Prosthetics and Orthotics International, 1992, 16, 174–182

Functional evaluation by gait analysis of various ankle-foot assemblies used by below-knee amputees

N. MIZUNO[†], T. AOYAMA*, A. NAKAJIMA
T. KASAHARA* and K. TAKAMI*

**Rehabilitation Engineering Centre for Employment Injuries, Nagoya City, Japan.*
[†]Department of Orthopaedic Surgery, Chubu Rosai Hospital, Nagoya City, Japan

Abstract

Twelve different prosthetic feet were tested by 10 male subjects with right below-knee amputations. Level walking with each prosthetic foot was investigated using a pair of force plates.

Five parameters were selected to compare the functional characteristics of the feet: 1) step length, 2) walking velocity on the sound side in relation to the prosthetic side, 3) depth of valley in the pattern of the vertical component of the floor reaction force, 4) efficiency of the deceleration and acceleration by the prosthetic foot, and 5) irregular patterns in the wave form of the fore and aft components of the floor reaction force. Each of the above parameters was rated numerically. The total score of the objective evaluation attained by analysing the five parameters showed some coincidence to the results of subjective evaluation.

However, a good correlation existed between the objective negative score and the subjective negative rating ($p<0.05$). Non-axial feet developed recently, such as the SAFE II and Seattle Light feet achieved higher scores in the older age group, while single-axis feet, such as the LAPOC and Otto Bock feet achieved higher scores in the younger age group ($p<0.05$).

Introduction

Many ankle-foot assemblies have been developed recently and are now available. However, none of them is equipped with a mechanism that allows an in-use adjustment by the prosthetist or patient in order to respond to the individual needs of the amputee (Aoyama, 1987). Many physicians who prescribe prostheses are hampered by the lack of objective, functional data that would allow selection of the most suitable foot for a specific amputee. To facilitate the task of prescription the functional features of various prosthetic feet were investigated in this study.

All correspondence to be addressed to Mr. N. Mizuno, Department of Orthopaedic Surgery, Chubu Rosai Hospital, 1-10-6 Koumei, Minato-ku, Nagoya City, Japan.

Subjects and methods

Twelve different prosthetic feet were selected. There were three single-axis (domestic, Otto Bock, LAPOC), two multi-axes (Greissinger, Multiflex) and seven non-axial feet (Otto Bock Dynamic, domestic SACH, SAFE II, Carbon Copy II, Quantum, Seattle, Seattle Light). These were fitted on ten male subjects (mean age: 51.1 years) with right below-knee amputations. Five of the subjects were under the age of 50 (30 to 49 years; mean age: 39.4 years), while the rest were aged over 50 (53 to 71 years; mean age: 62.8 years) (Table 1). During level walking at the velocities at which the subjects could walk comfortably the ground to foot force components were measured for each prosthetic foot using a pair of force plates. The walking velocities were determined by dividing the stride length by the swing phase period. The walking velocities were distributed between 1.07 and 1.23 m/s. A force plate with a sampling rate of 50 Hz was used to measure the three components of the floor reaction force of the left and right foot

Table 1. Clinical profiles of the 10 male subjects with below-knee amputations.

	subject	age (yrs)	height (cm)	weight (kg)	stump length (cm)	stump length /height (%)	foot in normal use	socket	duration after amputation (yrs)	activity (score)
over 50 years	T.S.	71	180	47.6	27.0	15.0	LAPOC single-axis foot	PTB	48	31
	M.S.	66	161	54.9	13.5	8.4	LAPOC single-axis foot	KBM	21	20
	T.I.	53	165	58.0	14.0	8.5	DYNAMIC foot	PTB	2	33
	K.K.	61	157	55.0	26.0	16.6	LAPOC single-axis foot	PTB	4	30
	M.U.	63	160	56.0	13.0	8.1	LAPOC single-axis foot	PTB	7	23
under 50 years	T.H.	49	165	61.5	12.0	7.3	LAPOC single-axis foot	PTB	28	36
	S.H.	38	173	64.3	22.0	12.7	LAPOC single-axis foot	PTB	19	46
	H.H.	30	165	61.0	19.0	11.5	QUANTUM foot	PTB	10	37
	S.K.	40	165	65.0	11.5	7.0	OTTO BOCK single-axis foot	PTB	14	39
	K.Y.	40	168	45.8	13.5	7.7	LAPOC single-axis foot	PTB	30	26
mean values		51.1	165.9	56.9	17.2	10.3			18.3	32.1

during the support phase. The floor reaction force was normalised according to the weight and period of double support for each subject. In addition, level walking was analysed in five healthy males (control subjects) aged from 28 to 54 years (mean age: 40.8 years).

