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Running gait impulse asymmetries in below-knee amputees

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Abstract

In running, large gait asymmetry is expected due to the inability of the foot prosthesis to comply with the kinematic demands and produce a powerful plantarflexion moment. In this work, interlimb asymmetry in below-knee (BK) amputee running gait was assessed for one rigid and three flexible keel prostheses, using vertical and anteroposterior ground reaction forces and respective impulses. Nine BK amputees and 6 controls participated in this study. The running speed was monitored by two light sensitive detectors while the ground reaction forces were measured with a Kistler force plate. Between the prosthetic side and the sound limb the impulse indicator showed greater asymmetry than the force. Interlimb asymmetry was very much present in all types of prosthesis tested but is less pronounced in the flexible keel prostheses. In the latter, the asymmetry may be associated with the force-time history modulation rather than its magnitude alone. Generally, the impulses better describe interlimb asymmetry and the forces allow a greater discrimination between prosthetic foot types.

Introduction

Gait asymmetry has been reported during walking in unilateral below-knee (BK) amputees (Breakey, 1976; Culham *et al.*, 1986; Doane and Holt, 1983). It appears to be linked with an overloading of the musculoskeletal system leading to degenerative changes in the lumbar spine and knees (Burke *et al.*, 1978; Perry, 1975). Temporal, kinematic and kinetic asymmetry indices have been developed to describe the differences between the amputee's prosthetic and sound limbs (Hurley *et al.*, 1990; Seliktar and Mizrahi 1986; Skinner and Effeney, 1985; Winter and Sienko, 1988). Among these, Seliktar and Mizrahi (1986) concluded that the peak vertical forces and their ratios are not meaningful indicators in representing locomotor problems in BK walking gait, while the anteroposterior (AP) force perturbations are most useful in reflecting instabilities arising from the prosthesis. The impulses were, however, sensitive to the quality of gait.

With more and more amputees regularly taking part in strenuous recreational sports in which running is often an important activity, Brouwer *et al.*, (1989) suspect larger interlimb asymmetries. This is due in part to the inability of the foot prosthesis to satisfy the kinematic demands accompanying the large ankle excursion as well as to the lack of the powerful plantarflexion moment required for a strong propulsion. Although the running gait patterns of BK amputees have been described by Enoka *et al.* (1982) and Miller *et al.* (1984; 1987), the impulse parameters have not been extensively used to highlight the effect of different types of foot prostheses, on running gait asymmetry.

It was the purpose of this study to

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demonstrate that the impulse parameter was more appropriate than the ground reaction force in describing interlimb asymmetry in BK amputee running gait and to determine the effect of rigid and flexible keel foot prostheses on gait asymmetry. Emphasis was placed on the general functional characteristics of the prosthesis rather than on the individual type of foot.

Subjects and methods

Nine BK amputees and 6 control subjects participated in this study. In 5 cases, the amputation was consequent to either bone cancer or trauma while for the remaining 4 cases, surgery was carried out to correct congenital malformations. There were 3 female and 6 male amputees with a mean age of 16.4 years ±3.8 years and a weight of 58.6 kg ±12.9 kg. The control group, consisting of one female and 5 male subjects had a mean age and mass of 22.2 years ±3.5 years and 72.1 kg ± 12.4 kg respectively. The forces and impulses were corrected to take into account the weight difference between the amputee and control groups.

Four different types of prosthetic feet were tested. Five amputees had a SACH foot representing the rigid keel group. In the flexible keel group, 2 amputees were wearing the Seattle foot while the 2 others had a SAFE foot. Two of them were also fitted with a modified version of the Flat-Spring foot (FSF) prosthesis (Allard *et al.*, 1988). Because of its form, the SAFE foot has been included in the flexible keel group just as Wing *et al.*, (1989) did; although, Michael (1987) does not consider it to be an "energy storing" foot.

The least time since amputation was 2 years and all amputees had been wearing a PTB socket fitted with either a SACH, Seattle or SAFE foot for at least 2 years. The FSF prosthesis was worn only for the duration of the gait trials.

Physical examination revealed no important orthopaedic abnormality other than amputation. Muscle function was normal and all amputees had a healthy stump.

The ground reaction forces were sampled at 600 Hz using a Kistler force plate while the running speed was monitored by two "Speedtract" light sensitive detectors located at 3m on each side of the force plate along the 25m walkway. The subjects, wearing sport shoes, had about 7 trial runs to adjust their running speed to fall between 2.8m/s and 3.2m/s. Five trials were then recorded for the sound and affected limbs.

