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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.

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

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Table 1
ILEA subject characteristics.

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

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 toward 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 2.8–3.0 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 (Fig. 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

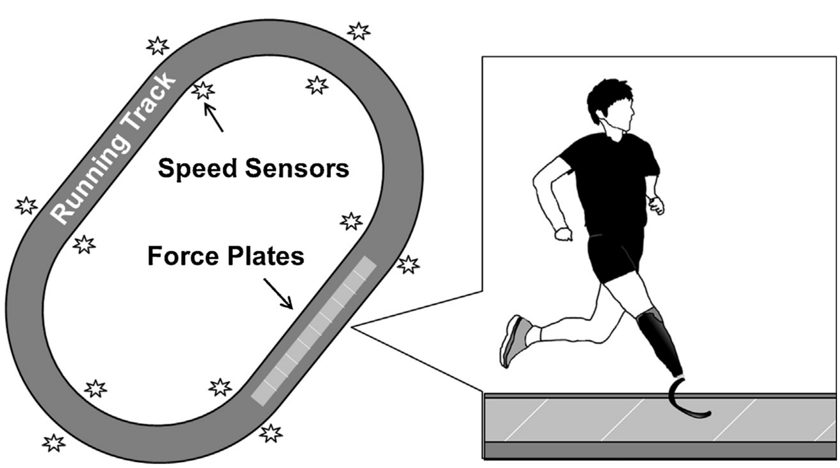

Fig. 1. Schematic of experiment setup. Each subject ran around a 100 m track containing 10 force plates that recorded ground reaction force data. Six sets of sensors around the track monitored running speed in real-time.