Five parameters and two types of evaluation were identified as effective in comparing the walking of normal subjects and amputees using prostheses. The parameters used to characterise the performance of the ankle-foot assemblies were as follows:

1. Step length ratio: The ratio of the step length of the left leg (sound side) to the step length of the right leg (prosthetic side).
2. Walking velocity ratio: The ratio of the walking velocity of the right lower leg (prosthetic side) to the walking velocity of the left lower leg (sound side). The walking velocities of both lower feet were measured separately and determined by dividing the stride length by the swing phase period.
3. Depth of the valley: The depth of the valley in the pattern of the vertical component of the floor reaction force (the level of minus velocity at mid-stance) was determined as an indicator of the smoothness of walking. The difference between the mean value of the first peak (P1) and second peak (P2) and the valley (V): (P1+P2)/2-V.
4. Efficiency of deceleration and acceleration: The efficiency of deceleration and acceleration was determined by adding the absolute values of the maximum deceleration force (Dmax) and the maximum acceleration force (Amax) according to the fore and aft component of the floor reaction force: Dmax+Amax.

The mean values and standard deviation (SD) of the above four parameters were

Table 2. Questionnaire for subjective evaluation.

1. Do you feel the hardness of the heel is appropriate or not?
too hard, appropriate, too soft.

2. Is it possible to roll-over on your prosthetic foot smoothly or not?
smooth, not smooth (feels like climbing over hill)

3. At push-off, is the knee of your amputated side stable enough or not?
stable enough, unstable (premature knee flexion)

4. Do you feel the weight of prosthetic foot is too heavy or not?
too heavy, reasonable, light enough

5. Does the prosthetic foot match to your walking style or not?
yes, no

Subjective evaluation of each prosthetic foot was classified into the following three groups according to the answers for above questionnaire as;
A: good, B: acceptable, C: unacceptable

determined for each individual subject. A score of +10 points was assigned when a value of an ankle-foot assembly was equal to or greater than +SD, a score of 0 points was assigned when the value was within ± SD, and a score of −10 points was assigned when the value was equal to or less than − SD.

5. An irregular pattern in the wave of the fore and aft component of the floor reaction force on the prosthetic side: There are cases in which at the beginning of the heel contact or push-off stage an irregular wave pattern occurs in the fore and aft component of the floor reaction force on the prosthetic side. As this is evidence that