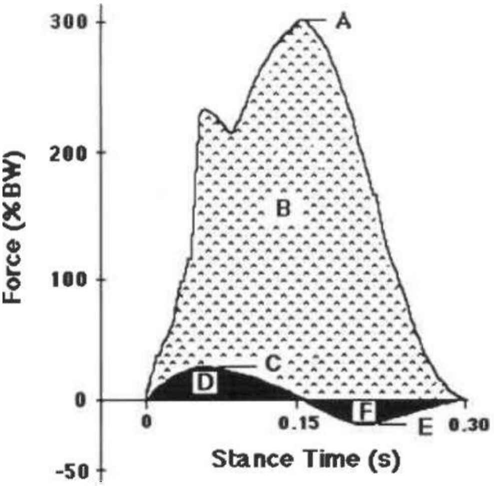

Fig. 1. Below-knee amputee ground reaction forces normalised with respect to body weight as a function of stance time for the prosthetic limb taken at a speed of 3.0m/s. A represents the maximum thrust, B the vertical impulse, C the maximum braking force, D the braking impulse, E the maximum push-off force and F the push-off impulse.

For a BK amputee running at 3.0m/s, Figure 1 illustrates typical vertical and AP ground reaction forces, expressed in percent of body weight (%BW), as a function of the stance time. Six values were extracted from these curves. From the vertical ground reaction force the maximum thrust, A, corresponded to the peak force developed by the amputee during the stance phase of running while the vertical impulse, B, was the total area under this curve. The maximum braking force, C, and impulse, D, associated with the deceleration of the body centre of mass were taken from the AP ground reaction force. The last two parameters were the push-off force, E, and impulse, F, partly representing the acceleration of the body centre of mass in the forward direction.

For these 6 parameters, several one way ANOVAs were used to test the significant difference between prosthetic foot types with respect to the sound or the affected limbs. A confidence level of $\alpha=0.05$ was chosen. Additionally, several asymmetry or symmetry indices were calculated from the force and

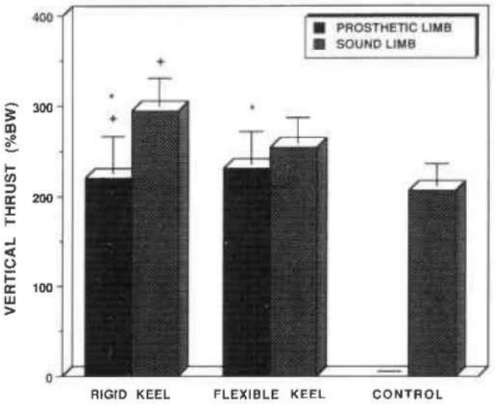

Fig. 2. Maximum vertical thrust for the rigid keel, flexible keel and control groups. Significant differences ($p<0.05$) with the amputee's sound limb are denoted with an asterix (*) while significant differences with the control group are reported with the symbol (+). This applies also to the following figures.

impulse values. These ratios were taken from Seliktar and Mizrahi (1986) and Robinson *et al.* (1987). Among these, the forces and impulses of the prosthetic limb over the corresponding sound limb values were the most consistent ratios.

Results and discussion

The force values have been normalized with respect to body weight and are expressed as percentages. The impulse values have been normalized only with respect to body weight, leaving the time component untouched. The normalized impulse is then expressed in percent body weight-second (% BW· s). Lee *et al.* (1989) normalized both the force and time units of the impulse. This may be justified in normal walking or running if speed is not controlled. Knowing that the amputee spends more time on the sound limb than on the prosthetic limb (Seliktar and Mazrahi, 1986), it is felt that an adjustment on the stance by normalizing it would be to ignore the important time factor in the impulse calculation. The amputee can compensate gait asymmetry by modulating both the force and time parameters rather than one or the other.

The results are reported for the SACH foot or rigid keel, the flexible keel foot prostheses and for values obtained from the right limb of the control group which are included for reference. The maximum forces are presented first, followed by the corresponding impulse values and their respective ratios.

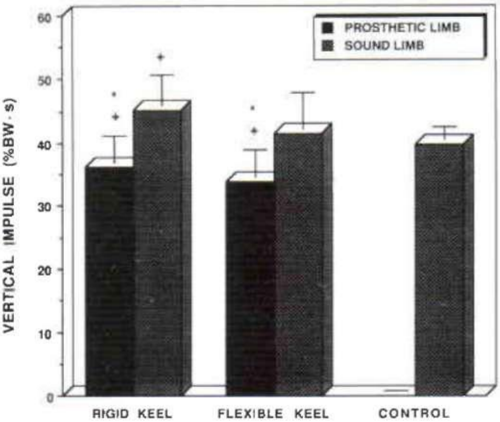

Fig. 3. Vertical impulse for the rigid keel, flexible keel and control groups.

