GRF ANALYSIS OF TWO ELITE PARALYMPIC SPRINTERS IN STEADY AND RESISTED ACCELERATED TREADMILL RUNNING

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Analysis of ground reaction forces (GRFs) allows evaluating performances of paralympic runners with transfemoral amputation. Instrumented treadmills are expensive and low-cost solutions to gather GRFs are worth to be studied. This study aimed to use a commercial treadmill placed on four force platforms to evaluate vertical impulse, braking and propulsive horizontal impulses during steady-speed (SSR) and resisted accelerated (RAR) running. The RAR vertical impulses of the unaffected limb (UL) of the two athletes doubled the values of the affected limb (AL) that has, however, on average 23% larger propulsive action than UL in SSR. The horizontal impulse of AL remains positive in the first 10 steps during RAR, as expected. Agreement between present results and literature confirms that the proposed setup gives sufficient confidence in the evaluation of the sprint technique.

KEYWORDS: running prosthetic feet, ground reaction forces, treadmill, resisted running

INTRODUCTION: The in-vivo evaluation of forces acting on Running Prosthetic Feet (RPF) of paralympic athletes is important to evaluate running kinetics and to improve their performance. The knowledge of peak values and impulses of the Ground Reaction Forces (GRFs) of both limbs during sprinting in unilateral transfemoral amputees gives fundamental information to understand and evaluate athletic performance as well as optimize prosthesis stiffness choice and overall alignment. Several studies demonstrated that GRFs are used by sprinters as the greatest external forces to accelerate their centre of mass forward. It was demonstrated that during sprinting, unilateral transfemoral amputees have asymmetrical kinetics between affected and unaffected limbs (Makimoto et al., 2017). In this context, the study of Sakata et al. (2019) suggested that to maintain a constant running speed, unilateral transfemoral athletes using RPF must accelerate on the affected limb and decelerate on the unaffected one. As regards accelerated running, Nagahara et al. (2018), studying the GRFs of able-bodied sprinters, demonstrated that the horizontal impulse was mainly propulsive during the entire acceleration phase and at the maximal speed. The braking and propulsive horizontal impulses must be minimized and maximized respectively to faster accelerate sprinter body.

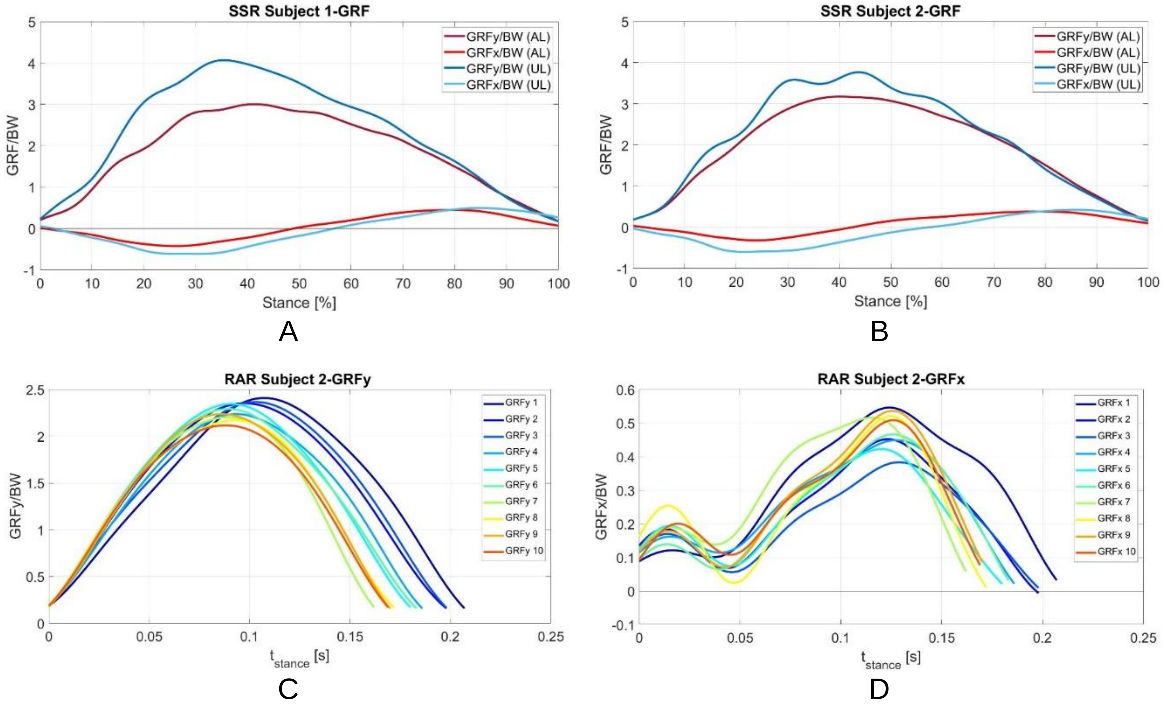
The purpose of this study is to evaluate the possibility of adopting a commercial treadmill placed on four force platforms to assess running performance of two elite Paralympic sprinters. GRFs peak values, vertical impulse, braking and propulsive horizontal impulses collected in SSR and RAR tests are compared with those available in literature.