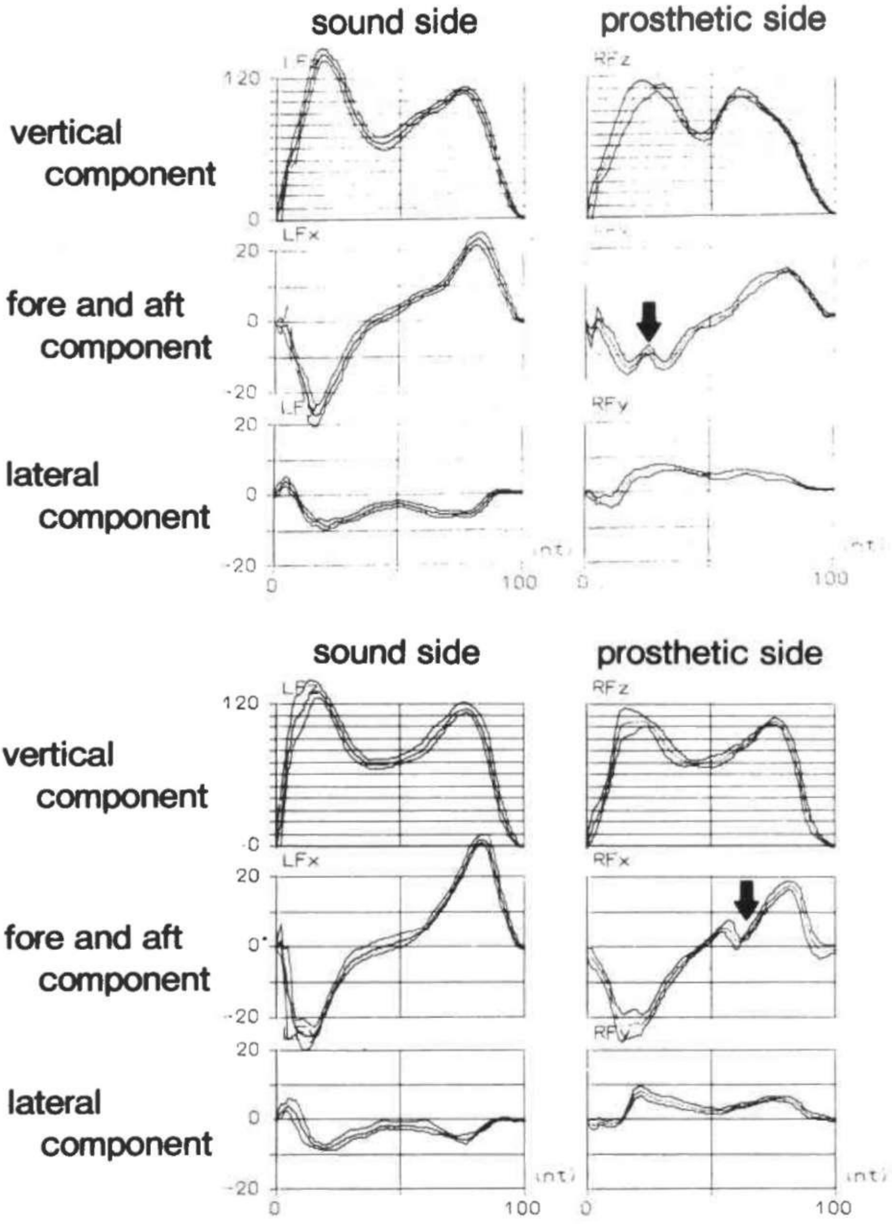

Fig. 1. Irregular wave patterns of the fore and aft component of the floor reaction force. Arrows indicate the irregular wave patterns at the beginning of the heel contact or push-off stage.

roll-over of the lower foot was not occurring smoothly, 10 points were subtracted when such a pattern was observed (Fig. 1).

6. Subjective Evaluation: In order to provide a comparison with the objective evaluation, a subjective evaluation of the ankle-foot assemblies was obtained from the subjects using a simple questionnaire. Subjective evaluation of each prosthetic foot was classified into the following three groups according to the answer to the above questionnaire as; A: good, B: acceptable, and C: unacceptable (Table 2).
7. Activity Evaluation: The activity level of each amputee was scored using the activity evaluation chart prepared by Day (1981).

The t-test, chi-squared test, correlation coefficients, and linear regression were used for statistical analysis. The level of significance was set at $p<0.05$.

Results

Measured parameters

Some ankle-foot assemblies could not be evaluated on some amputees because the stump was too long to allow attachment.

1. Step length ratio: The ratio of the left step length to the right step length was 96.1 ± 1.36(%) in the control group and 85.9 ± 6.29(%) in the amputee group (Table 3). The step length on the prosthetic side was significantly longer than the sound side ($p<0.01$). In addition, this ratio was observed to vary for different ankle-foot assemblies. For example, the ratio values of the domestic single-axis foot and foot normally used were large, while those of the Carbon Copy II and Greissinger feet were small.

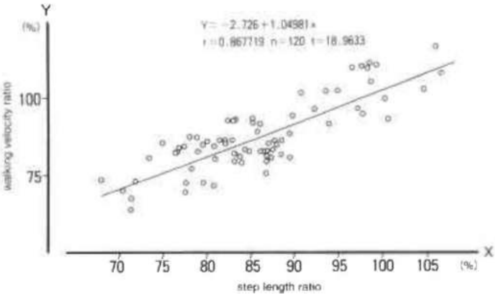

Fig. 2. The relationship between the two variables satisfies a linear regression of $Y=-2.726+1.04981\,X$, ($n=120$).

2. Walking velocity ratio: The ratio of the walking velocity of the right lower leg to the walking velocity of the left lower leg was 94.3 ± 2.70(%) in the control group and 87.3 ± 8.12(%) in the amputee group (Table 3). Although no significant difference was observed between the two groups of subjects, the walking velocity ratios differed among the various ankle-foot assemblies. For example, the ratio values of the SAFE II and domestic single-axis feet were large, while those of the Greissinger and Quantum feet were small (Table 4).

The correlation between the step length ratio and the walking velocity ratio was quite strong ($r=0.867719$) (Fig. 2).

