# BRAKING AND PROPULSIVE IMPULSES ACROSS A RANGE OF RUNNING SPEEDS IN UNILATERAL TRANSFEMORAL AMPUTEES

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Braking and propulsive ground reaction force impulses (GRIs) are mechanical parameters affecting the running performance. The purpose of this study was to determine the braking and propulsive GRIs across a range of speeds in unilateral transfemoral amputees. Ten unilateral transfemoral amputees ran on an instrumented treadmill at incremental speeds of 30%, 40%, 50%, 60%, and 70% of their maximum speed. At all given speeds, the braking GRI of affected limb was significantly smaller than unaffected limb; however, the propulsive GRIs were similar for both limbs. Consequently, the net anteroposterior GRI was positive in affected limb and negative in unaffected limb. These results suggest that the functional role of braking and propulsion is not the same between the limbs. Training for unilateral transfemoral amputees could focus on reducing the braking GRI of unaffected limb.

**KEYWORDS:** amputee running, running-specific prosthesis, ground reaction force.

**INTRODUCTION:** Analyzing ground reaction forces (GRFs) is a classical and basic approach to evaluate human locomotion (Baum, Hobara, Kim & Shim, 2016; Munro, Miller & Fuglevand, 1987). Braking and propulsive ground reaction force impulses (GRIs) are the major determinants of forward velocity of a runner’s body (Hunter, Marshall & McNair, 2005) and can be used as mechanical parameters affecting the running performance for prosthetic feet (Baum, Hobara, Kim & Shim, 2016). During constant-speed running, the braking and propulsive components of GRFs are important for postural balance because the corresponding GRFs maintain the alignment of the resultant GRF with the center of mass of the body (Roberts & Scales, 2002).

In runners with unilateral transfemoral amputation using running-specific prosthesis (RSP), Makimoto et al. (2017) identified that the affected limb generated significantly smaller braking GRI and similar propulsive GRI compared to the unaffected limb during maximal sprinting (5.71 ± 0.70 m/s) where the participants slightly accelerated on their affected limb. However, it remains unclear how runners with unilateral transfemoral amputation modulate the braking and propulsive GRIs at different running speeds because the braking and propulsive GRIs are speed dependent (Munro, Miller & Fuglevand, 1987). The ability to run at different speeds is vital for participation in sports activities; therefore, a deeper understanding of the biomechanics with RSP across a range of speeds can provide insights into the running performance and prosthesis designs for individuals with lower-limb amputation.

The purpose of this study was to determine braking and propulsive GRIs across a wide range of speeds in runners with unilateral transfemoral amputation using RSP. Since braking and propulsive GRIs during running are speed dependent (Munro, Miller & Fuglevand, 1987), we hypothesized that the braking and propulsive GRIs would increase with speed for both the unaffected and affected limbs. Further, as the braking and propulsive GRIs must be of equal magnitude but opposite direction during level running at a constant speed (Chang & Kram, 1999; Gottschall & Kram, 2005), we hypothesized that the net anteroposterior GRIs would be zero in each limb at all given speeds.

**METHODS:** Ten runners with unilateral transfemoral amputation (6 males and 4 females; age: 28 ± 11 years old, body height: 1.63 ± 0.09 m, body mass: 58.8 ± 10.8 kg, mean ± SD) participated in our study. 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 subjects gave informed written consent before participating. Each participant used their own prescribed RSP and prosthetic knee joint. Six subjects wore the Sprinter 1E90 (Ottobock, Duderstadt, Germany), 2 subjects wore the Runner 1E91 (Ottobock, Duderstadt, Germany), 1 subject wore the Flex-Run (Össur, Reykjavik, Iceland), and 1 subject wore the KATANA-$\beta$ (IMASEN & MIZUNO, Gifu, Japan). Nine subjects wore 3S80 (Ottobock, Duderstadt, Germany) and 1 subject wore 3R95 (Ottobock, Duderstadt, Germany).

Each participant performed running trials on an instrumented split-belt treadmill (FTMH-1244WA, Tec Gihan, Kyoto, Japan) at incremental speeds of 30%, 40%, 50%, 60%, and 70% of their maximum (100%) speed. The maximum speeds for each individual were estimated by dividing the race distance (100 m) by the official personal best time recorded in competitions (17.80 ± 2.62 s). The participants started a series of trials at 30% of their maximum speed and the speed for each subsequent trial was increased by 10% until subjects reached 70% of their maximum speed. Trials at slower speeds typically lasted 10 to 15 s, whereas trials at faster speeds lasted less than 10 s. Between the trials, the participants took as much rest as necessary to reduce the effects of fatigue (1 or 2 min). The running speeds for each trial were on average 1.76 ± 0.22 m/s for 30%, 2.35 ± 0.30 m/s for 40%, 2.93 ± 0.36 m/s for 50%, 3.52 ± 0.44 m/s for 60%, and 4.10 ± 0.50 m/s for 70%.

