

Effect on gait using various prosthetic ankle-foot devices

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Abstract—Five different commonly prescribed ankle-foot devices for below-knee prostheses were tested for effects on gait: SACH, SAFE, SEATTLE, SINGLE AXIS, and MULTIPLE AXIS. Subjective ratings by the amputees served to resolve which physical variables determined the preferred ankle-foot device. Ratings were related to age, body weight, length of residual limb, and ratio of stride frequency to stride length. Distinctions in performances were derived from analyses of anterior-posterior angular accelerations occurring in the prosthesis immediately following heel strike. The accelerations were characterized as a damped oscillatory waveform. These objective findings, when related to the subjective ratings, showed that the amputees preferred devices which developed the lesser shock and greater damping.

Key words: *ankle-foot device, below-knee prostheses, gait analysis, stride frequency and length, unilateral amputees.*

INTRODUCTION

Early development efforts in lower limb prostheses placed major emphasis in the area of socket design and limb-socket relations and only a minor emphasis on distal components. Subsequent to progress in the socket design, the focus changed biomechanical interest to the distal portions of the prosthesis and to ambulatory perfor-

mance with existing ankle-foot devices. As a result, there has been a proliferation of designs attempting to meet various requirements. Requirements vary because of differing physical characteristics and activity objectives of patients.

Ground reaction forces are transmitted through the ankle-foot assembly to the prosthesis, the residual limb, and to the rest of the body. How and where these forces act are often conditioned by the characteristics of the ankle-foot assembly. The issue is compounded by the varying nature of the substratum which in turn affects the ambulatory function and comfort of the patient.

While substantial progress has been made in the design of ankle-foot devices, sometimes indications and contra-indications for their use have not been clear. This has left clinicians without a sound base or reason for a choice. The purpose of this study was to analyze the effect on gait of five commonly prescribed devices and to suggest additional guidelines for their selection and prescription.

METHOD

Test subjects

The test sample included 19 unilateral amputees who were active community ambulators, had no balance problems, and were compliant with test procedures. The 15 males and 4 female below-knee amputees averaged 46.3 years of age ranging from 24 to 72. Average height was 177.7 cm ranging from 160 to 191 cm. The average weight was 86.8 Kg ranging from 57 to 116. Residual limb lengths averaged 14.6 cm ranging from 8 to 23 cm; in percent of height, these lengths averaged 8.2 and ranged from

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4.5 to 12.8 percent (see **Table 1**). Eight subjects were left amputees and 11 were right. One subject's test data were not included in the sample. This subject was a diminutive female, 166 cm tall, 60 Kg in weight, and 52 years of age. She was unable to perform tests with the multiple axis device because she said "it was too heavy and cumbersome."

Ankle-foot devices

The five ankle-foot devices used in this study were: SACH, SAFE, SEATTLE, SINGLE AXIS (Otto Bock IH31), and MULTIPLE AXIS (Greissinger), and were presented in the order listed. The order had to do with the length of pylon, with the SACH requiring the longest and the MULTIPLE AXIS requiring the shortest. The devices were selected, adjusted, and aligned in accordance with the manufacturers' specifications. Taken into consideration were the subjects' weights, ages, and nominal activity levels.

Each subject was fitted with a patellar-tendon bearing (PTB) socket constructed according to standard procedures. Construction was of a plastic laminate with a Pelite insert and suprapatellar cuff. The Otto Bock or United States Manufacturing Company adjustable pylon was used to

allow easy exchange of ankle-foot devices. Each prosthesis was dynamically aligned with each of five different ankle-foot devices prior to testing. Lightweight, three-quarter inch heel, crepe sole (Hush Puppy) footwear were applied.

Procedure

The subjects were attired in comfortable foot wear, shorts, and shirt. Body-mounted instrumentation included bilateral knee electrogoniometers, bilateral foot switches which covered the heel and sole areas, a triaxial accelerometer mounted on a snug-fitting hip-waist band, and a lightweight backpack containing an electrical junction box.

Wires from the body-mounted instrumentation were plugged into the back pack. Signals were conducted to the signal conditioner through a festooned flat multiconductor cable supported by an overhead carrier. The force needed to pull the cable was about one newton. Signals were conditioned by amplification, filtering with a 33 Hz roll off, and conversion from analog-to-digital. Sixteen channels of data were sample at 60 times per second and stored in the microcomputer and transferred to diskettes for storage and processing.

A lightweight accelerometer pack was secured firmly

Table 1.

Physical characteristics of test subjects.