3. Depth of the valley: A value of 28.87 ± 12.398 (BW%) was determined for the prosthetic side of the amputee group in contrast to a value of 46.23 ± 4.60

Table 3. Comparison of normal limbs and prostheses during walking in 10 men with below-knee amputations.

group classification \ parameter		step length ratio (%)	walking velocity ratio (%)	depth of valley (BW%)	efficiency of deceleration and acceleration (BW%)	frequency of irregular wave patterns (%)
control group		96.1±1.36 ⎤ *	94.3±2.70	46.23±4.60 ⎤ *	45.85±3.93 ⎤ *	0.0
prosthetic side		85.9±6.29 ⎦	87.3±8.12	28.87±12.39 ⎦	29.31±5.56 ⎦	21.7
Age	over 50 yrs	87.8±2.94	88.5±2.79	29.25±8.96	26.99±3.35	23.7
	under 50 yrs	84.0±7.95	86.1±11.00	28.48±15.05	31.62±6.62	19.7
Stump length /height	large	84.2±5.13	86.4±4.16	38.17±8.86 ⎤ **	31.74±6.26	12.3 ⎤ **
	small	87.7±6.83	88.2±10.63	19.56±7.46 ⎦	26.87±3.31	30.2 ⎦
Time since amputation	long	87.9±7.66	90.4±9.73	25.11±9.21	30.70±6.53	12.3 ⎤ **
	short	84.0±3.57	84.2±4.20	32.62±13.93	27.91±3.92	30.2 ⎦

$^{*}P<0.01$ $^{**}P<0.05$

Table 4. Comparison of the 12 ankle-foot assemblies.

prosthetic foot \ parameter	step length ratio	walking velocity ratio	depth of valley	efficiency of dec. and acc.
foot normally used	88.4	89.1	28.76	28.75
DYNAMIC foot	86.3	87.2	28.45	29.23
domestic SACH foot	88.0	88.6	33.36	27.44
SAFE II foot	87.7	91.0	25.51	26.36
CARBON COPY II foot	83.9	86.8	24.14	25.91
QUANTUM foot	84.2	85.8	28.97	30.98
SEATTLE foot	85.4	86.5	27.71	29.32
SEATTLE LIGHT foot	85.5	86.4	28.80	27.38
domestic single-axis foot	90.2	90.0	24.98	28.76
OTTO BOCK single-axis foot	86.3	86.6	30.80	32.81
LAPOC single-axis foot	86.1	86.4	30.90	31.12
GREISSINGER foot	82.3	85.9	26.40	29.27
MULTIFLEX foot	85.3	88.7	27.65	31.55
mean values	85.9	87.3	28.87	29.31

dec.: deceleration, acc.: acceleration

(BW%) for the control group (Table 3). The depth of the valley was significantly reduced on the prosthetic side ($p<0.01$). A value of 46.45 ± 10.40 (BW%) for the sound side of the amputee group was almost equal to the value of the control group. Values for the individual types of ankle-foot assembly varied; the values of the domestic SACH and LAPOC single-axis feet were large, but those of the domestic single-axis and Carbon Copy II feet were small (Table 4).

4. **Efficiency of deceleration and acceleration:** A value of 29.31 ± 5.56 (BW%) was determined for the prosthetic side of the amputee group in contrast to a value of 45.85 ± 3.93 (BW%) for the control group (Table 3). The efficiency of deceleration and acceleration was significantly inferior on the prosthetic side ($p<0.01$). A value of 46.29 ± 6.66 (BW%) for the sound side of the amputee group was almost equal to the value of the control group. Values for individual types of ankle-foot assembly varied; the values of the Otto Bock single-axis and Multiflex feet were large, but those of the SAFE II and Carbon Copy II feet were small (Table 4).

The correlation between the depth of the valley and the efficiency of deceleration and acceleration was moderate ($r=0.53486$) (Fig. 3).