Two force plates embedded in the treadmill were used to collect GRF data at 1000 Hz. The GRF data were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 25 Hz (Clark & Weyand, 2014; Kram, Griffin, Donelan & Chang, 1998). From the filtered vertical GRF data, the instants of touch-down and toe-off were detected using a threshold of 40 N (Grabowski, McGowan, McDermott, Beale, Kram & Herr, 2010). Braking and propulsive GRIs were calculated as the time integrals of the posterior and anterior GRF for each step. We analyzed 14 consecutive steps and averaged 7 steps of each limb to determine the representative values for each variable. All GRF variables were normalized to the subject's body weight (BW), including the weight of the RSP.

The two-way repeated-measures ANOVA with two factors, speed (five levels) and limb (two levels), followed by Bonferroni post-hoc multiple comparison was performed to compare the variables between the unaffected and affected limbs at five running speeds. Statistical significance was set at $p < 0.05$. All statistical calculations were performed using SPSS for Windows version 22 (IBM, Armonk, NY, USA).

**RESULTS:** Figure 1 shows typical time-course profiles of the anteroposterior GRFs across 5 running speeds for each unaffected and affected limb (recorded from a runner).

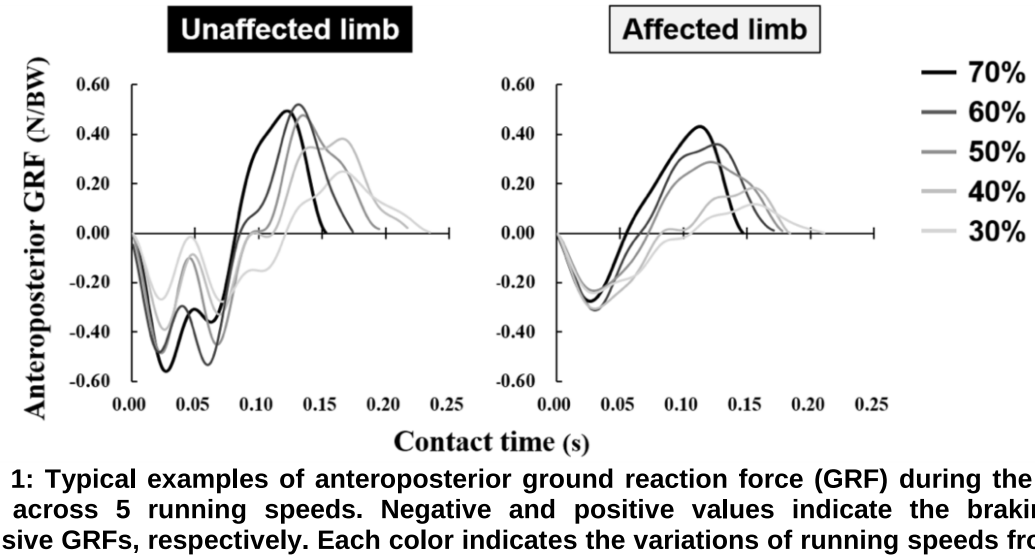

**Figure 1: Typical examples of anteroposterior ground reaction force (GRF) during the stance phase across 5 running speeds. Negative and positive values indicate the braking and propulsive GRFs, respectively. Each color indicates the variations of running speeds from 30% to 70%. With increase in speed, contact time decreased. Peak braking GRF increases with speed for the unaffected limb, but not for the affected limb. Peak propulsive GRFs increase with speed for both limbs.**

As shown in Figure 2-A, significant main effects of speed ($p < 0.01$) and limb ($p < 0.01$) were seen on braking GRI; whereas, no significant interaction was observed between speed and limb on braking GRI ($p = 0.09$). Figure 2-A also demonstrates that braking GRI significantly increased with speed for the unaffected limb, but not for the affected limb. The affected limb generated significantly smaller braking GRI than the unaffected limb at all speeds.

Figure 2-A shows a significant main effect of speed ($p < 0.01$), but no significant main effect of limb ($p = 0.65$) on propulsive GRI and no significant interaction between speed and limb ($p = 0.07$). The propulsive GRIs for both limbs significantly increased with speed, but no significant difference was observed between the limbs at any speeds (Figure 2-A).

Statistical analysis revealed was no significant main effect of speed on net anteroposterior GRI ($p = 0.27$). Although, there was a significant main effect of limb on net anteroposterior GRI ($p < 0.01$), no significant interaction was observed between speed and limb ($p = 0.08$). As shown in Figure 2-B, the net anteroposterior GRIs for both limbs did not change with speed. Across all speeds, the affected limb generated positive net anteroposterior GRI, whereas the unaffected limb generated negative net anteroposterior GRI (Figure 2-B).