METHODS: Two Paralympic medallist female athletes with left unilateral transfemoral amputations participated in this study: Subject 1 (55 kg) and Subject 2 (59 kg). Both athletes used Ottobock 1E91 standard RPF, respectively Cat 3.5 and Cat 4: prosthetic knee joint was a mono-axial knee Ottobock 3S80. The two athletes adopted the same alignment A1 of the socket and the foot (Migliore et al., 2021). After adjusting a safety harness, elite sprinters performed running on a commercial treadmill (SkillRun Technogym) placed on four force platforms (BTS P6000 - acquisition rate 1000 Hz), integrated into a BTS motion capture system (D 6000, acquisition rate 250 Hz). Two types of tests were conducted: SSR and RAR. SSR consisted in reaching a constant speed and maintaining it for at least 7 seconds. Running speed was set on the treadmill controller in agreement with the speed reached by athletes during the pilot test. In SSR tests, athletes reached a speed of 5 m/s (Subject 1) and 4.4 m/s (Subject 2). As regards RAR, athletes reached a steady speed of 3.4 m/s (Subject 1) and 3.7

m/s (Subject 2) starting from zero. RAR was performed with the treadmill switched to passive mode to simulate inertial and air resistance. During RAR tests, a uniaxial load cell (FS 1000 N-acquisition rate 1000 Hz) was fixed to each athlete's back through a pre-loading elastic band, to measure the instantaneous resistance applied to the harness at the sacrum bone.

GRFs (anterior-posterior component GRF_x and vertical component GRF_y) were collected at 1000 Hz and filtered differently in the case of SSR and RAR. In the first case, a second-order bandstop Butterworth filter (15-35 Hz cut-off frequency) and a second-order low-pass Butterworth filter (43 Hz cut-off frequency) were used. In the second case, a fourth-order low-pass Butterworth filter at a 15 Hz cut-off frequency was applied to remove treadmill noise input. From the filtered GRF, instants of touch-down and toe-off were detected from GRFy using a 100 N threshold. As regards SSR, average curves of GRF_x and GRF_y for the last 10 consecutive steps for each limb were collected. Vertical (IV), as well as braking (IHb) and propulsion (IHp) horizontal impulses, were computed respectively as the time integrals of GRF_y and GRF_x. During RAR tests, the same protocol was adopted, with the focus on the first 10 consecutive steps for each limb. GRF data were normalized to the subject body weight including RPF.

