RUNNING MECHANICS IN UNILATERAL TRANSFEMORAL AMPUTEES ACROSS A RANGE OF SPEEDS

Hiroyuki Sakata[1,2] , Satoru Hashizume[1], Yoshiyuki Kobayashi[1], Hiroshi Takemura[1,2] , Hiroaki Hobara[1]

National Institute of AIST, Tokyo, Japan[1]
Tokyo University of Science, Chiba, Japan[2]

Running-specific prostheses (RSP) allows individuals with lower extremity amputations to participate in running activities. The aim of this study was to investigate the average vertical ground reaction force (F_{avg}), step frequency ($Freq_{step}$) and contact length (L_c) between intact and prosthetic limb across a range of running speeds. Nine unilateral transfemoral amputees with RSP performed running on instrumented treadmill at incremental speeds of 30, 40, 50, 60 and 70% of their maximum speed. We found that prosthetic limb generated smaller F_{avg} than intact limb, and had similar $Freq_{step}$ between limbs. However, prosthetic limb had longer L_c than intact limb at faster speeds. These results suggest that unilateral transfemoral amputees using RSP have asymmetrical running mechanics between limbs to adapt to the increasing running speed.

KEYWORDS: amputation, running-specific prostheses, vertical ground reaction force.

INTRODUCTION: Running-specific prostheses (RSP) allows individuals with lower extremity amputations to participate in running activities. According to previous studies (Weyand et al., 2000, Weyand et al., 2010), constant running speed is the product of the body weigh-specific average vertical ground reaction force (F_{avg}), step frequency ($Freq_{step}$), and contact length (L_c: forward distance the body travels during the foot-ground contact period). Therefore, one or more of these variables must be improved to adapt to the increasing running speed.
Understanding the adaptations to the increasing running speed in lower extremity amputees using RSP can provide insight to develop more effective running gait rehabilitation and further sprint-specific training. Grabowski et al. (2010) compared F_{avg}, $Freq_{step}$ and L_c between prosthetic and intact limb in unilateral transtibial amputees with RSP using instrumented treadmill. In their study, F_{avg} and $Freq_{step}$ of prosthetic limb was 9% and 8% lower, but L_c was 4% greater than those of intact limb. These results suggest that unilateral transtibial amputees using RSP adapt to the increasing running speed by adopting different running mechanics between intact ant prosthetic limbs.
On the other hand, very few studies have been conducted on running mechanics in unilateral transfemoral amputees using RSP. A recent study revealed that the peak vertical ground reaction force of prosthetic limb was 26% lower than that of intact limb in unilateral transfemoral amputees using RSP during maximal sprinting (Makimoto et al., 2017). However, the study only analysed maximal sprinting speed trials of each individual (5.71 ± 0.70 m/s). Therefore, it remains unclear how unilateral transfemoral amputees increase running speed by using RSPs. The aim of this study was to investigate F_{avg}, $Freq_{step}$ and L_c of intact and prosthetic limb across a range of running speeds in unilateral transfemoral amputees using RSP.

METHODS: Nine individuals with unilateral transfemoral amputations participated in this study (Table 1). All participants used their own prosthetic knee joints and RSP (Table 1). They performed running on instrumented treadmill (FTMH-1244WA, Tec Gihan, Kyoto, JPN) at incremental speeds of 30, 40, 50, 60 and 70% of their maximum speed. In this study, we determined maximum (100%) speeds of each individual by dividing the race distance (100-m) by the official personal best record in competitions. Participants rested for as long as needed between trials to reduce the effects of fatigue.
Ground reaction force (GRF) was collected at 1000 Hz by using a treadmill-mounted force plate. The GRF data were filtered using a zero-lag fourth-order low-pass Butterworth filter at a 25 Hz cut-off frequency (Kram et al., 1998). From the filtered GRF data, we detected the

instants of touch-down and toe-off using a 40 N threshold (Grabowski et al., 2010), and determined F_{avg}, $Freq_{step}$ and L_c for 14 consecutive steps, 7 intact limb and 7 prosthetic limb steps in each speed. GRF data were normalized by the participant's body weight including RSP. $Freq_{step}$ was calculated as the inverse of the time from footstrike to contralateral footstrike (Grabowski et al., 2010). Further, L_c were determined by multiplying the contact time by the belt speed (Grabowski et al., 2010).
Two-way repeated-measures ANOVA with two factors, speeds (five levels) and limbs (two levels) was performed to compare intact and prosthetic limbs at five running speeds. Bonferroni post hoc multiple comparison was performed if a significant main effect was observed. Statistical significance was set at $p < 0.05$. All statistical calculations were conducted using SPSS for Windows version 22 (IBM, Armonk, NY, USA).

Table 1. Demographic data, RSP models, prosthetic knee joints, official 100m personal records and 100% running speeds for each subject.