In Figures 2 and 3, the maximum vertical thrust and impulse are given respectively for the two types of prosthetic foot wearers as well as for the control limb. The sound limb of amputees fitted with the rigid keel always shows higher values than that of the control limb, illustrating its preponderant role during the support phase. The maximum thrust asymmetry is more marked for the rigid keel than for the flexible keel foot prostheses. Furthermore, there is no significant difference between the values of the flexible keel and those obtained from the control group.

The vertical impulse values (Fig. 3) show a similar trend. Significant differences are reported between the sound and the prosthetic limbs, regardless of the prosthesis being used. The affected side values are always smaller 36.2%BW· s for the rigid keel and 33.9 %BW· s for the flexible keel prostheses compared to the respective sound limb values which are about 43 %BW· s. The rigid keel prosthesis is different in that the force asymmetry is larger than the impulse asymmetry. This is mainly due to a significantly higher force and impulse being developed by the contralateral sound limb.

The braking force (Fig. 4) and the braking impulse (Fig. 5) present a similar pattern revealing significant interlimb asymmetry in amputee running gait. The SACH foot exhibits the highest force (33.2 %BW) and impulse (1.9 %BW· s) among the prosthetic feet in reducing the amputee's forward momentum. This is

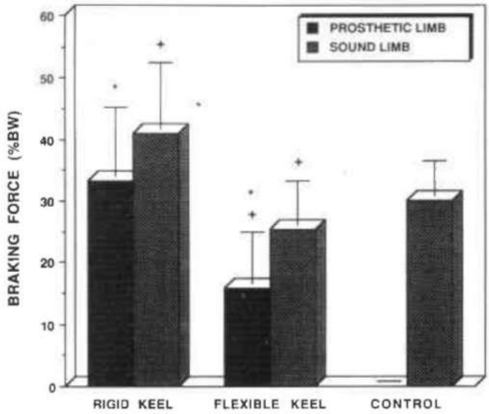

Fig. 4. Braking maximum force for the rigid keel, flexible keel and control groups.

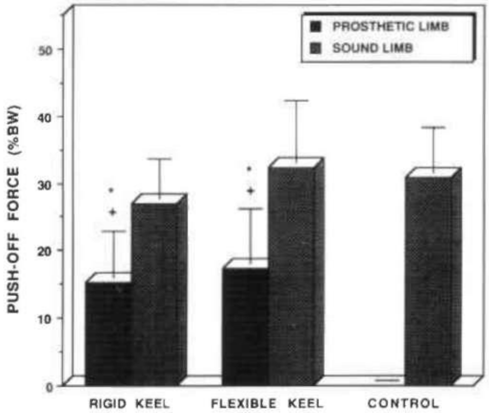

Fig. 6. Push-off maximum for the rigid keel, flexible keel and control groups.

related to the typical BK initial ground contact condition with the knee in total extension to prevent buckling (Enoka *et al.*, 1982).

The braking forces developed by the sound limb of amputees fitted with the flexible keel prostheses (25.3 %BW) are also different from the braking forces reported for the non-amputees (30.0 %BW). The corresponding impulse values on the other hand reveal no significant differences. The impulses reflect a good momentum conservation which could not be predicted from the braking forces alone. It is thought that better braking force and impulse conditions could have been obtained with the flexible keel prostheses if the FSF prosthesis had been fitted with a cushioned heel rather than just a rubber sole glued to its base. Without the FSF, the average braking force and impulse of the flexible keel group would have been much larger (20.2 %BW and 1.59 %BW· s) thus reducing the asymmetry between the affected and sound limbs.

With respect to the push-off force (Fig. 6), the flexible keel prostheses develop about the same propulsion force as the rigid keel; although the values are about 53% of the control limb. The sound limb push-off forces are essentially similar to those of the controls. The push-off impulses (Fig. 7) are significantly greater for the flexible keel foot prostheses (1.32 %BW· s) than for the SACH foot (0.86 %BW· s). The low impulse values for the flexible keel prostheses are attributed to the poor performance of the SAFE foot (0.90 %BW· s) which is comparable to that of the SACH foot. This would support Michael's

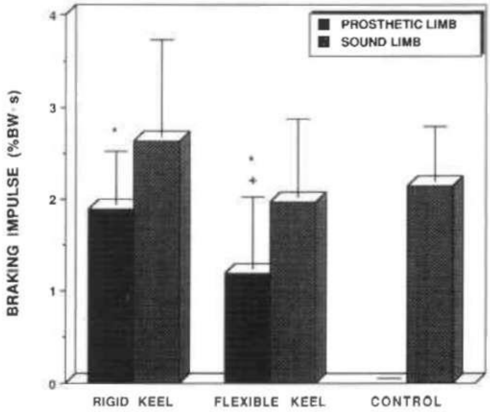

Fig. 5. Braking impulse for the rigid keel, flexible keel and control groups.