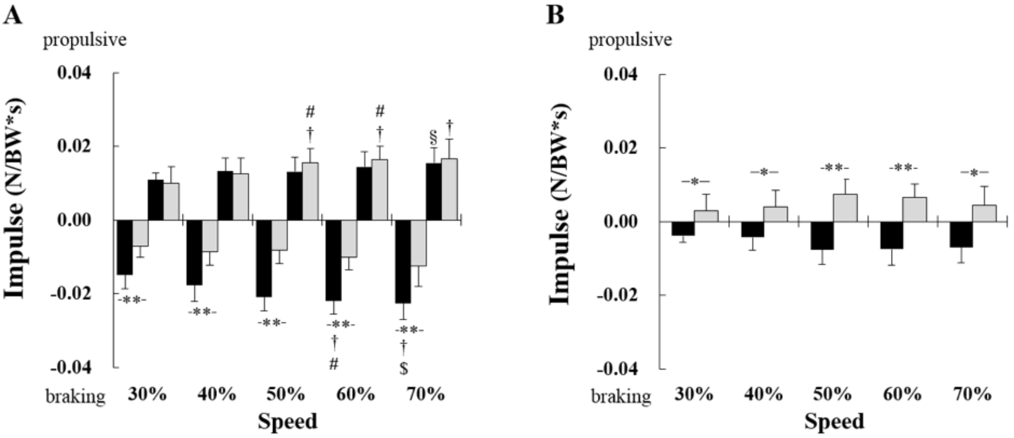

**Figure 2: Braking and propulsive ground reaction force impulses (GRIs) (A) and net anteroposterior GRI (B) for the unaffected (black) and affected (grey) limbs at 5 running speeds. Error bars represent 1 standard deviation. Asterisks (*, **) indicate significant differences between the limbs at $p < 0.05$ and $p < 0.01$, respectively. Dagger (†), sharp (#), dollar ($), and section (§) indicate significant differences from 30%, 40%, 50%, and 60% at $p < 0.05$, respectively.**

**DISCUSSION:** The purpose of this study was to determine the braking and propulsive GRIs across a wide range of speeds in runners with unilateral transfemoral amputation using RSP. Current results partly supported our first hypothesis that the braking and propulsive GRIs would increase with speed for both the unaffected and affected limbs expect for the braking GRI of affected limb (Figure 2-A). In contrast with non-amputees (Munro, Miller & Fuglevand, 1987), braking GRI of affected limb kept nearly constant across the speeds (Figure 2-A). On the other hand, similar results are observed in unilateral transtibial amputees using RSP, where braking GRI of affected limb did not change with speed (Baum, Hobara, Kim & Shim, 2016). The smaller braking GRI in the affected limb could be attributed to the smaller braking GRF and earlier zero fore-aft shear (the time when the fore-aft shear changed direction from braking to propulsion). In fact, the affected limb exerted smaller peak braking GRFs and spent the majority of contact time in propulsion than the unaffected limb (Figure 1). Similar trends were also observed in runners with unilateral transfemoral (Makimoto, Sano, Hashizume, Murai, Kobayashi, Takemura & Hobara, 2017) and transtibial (Baum, Hobara, Kim & Shim, 2016) amputation using RSP. Therefore, the results of the present study and previous studies suggest that regardless of the running speed, the affected limb generates less braking and equivalent propulsive GRIs compared to the unaffected limb in runners with unilateral lower-limb amputation using RSP. The similar propulsive GRI in the affected limb may be due to RSP shape and/or mechanical property, because daily-use prostheses generated significantly smaller propulsive GRI than the unaffected limb (Engsberg, Lee, Tedford & Harder, 1993; Prince, Therrien & McFadyen, 1992).

In contrast with our second hypothesis, net anteroposterior GRI was positive in the affected limb, whereas negative in the unaffected limb at all speeds (Figure 2-B). Similar results were not observed in non-amputees (Chang & Kram, 1999; Gottschall & Kram, 2005), but observed in unilateral transfemoral amputees during walking (Schaarschmidt, Lipfert, Meier-Gratz, Scholle & Seyfarth, 2012), where the affected limb accelerated the body but the unaffected limb decelerated the body in an anteroposterior direction. Therefore, these results suggest that the functional role of the braking and propulsion is not the same between the unaffected and affected limbs in unilateral transfemoral amputees during running as well as during walking. Further research is needed to identify factors affecting functional differentiation of the braking and propulsive roles of the unaffected and affected limbs in unilateral transfemoral amputees. Specifically, in unilateral transfemoral amputees, altered touch-down kinematics in the affected limb caused by the missing active knee extension (Buckley, 1999; Schaarschmidt, Lipfert, Meier-Gratz, Scholle & Seyfarth, 2012) might affect the functional differences.

**CONCLUSION:** This study identified that propulsive GRIs of both limbs increased with speed and was not significantly different between the limbs at any speeds. Braking GRI of the unaffected limb also increased with speed; however, braking GRI of the affected limb was not speed dependent. Consequently, the net anteroposterior GRI was positive for the affected limb and negative for the unaffected limb at all given speeds. Therefore, the current results suggest that unilateral transfemoral amputees using RSP tend to maintain constant running speed by combining the acceleration on the affected limb and deceleration on the unaffected limb across a wide range of speed. Although the range of speed tested in the present study might underestimate actual overground running speed, training for runners with unilateral transfemoral amputation could focus on reducing the braking GRI on the unaffected limb, which might result in reduced propulsive GRI on the affected limb and allow them to maintain a running speed with smaller GRI.

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