Subj	Ht cm	Wt Kg	Age yrs	Sex	LRL cm	Pers A-F D
1	191	88	30	M	17	SAFE
2	185	91	72	M	10	SACH
3	160	57	64	F	13	SAFE
4	178	116	52	M	19	SAFE
5	187	107	24	M	17	SAFE
6	178	80	40	M	8	SEATTLE
7	183	111	59	M	19	SACH
8	165	74	70	M	12	M.AXIS
9	180	77	33	M	23	SAFE
10	183	83	53	M	13	SACH
11	188	102	37	M	15	SEATTLE
12	180	102	43	M	17	M.AXIS
13	173	87	39	M	11	SEATTLE
14	160	84	60	F	14	SACH
15	165	66	51	F	11	SACH
16	188	93	33	M	19	SACH
17	180	85	38	M	16	SEATTLE
18	165	68	42	F	14	SAFE
19	188	79	39	M	9	SACH

LRL = Length, residual limb

Pers A-F D = type of personal ankle-foot device

to the lateral side of the socket. This assembly contained five miniature accelerometers (Entran EGAXT): one pair sensed anterior-posterior acceleration, another pair sensed medial-lateral acceleration, and the fifth sensed acceleration parallel to the longitudinal axis of the prosthesis. The paired accelerometers, spaced 10 cm apart, provided differential signals to register angular accelerations calibrated in radians per second squared.

Forward velocity of the body was measured with a tachometer consisting of a low inertia DC generator mounted on a stationary base at one end of the walkway. A braided steel cable 0.014 inch in diameter connected the tachometer to the waist band on the subject. A weight and pulley arrangement maintained constant tension of about one newton on the cable.

Whole body accelerations were monitored with a miniature triaxial device used in a biaxial mode to register longitudinal (forward) and vertical axes of motion. The device was mounted in a two-axis gimbal arrangement secured to the sacro-lumbar area on the hip-waist band. The gimbal was stabilized to the direction of forward progression by the tachometer cable.

The walkway was a level, vinyl tiled floor 7.5 m long and 2 m wide. In addition, two specially constructed, moveable sections, 3 m long and 75 cm wide, were used to provide nonlevel walking surfaces. Laid on the walkway, they provided a surface tilted 7 degrees from horizontal laterally. In one mode, the subjects walked with the prosthesis on the "uphill" side (inclined) and in the other mode they walked with the prosthesis on the "downhill" side (declined). When the same sections were placed on supports, the assembly provided an up ramp and down ramp surface tilted 7 degrees from horizontal.

Test protocol

Each subject was asked to wear the test prosthesis at least 2 hours per day during the week prior to test appointments to become accustomed to the assembly.

Seven test walks were recorded with each of the five ankle-foot devices: 1) three tests on the level surface consisted of "usual," "fast," and "slow" speeds. These speeds were arbitrary and subjectively chosen by each subject; 2) one test each at "usual" speed with the surface inclined laterally and declined laterally; and, 3) two tests at "usual" speed on the ramp assembly to yield two ascents and two descents. In subsequent data processing the two ascending and two descending test data were averaged to yield one representative up ramp and one down ramp performance.

Subjects completed a one page questionnaire: 1) rate the ankle-foot devices according to poor, fair, good, excellent, and superior; and, 2) write a brief comment about each device.

Data treatment

Data collected from each test condition were analyzed by gait cycles. The beginning of the prosthetic limb support period was defined as the beginning of the cycle. Primary indication of this event was the signal from the accelerometer mounted on the prosthesis which sensed acceleration parallel to the longitudinal axis of the prosthesis. Confirmation of this event was closure of the heel switch.

Depending on the speed of walking, three to five gait cycles were obtained for analysis for each test condition. Gait cycles not included were those clearly accelerative at initiation of gait and decelerative at cessation of gait.

Two of the gait variables measured were the forward velocity, V , and the duration of the gait cycle, t . Stride frequency, F , was calculated from the reciprocal of the cycle time: $F = 1/t$. Stride length, L , was calculated as the product of the average velocity, V_a , and cycle time, T : $L = V_a \times t$. The ratio of stride frequency to stride length was calculated by dividing stride frequency, F , by stride length, L .

Body movement waveforms were quantitated using a Fourier series technique. Fourier coefficients for 18 harmonics were calculated for the anterior-posterior (AP) and medial-lateral (ML) angular accelerations of the prosthesis, and coefficients for 12 harmonics were calculated for the fore-aft and vertical accelerations of the body and for the tachometer. Coefficients for each waveform were averaged from the selected gait cycles to represent a given test condition. Waveforms for the AP and ML angular accelerations of the prosthesis were subsequently synthesized from the Fourier coefficients.

The angular acceleration of the prosthesis at the beginning of the support phase was characterized mathematically as a damped oscillatory wave. Regression analysis was used to determine the best estimate of initial acceleration and the damping factor.