The subjects were divided into three classes each containing two groups of five subjects each according to: 1) those over 50 years old (53 to 71 years; mean age: 62.8 years) those under 50 years old (30 to 49 years; mean age: 39.4 years); and 2) those whose ratio of residual limb length to

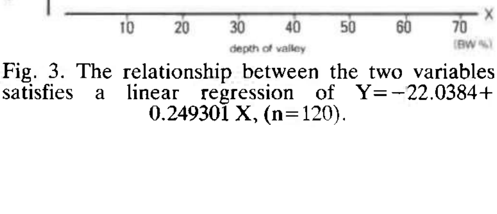

Fig. 3. The relationship between the two variables satisfies a linear regression of $Y=-22.0384+0.249301X$, ($n=120$).

height (abbreviated as stump length/height) was large (8.5 to 16.6%; mean: 12.9%) versus those whose stump length/height ratio was small (7.0 to 8.4%; mean: 7.7%), and 3) those whose time since amputation was long (19 to 48 years; mean: 29.2 years) versus those whose time since amputation was short (2 to 14 years; mean: 7.4 years). When examined in this manner, although the values for the depth of the valley were larger in the group with the larger stump length/height ratio ($p<0.05$), no differences were observed with respect to the other parameters (Table 3).

5. An irregular pattern in the wave of the fore and aft component of the floor reaction force on the prosthetic side.

No cases had irregular wave patterns on the sound side. But the frequency of irregular wave pattern on the prosthetic side was highest in the domestic SACH foot and the Seattle foot. There were no irregular wave patterns in the Otto Bock single-axis foot (Table 5). In addition, when the frequency of irregular wave pattern was examined by dividing the subjects into the three sub-groups described above, although no difference was observed between the group over 50 years old and the group under 50 years old, the irregularity was decreased in proportion to stump length or time since amputation. Those with longer stump or greater time since amputation demonstrated smaller wave disturbances ($p<0.05$) (Table 3).

6. Subjective evaluation: The distinction between "good" and "acceptable" was not always clear and appeared to be influenced by the intelligence, comprehension, and level of interest of the subjects. Some replies were vague, for example, "not bad" and "fairly good". With respect to "unacceptable" ratings, however, those ankle-foot assemblies that did not function well were identified with relative ease, and were described in such terms as "difficult to walk with".

7. Activity evaluation: The activity score rating of the subjects varied between +46 to +20 (mean: +32.1). Their activities were all classified as "very high" or "high" according to the rating of Day (1981). No significant correlation was observed

Table 5. Irregular wave patterns of the fore and aft component of the floor reaction force on the prosthetic side.

prosthetic foot \ subject	T.S.	M.S.	T.I.	K.K.	M.U.	T.H.	S.H.	H.H.	S.K.	K.Y.
foot normally used	○	○	○	○	○	○	○	○	○	×
DYNAMIC foot	○	○	○	○	×	○	×	×	○	○
domestic SACH foot	×	×	×	○	×	○	○	○	○	○
SAFE II foot	○	○	○	○	○	○	○	○	○	×
CARBON COPY II foot	○	×	×	○	×	○	○	○	○	○
QUANTUM foot	○	○	○	/	×	○	○	○	○	○
SEATTLE foot	○	○	○	/	×	×	○	○	×	×
SEATTLE LIGHT foot	○	○	○	○	×	○	/	○	○	×
domestic single-axis foot	○	○	○	/	×	○	×	/	/	×
OTTO BOCK single-axis foot	○	○	○	○	○	○	○	○	○	○
LAPOC single-axis foot	○	○	×	○	○	×	○	○	○	○
GREISSINGER foot	○	○	○	/	×	○	○	○	○	○
MULTIFLEX foot	○	○	○	/	/	○	/	○	×	○

×: irregular wave patterns were observed. ○: irregular wave patterns were not observed.

between the stump length/height and activity level ($p<0.05$). In addition, because the elderly subjects also demonstrated high levels of activity, no significant correlation was observed between age and activity level (Table 1).

Scoring of the objective evaluation

1. Comparison of the objective and subjective evaluations: The objective and subjective evaluations were not always in agreement. However, in the 13 cases where the subjective evaluation was "unacceptable", 6 also yielded negative scores in the objective evaluation, and only 2 had positive scores. In contrast, among 66 cases where the subjective evaluation was "good", only 11 had a negative score in the objective evaluation. Thus, a subjective evaluation of "unacceptable" was associated more often with a negative score in the objective evaluation than an evaluation of "good" ($p<0.05$). These findings suggest that the objective evaluation standards that were selected identify a negative score with ankle-foot assemblies that do not function properly (Table 6).
2. Suitability of the prosthetic feet: The total scores of the objective evaluations showed that non-axial feet developed recently, such as the SAFE II and Seattle Light feet, received a higher score in the older age group (over 50). Single-axis feet such as the LAPOC and Otto Bock feet, received a higher score in the younger age group (under 50) ($p<0.05$) (Table 7).

