.


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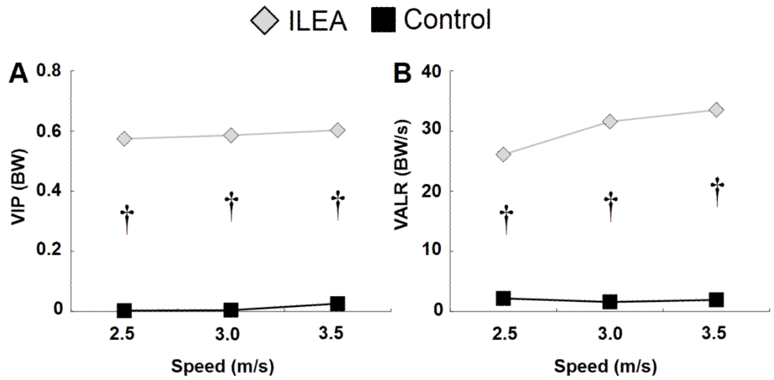


**Figure 4.**
Absolute difference in (A) vertical impact peak (VIP) and (B) vertical average loading rates (VALR) between the limbs in ILEA and AB Control groups at three running speeds. A dagger (†) identifies statistical significance for limb differences in loading variables between the groups.


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**Table 1**

ILEA subject characteristics.

| Subject | Age (years) | Height (m) | Total Mass (kg) | Running Experience (months) | RSP model |
|---|---|---|---|---|---|
| 1 | 48 | 1.75 | 73.4 | 46 | Flex-Run |
| 2 | 31 | 1.71 | 67.9 | 48 | Flex-Run |
| 3 | 34 | 1.72 | 110.2 | 60 | Flex-Run |
| 4 | 27 | 1.80 | 73.8 | 9 | Cheetah |
| 5 | 23 | 1.88 | 85.3 | 9 | Cheetah |
| 6 | 27 | 1.84 | 85.3 | 3 | Flex-Run |
| 7 | 46 | 1.81 | 84.3 | 256 | Catapult |
| 8 | 20 | 1.89 | 78.0 | 12 | Catapult |
| Mean | 32.0 | 1.80 | 82.3 | 55.4 | |
| SD | 10.2 | 0.07 | 13.0 | 84.0 | |