RESULTS: In Figures 1-A and 1-B, the GRFs' average curves calculated during the SSR test are shown, respectively for Subject 1 and Subject 2, normalized as a percentage of stance. GRFs of the AL are reported in red, while GRFs of the UL are reported in blue. It is possible to observe that normalized GRF_y of Subject 1 reaches a peak of 4.08 N/BW for UL and of 3.00 N/BW for AL, whereas GRF_x ranges from -0.42 to 0.45 N/BW for AL and from -0.62 to 0.50 for UL. In Figures 1-C and 1-D, RAR test GRFs for each of the first 10 steps of Subject 2 are shown, respectively GRF_y and GRF_x. Steps from 1st to 10th are plotted with colours from blue to red. For both athletes, the total number of steps collected for each limb was 20.



A B

C D

Figure 1: (A) SSR Subject 1-GRF_x and GRF_y average curves for both AL and UL limbs, (B) SSR Subject 2-GRF_x and GRF_y average curves for both AL and UL limbs, (C) RAR Subject 2-GRF_y curves over the first 10 steps for AL and (D) RAR Subject 2-GRF_x curves over the first 10 steps for AL.

Values extracted from average trends, presented in Figures 1-A and 1-B, are reported in Table 1. In particular, GRF_{ymax}, GRF_{xmax} and GRF_{xmin} are highlighted. Moreover, the impulse of GRF_y was calculated (IV), while GRFx was divided into the braking phase (negative) and propulsive phase (positive). The impulses of these two phases were calculated as well, defined as braking (IHb) and propulsive (IHp) horizontal impulses. In Table 2, the same values were calculated for the 3rd and 9th steps of the RAR test. Moreover, the instantaneous speeds at the 3rd and 9th steps are shown.

Table 1: SSR parameters' values: GRF_{ymax}, GRF_{xmax}, GRF_{xmin}, IV, IHb and IHp. Impulses' data (mean and SD) are multiplied by 10^3.

	AL				UL			
	Subject 1		Subject 2		Subject 1		Subject 2	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
GRF_y max [N/BW]	**3.00**	*0.09*	**3.18**	*0.12*	**4.08**	*0.12*	**3.79**	*0.09*
GRFx max [N/BW]	**0.45**	*0.03*	**0.39**	*0.03*	**0.50**	*0.06*	**0.43**	*0.01*
GRFx min [N/BW]	**-0.42**	*0.05*	**-0.32**	*0.05*	**-0.62**	*0.07*	**-0.61**	*0.05*
IV [10^3*N*s/BW]	**142.1**	*7.70*	**148.2**	*11.00*	**186.0**	*6.80*	**170.1**	*7.50*
IHb [10^3*N*s/BW]	**-19.2**	*2.30*	**-11.2**	*2.10*	**-27.2**	*3.10*	**-28.8**	*3.40*
IHp [10^3*N*s/BW]	**23.3**	*2.00*	**23.3**	*2.20*	**19.7**	*2.70*	**17.7**	*1.30*

Table 2: RAR parameters values at the 3rd and 9th steps: GRF_{ymax}, GRF_{xmax}, GRF_{xmin}, IV, IHb and IHp. Impulses' data are multiplied by 10^3.

	AL				UL			
	Subject 1		Subject 2		Subject 1		Subject 2	
	Step 3	Step 9	Step 3	Step 9	Step 3	Step 9	Step 3	Step 9
Step Speed [m/s]	**1.89**	**3.08**	**2.15**	**3.31**	**2.11**	**3.14**	**1.99**	**3.19**
GRF_y max [N/BW]	**2.03**	**2.06**	**2.36**	**2.24**	**3.09**	**3.16**	**3.33**	**3.50**
GRFx max [N/BW]	**0.45**	**0.50**	**0.38**	**0.54**	**0.59**	**0.64**	**0.69**	**0.64**
GRFx min [N/BW]	**0.004**	**-0.03**	**0.01**	**0.07**	**0.11**	**0.05**	**0.03**	**-0.05**
IV [10^3*N*s/BW]	**80.4**	**76.7**	**89.4**	**73.6**	**154.7**	**161.9**	**149.0**	**150.5**
IHb [10^{3*}N*s/BW]	**<0.1**	**<0.1**	**<0.1**	**<0.1**	**<0.1**	**<0.1**	**<0.1**	**<0.1**
IHp [10^3*N*s/BW]	**59.5**	**52.6**	**40.0**	**47.8**	**61.7**	**54.3**	**65.9**	**46.9**