Discussion

Many researchers have investigated the temporal and spatial parameters of prosthetic gait with below-knee amputees. Breakey (1976) has reported that the stance phase of the amputated limb occupied 37% of one gait cycle, while the sound side occupied 43%. Robinson *et al.* (1977) have investigated the walking of below-knee amputees using a SACH foot and stated that the step length on the prosthetic side was somewhat longer than that on the sound side. The difference in the mean length was 5 cm at a walking speed of 1.07 m/s. Doane and Holt (1983) have compared the SACH foot to the single-axis foot, and found no difference in walking velocity between the two (both 1.22 m/s).

The results of this study suggest that time-

Table 6. Comparison of objective evaluations and subjective rating.

prosthetic foot \ subject	T.S.	M.S.	T.I.	K.K.	M.U.	T.H.	S.H.	H.H.	S.K.	K.Y.
foot normally used	0A	0A	10A	0A	10A	10A	0A	−10A	0A	−10A
DYNAMIC foot	30A	0A	0A	−10B	−20B	20A	0B	0A	10A	0A
domestic SACH foot	0C	10B	−10B	10A	0A	−10B	−10B	0B	10A	20B
SAFE II foot	0B	0A	20B	20B	0A	−20C	0B	−10C	−10C	0B
CARBON COPY II foot	−20A	−40C	−20A	10A	−40A	−20B	10B	−10B	−20B	−10A
QUANTUM foot	30B	0A	0A	/	−10B	0A	−20B	10A	20A	−10B
SEATTLE foot	0A	0A	0A	/	10A	0C	−20A	0B	−30B	−10B
SEATTLE LIGHT foot	0B	0A	10A	10A	10B	0A	/	0A	−10B	0A
domestic single-axis foot	−30C	20B	−10B	/	0C	0A	10A	/	/	0C
OTTO BOCK single-axis foot	0B	0A	0B	−10A	0A	0A	20A	10B	20B	0A
LAPOC single-axis foot	−30A	0B	−10A	0A	10A	0B	20A	10C	20A	10A
GREISSINGER foot	0B	10A	−10A	/	−30A	0A	0A	−20B	10C	0C
MULTIFLEX foot	20B	20A	0A	/	/	10A	/	30B	−20B	−20C

Table 7. Suitability of the prosthetic feet.

prosthetic foot \ group classification	Age		Stump length/height		Time since amputation	
	over 50 yrs. (av. 62.8 yrs.)	under 50 yrs. (av. 39.4 yrs.)	large (av. 12.9%)	small (av. 7.7%)	long (av. 29.2 yrs.)	short (av. 7.4 yrs.)
foot normally used	4±4.9	−2±7.5	0±6.3	2±7.5	0±6.3	2±7.5
DYNAMIC foot	0±16.7	6±8.0	0±13.6	2±13.3	4±13.6	−4±10.2
domestic SACH foot	2±7.5	2±11.7	−2±7.5	6±10.2	−2±7.5	2±7.5
SAFE II foot	8±9.8	−8±7.5	6±12.0	−6±8.0	6±12.0	4±13.6
CARBON COPY II foot	−22±18.0	−10±11.0	−6±13.6	−26±12.0	−6±13.6	−16±16.2
QUANTUM foot	5±15.0	0±14.1	5±18.0	0±11.0	5±18.0	5±11.2
SEATTLE foot	2.5±4.3	−12±11.7	−5±8.7	−6±13.6	−5±8.7	−5±15.0
SEATTLE LIGHT foot	6±4.9	−2.5±4.3	−10±16.3	0±6.3	5±5.0	4±8.0
domestic single-axis foot	−5±18.0	3.3±4.7	4±10.2	5±8.7	−10±16.3	−5±5.0
OTTO BOCK single-axis foot	−2±4.0	10±8.9	−2±17.2	4±8.0	4±10.2	4±10.2
LAPOC single-axis foot	−6±13.6	12±7.5	−2±17.2	8±7.5	−2±17.2	6±10.2
GREISSINGER foot	−7.5±14.8	−2±9.8	−7.5±8.3	−2±14.7	−7.5±8.3	−12.5±14.8
MULTIFLEX foot	13.3±9.4	0±21.2	16.7±12.5	−2.5±17.9	16.7±12.5	3.3±20.5

** $p < 0.05$

distance parameters are important for evaluating prosthetic walking. The step length and walking velocity varied with the type of ankle-foot assembly tested as well as the site of amputation. The strong positive correlation between the step length and the walking velocity emphasized the fact that an amputee wearing a prosthetic foot suitable for his activity level can walk faster with longer steps on the sound side, while the opposite also holds true. Thus the speed and step length of the sound limb provide useful guidelines for the selection of an appropriate prosthetic foot.