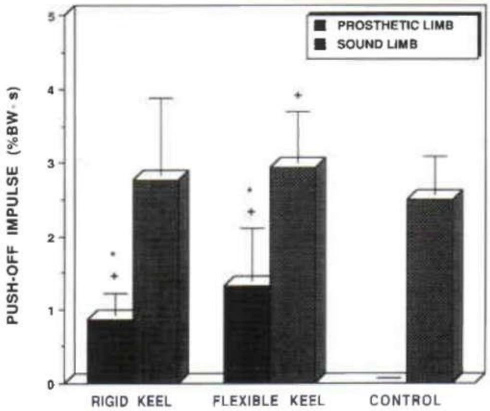

Fig. 7. Push-off impulse for the rigid keel, flexible keel and control groups.

(1987) rationale for not considering the SAFE prosthesis as a so-called energy storing foot. For both prosthetic types, average impulse values for the amputee's sound limb are higher than for the control group, reflecting a form of compensation mechanism for the inefficiency of the prosthetic device. For the rigid keel prosthesis group, this difference is not significant due to its large standard deviation. Results for the flexible keel group are different from the control group due to their lesser variability than that of the rigid keel group.

Different ratios were calculated using vertical, braking and push-off forces and impulses. The symmetry index defined by Robinson *et al.* (1987) was applied successfully by Herzog *et al.* (1989) in 34 ground reaction force variables to assess asymmetry in normal human gait. Using the same index, an abnormal characteristic trend associated with amputee running gait was observed but no significant differences were found between the two types of prosthetic feet. Only the ratio of the prosthetic forces and impulses over the corresponding sound limb values (Seliktar and Mizrahi, 1986) respectively yielded consistent results (Table 1).

With respect to the interlimb running gait asymmetry, all the impulse ratios were usually lower than the force ratios giving greater empahsis to asymmetry. The asymmetry in these feet may be explained in part by the time response characteristics of the keel, affecting both the force modulation as well as the force amplitude. This is mostly manifested during the critical push-off period where the amputee must assure his forward displacement and prepare himself for the following step while maintaining a steady state velocity. Difference between braking forces and impulses are less pronounced. This can be attributed to the relatively passive function of the braking phase when the prosthetic limb strikes the ground. The lack of muscle action and the use of cushion heel on both types of prostheses result in a similar force and impulse relationship pattern. The vertical force and impulse ratios show an opposite trend for the rigid keel prostheses. This difference can be attributed to the higher than normal values for the sound limb of amputees fitted with the SACH foot. Zahedi *et al.* (1987) reported that kinetic measurements are variable in assessing amputee locomotion and prosthetic alignment. The authors' results using ground reaction forces only, confirm their findings. However, impulse values which were not discussed by Zahedi *et al.* (1987) displayed a greater interlimb asymmetry than the forces.

Table. 1. Force and impulse ratios obtained from rigid keel (RK) and the flexible keel (FK) groups expressed in percentage.

	Vertical		Braking		Push-off	
	RK	FK	RK	FK	RK	FK
Forces (% BW)	75	91	81	62 (80)*	57	78
Impulses (% BW· s)	80	81	72	60 (80)*	42	45

(*) Values without the FSF prosthesis.

The effect of prosthetic type on running gait asymmetry is well discriminated by the force and impulse ratios. The flexible keel prostheses display less asymmetry than the rigid keel group relfecting their dynamic elastic characteristics. The vertical and push-off force ratios are closer to normal when the flexible keel prostheses are used. A similar trend is also noticed with the impulse ratios but, the differences are less apparent. It can still be assumed that the flexible keels are better than the rigid ones in respect of asymmetry, but further improvements are warranted to reduce the running gait asymmetry.

Conclusions

In this work interlimb asymmetry in BK amputee running gait was assessed for rigid and flexible keel foot prostheses using vertical and AP ground reaction forces and corresponding impulses. The impulse indicator showed greater asymmetry between the prosthetic side and the sound limb than the force parameters; whereas the impulse parameter was more consistent.

Interlimb asymmetry, evidenced by force and impulse ratios, is very much present in both types of prosthesis. The force ratios better differentiate between prosthetic foot types than the impulse ratios. The asymmetry in flexible keel prostheses may be more associated with the force profile modulation than its magnitude. Notwithstanding the present limitations of flexible keel prostheses, the resulting asymmetry is relatively lower than with the SACH foot. It appears that the elastic characteristics of the flexible keel prostheses are mainly responsible for the decreased asymmetry in running gait. In general, the impulses better describe interlimb asymmetry and the forces allow a greater discrimination between prosthetic type.

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