DISCUSSION: This study aimed to analyse and compare GRFs, IV, IHp and IHb of two elite Paralympic sprinters during SSR and RAR. The current findings highlighted that during SSR the prosthetic limb has mainly a propulsive horizontal action, while the intact limb is mainly braking. As far as GRF_x average curves are concerned, it could be observed that the braking phase of the average curve corresponding to UL is greater than that of AL. Makimoto et al. (2017) demonstrated that, regardless of the amputation levels, unilateral transfemoral amputee sprinters generate less braking impulse in their prosthetic limb to the intact limb. As shown in Figures 1A-1B, GRF_y average curve for UL has greater values than that of AL. These results were consistent with Sakata et al. (2018) study in which the peak of GRF_y reached greater values for UL than AL. In Table 1 it could be observed that IHp is greater in AL, while IHb is greater in UL for both athletes: this trend confirmed findings from previous studies (Makimoto et al., 2017; Sakata et al, 2019). IV Values of both athletes reported in Table 1 are consistent with Hobara et al. (2014) study. This demonstrates that GRF_y is greater in UL than that in AL; IV of UL of Subject 1 is quite larger than that of Subject 2.

As regards RAR, the AL GRF_y peak values tend to decrease, and stance time decreases as the steps progress. AL GRF_x curves do not present a braking phase, but only a propulsive one within the first ten steps: horizontal impulse must be propulsive to achieve a larger increase of running speed (Nagahara et al., 2018). In Table 2, IV, IHb and IHp are presented. These data have been calculated at the 3rd and 9th steps that can be representative, respectively, of the initial and the final steps of the acceleration phase. IV in RAR tests is again larger in the UL like during SSR tests. Furthermore, it could be seen that UL vertical impulse increases from step 3 to step 9 and decreases for AL. Nagahara et al. (2018) demonstrated that able-body sprinters show greater GRF_y during the maximal speed to achieve better time performance: this shall be appropriately applied to amputee-sprinters where the two limbs are unequal.

However, higher GRF_y peak values can increase centre of mass vertical oscillations during running, in turn associated with knee pain and other running-related injuries (Adams et al., 2018). Results show that AL responded differently for the two elite athletes of the present study. The analysis of IHp shows that Subject 2, as confirmed by Figure 1D, increases its propulsion contribution from step 3 to step 9, whereas Subject 1 shows an opposite trend, possibly indicating further margins of improvement in her acceleration technique. Results are shared with athletes, coaches and orthopaedic technicians to improve their awareness.

One of the limitations of the present study may regard the test setup used to collect GRFs, where a training treadmill placed over force platforms was used rather than an instrumented treadmill. Results in accordance with previous literature obtained on ground force platforms or on commercial instrumented treadmills give sufficient confidence in the evaluation of sprint technique with such an approach. Moreover, it would be appropriate to extend the research to more elite athletes to have a broader GRFs dataset for a wide statistical analysis.

CONCLUSION: The present work showed that GRFs measured using a treadmill placed on four external force platforms can provide horizontal and vertical kinetic quantities useful to evaluate athlete's performance. In the case of SSR the analysis of IHb and IHp is fundamental to understanding the sprinter's kinetics. The AL gives the main propulsive action, while the UL has a larger braking action during sprinting. Furthermore, the knowledge of vertical loads is crucial for evaluating overall performance and prevention strategies with attention to the UL. In the case of the RAR, the method allows detecting how stance time and AL GRFy peaks tend to decrease as the steps increase. In addition, GRF_x curves do not present a braking phase within the first 10 steps, but there are differences between the two elite subjects in the acceleration phase that need further deepen investigations.

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