Assessment of prosthetic feet by the analysis of floor reaction force has also been reported by various researchers. Ehara *et al.* (1985) have compared the degree of irregularity in traces of the fore and aft component of the floor reaction force, and concluded that the main cause of such irregularities was the mechanism of the instep bumper. When dorsiflexion of the prosthetic foot is controlled by smoothly increasing resistance, a smooth transition between the fore and aft shearing forces is also attained.

In this study, the irregular wave pattern was found for the domestic SACH foot in the older age group. In contrast, multi-axes feet such as the Greissinger or Multiflex showed little disturbance of the wave pattern. The irregularity was also rarely seen in the subjects with longer stumps. In this group, the valley in the vertical component force curve was also deeper than in the patients with short stumps. The floor reaction forces are influenced not only by the physical characteristics of the prosthetic foot, but also by the length of the stump, the muscle strength of the lower limb and the duration since amputation. These physiological factors are the most important ones to consider when determining which prosthetic foot is the best choice for a particular patient.

It is well known that as a patient becomes weaker, a softer heel bumper should be chosen. Hardness of the heel bumper can also affect prosthetic walking. This was demonstrated by the gait analysis of an amputee wearing a single-axis foot when heel bumpers of different hardnesses were tested (Kasahara, 1983).

Several sets of clinical guidelines for the selection of prosthetic feet have been reported. Wing and Hittenberger (1989) have suggested that the Flex foot followed by the Carbon Copy II and Seattle feet are suitable for active patients due to their good propelling features. In contrast, those feet such as the SAFE or STEN feet are the choice for less active amputees. Wirta *et al.* (1991) have identified four variables to use in determining the optimal prosthetic foot (age, actual/ideal body weight ratio, residual limb length/height ratio, and frequency/length of stride ratio).

However, neither of the above mentioned reports has included an objective evaluation of amputee performance with the different prosthetic feet.

In this study, five parameters were selected to use in gait analysis and compared with the objective evaluations to subjective impressions of the amputees. With an optimal prosthetic foot, the amputee can walk faster and achieve an equal step length on both the prosthetic and sound sides. The floor reaction force on the prosthetic side, especially during deceleration and acceleration, will show a regular curve which indicates smooth transition of the centre of gravity.

The assessment of the various prosthetic feet in accordance with the objective evaluation clarified the factors for matching prosthetic feet with the activity level or physical condition of the amputees. It was found that clinical standards used for the selection of a prosthetic foot are fairly compatible with the objective evaluation of amputee performance. Consequently, the older age group (over 50) in the study showed a better performance using the non-axial feet equipped with elastic keel such as SAFE II and Seattle Light feet. On the other hand, the patients age under 50 years performed better with the single-axis feet such as LAPOC or Otto Bock. The results generally coincide with the mechanical features of the prosthetic feet such as weight, hardness of bumpers and toe-break. Both the SAFE II and Seattle Light feet are relatively light and are equipped with an elastic keel which provides firm support and smooth push-off for the older amputees.

Conclusion

1. A significant correlation was confirmed between the step length and velocity of the sound limb ($p<0.05$).
2. Irregularity of the curve describing the fore and aft component of the floor reaction force varied in proportion to the stump length and the duration since amputation. The longer the stump and the duration, the smaller the irregularity of the curve ($p<0.05$).
3. Objective evaluation of five parameters was compared to the subjective evaluation of the amputees. A good correlation existed between the objective score and negative preference by the patients ($p<0.05$).
4. The newly developed non-axial feet (SAFE II and Seattle Light) achieved high objective scores in the patients aged over 50. Single-axis feet of modular systems (LAPOC and Otto Bock) achieved high scores in the subjects under 50 years of age ($p<0.05$).
5. The propelling force at push-off stage and the walking speed increased in proportion to the length of the stump.

Acknowledgement

The authors would like to thank Professor Takayuki Miura of the Department of Orthopaedic Surgery, College of Medicine, Nagoya University, for his assistance in making revisions on this paper.

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