To minimize variance due to differences in height, weight, and length of residual limb, certain normalizing procedures were introduced:

a. To compare results among subjects of differing weight, relative weights of subjects were defined as the actual weight divided by ideal weight, W_a/W_i . The commonly accepted formulas (metricated) for ideal weight

are the following:

$$\text{Males: } W_i = 51 + (H - 152)$$

$$\text{Females: } W_i = 48 + 0.83(H - 152)$$

where:

W_i = ideal weight in Kg

H = height in cm

b. Normalized residual limb length was determined as a percentage of body height and termed RL.

c. To normalize leg-to-substrate angulations as they relate to stride length for subjects of differing stature, stride length, L , was divided by body height, H , to yield the L/H ratio.

Harmonic ratios were calculated in the manner described by Robinson (5) using the Fourier coefficients for whole body movements, namely, the longitudinal and vertical accelerations and forward velocity. In addition, the external work and efficiency of locomotion was calculated in the manner described by Cavagna (3) using the body accelerations and forward velocity, for the three speeds of level walking and for the lateral incline and decline test conditions. Work and efficiency were not calculated for the ramp tests because existing programming was designed for level walking. To modify programming to accommodate reliably the ascent and descent of ramps was deemed not warranted.

RESULTS

Subjective rating

The subjects rated each ankle-foot device in terms of excellent, superior, good, fair, and poor. The results were as follows: 1) SACH: 18 of 19 good to poor equally divided, none superior; 2) SAFE: 14 of 19 good to excellent, two superior, and two poor; 3) SEATTLE: 9 of 19 excellent, three superior, six good and fair, and one poor; 4) SINGLE AXIS: 14 of 19 good and fair, four poor, and one superior; and, 5) MULTIPLE AXIS: 16 of 19 excellent to fair, one superior and one poor. See **Table 2** for tabulated results.

Table 2.

Summary of subjective ratings of ankle-foot devices.

	SACH	SAFE	SEATTLE	S.AXIS	M.AXIS
Superior	0	2	3	1	1
Excellent	1	6	9	0	5
Good	6	8	4	7	7
Fair	6	1	2	7	4
Poor	6	2	1	4	1

Written comments provided reasons why individuals like or disliked given devices. From the varied responses, the following generalities were drawn:

a. SAFE and SEATTLE: These drew most of the favorable comments such as flexible, springy, comfortable, energy-saving, good on slopes and inclines. Older subjects, however, complained of balance and control problems and stated that they were being thrust forward.

b. SACH: The common complaint with this device was that it was too stiff. Heavier subjects objected less.

c. SINGLE AXIS and MULTIPLE AXIS: These devices drew varied reactions. Many opined that the devices were good for multi-terrain applications, with the MULTIPLE AXIS being favored over the SINGLE AXIS. The SINGLE AXIS device was said to lack "side to side" action, and some complained of not feeling secure. Shorter, slimmer individuals complained that the MULTIPLE AXIS was cumbersome. Many objected to the abrupt stop in movement during single support. This was expressed variously as two-point roll over, a clopping sensation, a sudden stop, or a knee-jerking effect. Many who liked these devices reported difficulty in getting accustomed to walking with them. Reactions regarding the resistance varied from too soft to too stiff.

Subjective rankings

Trends noted suggested that the subjective ranking order of the ankle-foot devices was influenced by four independent variables: age, relative weight, length of residual limb, and ratio of stride frequency to stride length. By applying discriminating thresholds to ankle-foot devices, a good match with subjective rankings was achieved:

1. Age, in years: if less than 39, then SEATTLE; if between 39.5 and 52, the SAFE; if over 52.5, the SACH.

2. W_a/W_i , actual weight divided by ideal weight: if less than 1.11, then SEATTLE; if between 1.12 and 1.21, the SAFE; if more than 1.22, then SACH.

3. RL/HT , residual limb length as percent height: if less than 7.2, then MULTIPLE AXIS; if between 7.3 and 9.5, the SEATTLE; if over 9.6, the SAFE.

4. F/L , stride frequency divided by stride length: if less than 0.6, then SAFE; if between 0.61 and 0.75, the SEATTLE; if more than 0.76, then SACH.

From these, the following may be inferred: 1) SEATTLE, if young, lightweight, medium length residual limb, and average step length; 2) SAFE, if middle-aged, slightly overweight, long residual limb, and tendency to long step length; and, 3) SACH, if old, overweight, medium to long residual limb, and tendency to short step length.