Subject	Sex	Age (years)	Height (m)	Mass (kg)	RSP model	Prosthetic knee joint	100m personal record (s)	100% running speed (m/s)
1	M	26	1.75	66.0	Sprinter 1E90	3S80	14.08	7.10
2	M	17	1.77	84.0	Sprinter 1E90	3S80	14.45	6.92
3	M	54	1.70	65.8	KATANA-β	3S80	16.25	6.15
4	M	23	1.68	55.7	Sprinter 1E90	3S80	16.81	5.95
5	M	42	1.67	57.2	Sprinter1E90	3S80	17.66	5.66
6	M	34	1.61	58.7	Runner 1E91	3S80	17.82	5.61
7	F	19	1.56	58.9	Runner 1E91	3S80	16.86	5.93
8	F	21	1.49	44.4	Sprinter 1E90	3S80	20.66	4.84
9	F	21	1.52	51.6	Sprinter 1E90	3R95	21.05	4.75
Mean		29	1.64	60.3			17.29	5.88
SD		12	0.09	10.5			2.26	0.76

RESULTS: As shown in Figure 1-A, there was a significant main effect of speeds ($p < 0.01$), but not limbs on F_{avg} ($p = 0.10$). However, there was significant interaction effect between speeds and limbs on F_{avg} ($p < 0.01$). From 30% to 70% speeds, F_{avg} were increased by 28% and 12% in intact and prosthetic limb, respectively. Although it did not reach statistical significance, F_{avg} of prosthetic limb was 12% lower than intact limb at 70% speed.
As shown in Figure 1-B, statistical analysis revealed the existence of a significant main effect of speeds on $Freq_{step}$ ($p < 0.01$), while there was no significant main effect of limbs ($p = 0.34$) and interaction effect on $Freq_{step}$ ($p = 0.66$). From 30% to 70% speeds, $Freq_{step}$ were significantly increased by 22% and 24% in intact and prosthetic limb, respectively. $Freq_{step}$ was not significantly different between limbs at any speeds, and the between-leg difference was only 1% at 70% speed.
As shown in Figure 1-C, both speeds ($p < 0.01$) and limbs ($p < 0.01$) has a significant main effect on L_c. Further, we also found a significant interaction between limbs and speeds on L_c ($p < 0.01$). From 30% to 70% speeds, L_c were significantly increased by 50% and 66% in intact and prosthetic limb, respectively. Between-leg difference in L_c was 3% at slower 30% speed, but prosthetic limb had 14% significantly longer L_c than that of intact limb at 70% speed.

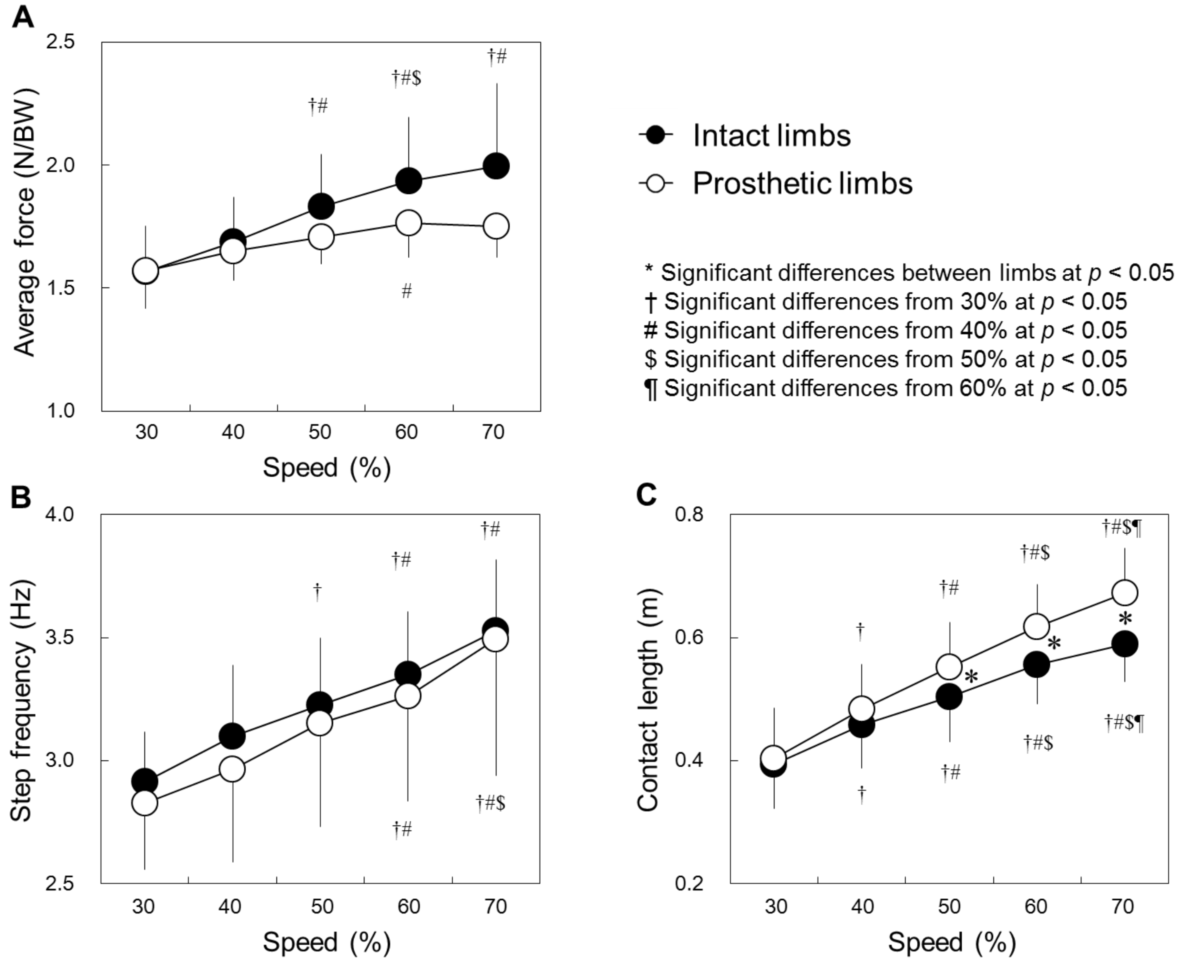

Figure 1: (A) average vertical ground reaction force (F_{avg}), (B) step frequency ($Freq_{step}$), and (C) contact length (L_c) of intact limb (black circles) and prosthetic limb (white circles) across five running speeds. Error bars represent a standard deviation.

DISCUSSION: The aim of this study was to investigate F_{avg}, $Freq_{step}$ and L_c of intact and prosthetic limb across a range of running speeds in unilateral transfemoral amputees using RSP. We found that F_{avg} were similar for both limbs at slower 30% speeds; however, the F_{avg} of prosthetic limb was significantly smaller than that of intact limb at faster speeds (Figure 1-A). The result was consistent with a recent study that the peak vertical ground reaction force of prosthetic limb was 26% lower than intact limb during maximal sprinting in unilateral transfemoral amputees (Makimoto et al., 2017). In addition, previous studies reported that prosthetic limb had lower F_{avg} than intact limb across a range of running speeds in unilateral transtibial amputees (Baum et al., 2016; Grabowski et al., 2010). One potential explanation of lower force production capability in prosthetic limb may be muscle weakness due to thigh muscle atrophy (Sherk et al., 2010). Therefore, current results suggest that residual limb with RSP may impair force production capability in lower extremity amputees regardless of the amputation levels.

We also found that $Freq_{step}$ were significantly increased with speed for both limbs; however, there were no significant differences between limbs at any speeds (Figure 1-B). Our results were inconsistent with a past finding which demonstrated that $Freq_{step}$ of prosthetic limb was 8% significantly lower than intact limb at top speed (mean: 8.8 m/s) in unilateral transtibial amputees (Grabowski et al., 2010). On the other hand, our results agreed with a previous study that there were no significant differences in $Freq_{step}$ between limbs during submaximal running (2.5, 3.0 and 3.5 m/s) in unilateral transtibial amputees (Hobara et al., 2013). Since our participants performed running at 1.8-4.1 m/s, greater running speed over 4.0 m/s may induce between-leg difference in $Freq_{step}$ in unilateral transfemoral amputees using RSP.

Figure 1-C showed that L_c were similar for both limbs at slower speeds, but prosthetic limb had significantly longer L_c than intact limb at faster speeds (50, 60 and 70%). Since L_c were determined by multiplying the contact time by the belt speed, the difference in L_c would be due to the difference in the contact time. Therefore, our result showed that prosthetic limb would have a significantly longer contact time than intact limb at faster speeds. According to a previous study (Makimoto et al., 2017), the contact time of prosthetic limb was 13% longer than that of intact limb during maximal sprinting in unilateral transfemoral amputees using RSP. Therefore, our participants would compensate for smaller F_{avg} in their prosthetic limb by using longer L_c to achieve the faster running speeds.

CONCLUSION: We found that unilateral transfemoral amputees using RSP generated smaller mean value of F_{avg} in prosthetic limb compared to intact limb, and had similar $Freq_{step}$ between limbs. However, prosthetic limb had longer L_c than intact limb at faster speeds. These results indicate that unilateral transfemoral amputees using RSP have asymmetrical running mechanics between intact and prosthetic limb to adapt to the increasing running speed. Therefore, our results suggest that limb-specific rehabilitation and training strategies should be developed for unilateral transfemoral amputees.

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