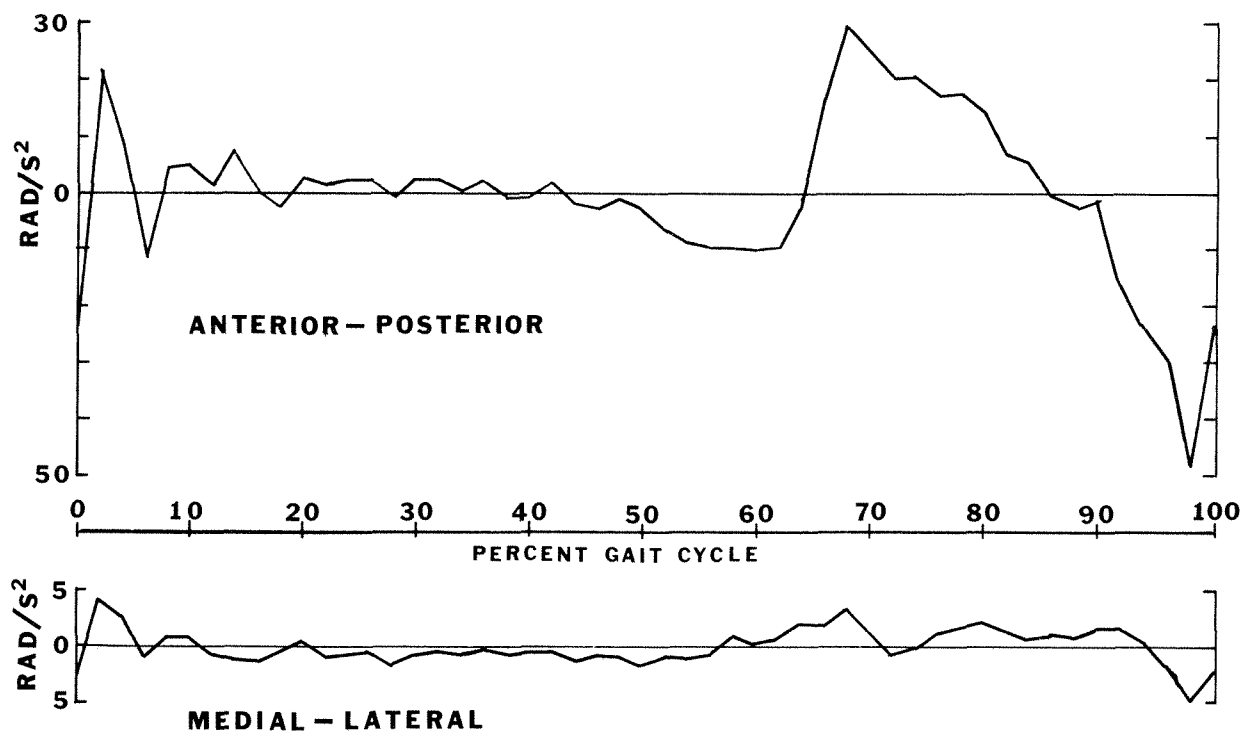


Figure 1.
Angular acceleration of prosthesis as a function of gait cycle.

Prosthesis angular acceleration

Angular acceleration curves were synthesized at two percent gait cycle intervals. Representative waveforms for the anterior-posterior and medial-lateral directions may be seen in **Figure 1**.

a. For all feet at initial stance, the curves typically showed an oscillatory waveform which subsided within two to three cycles (within 20 percent of the gait cycle). During this period, the magnitude of the ML acceleration ranged from about one-tenth to about one-fifth the magnitude of the AP acceleration.

b. At mid-stance (from 20 to about 40 percent gait cycle), the waveforms wavered a small amount.

c. At terminal stance (about 40 to 70 percent gait cycle), the waveforms departed in direction and between 60 and 70 percent gait cycle quickly reversed direction.

d. Between 70 and 100 percent gait cycle, the curves included a substantial acceleration and deceleration to characterize the swing phase.

The amount of "roughness" in the waveforms, from 20 to 40 percent gait cycle, did not relate to quality of performance. The area under the curve from 40 to about 65 percent gait cycle related to velocity of walking but did

not discriminate among ankle-foot devices. The curves during swing phase were not studied intensely because deviations in this segment of the waveforms were attributed to characteristics of the suspension system.

AP angular acceleration

The initial stance portion of the AP waveform was used to discriminate performances among the ankle-foot devices. The waveform damped logarithmically:

$$A = Be^{-dp}$$

where

A = Angular acceleration in r/s^2

B = acceleration at zero percent gait cycle

d = damping factor

p = percent gait cycle

This relation was used to define "shock." By assuming a point 8 percent into the gait cycle and applying the initial acceleration and rate damping, values were calculated to represent shock for each performance.

Shock was related to F/L (stride frequency to stride length ratio) and L/H (stride length divided by height). The relation is demonstrated as a nomograph in **Figure 2** to offer a comparison of the five ankle-foot devices. The

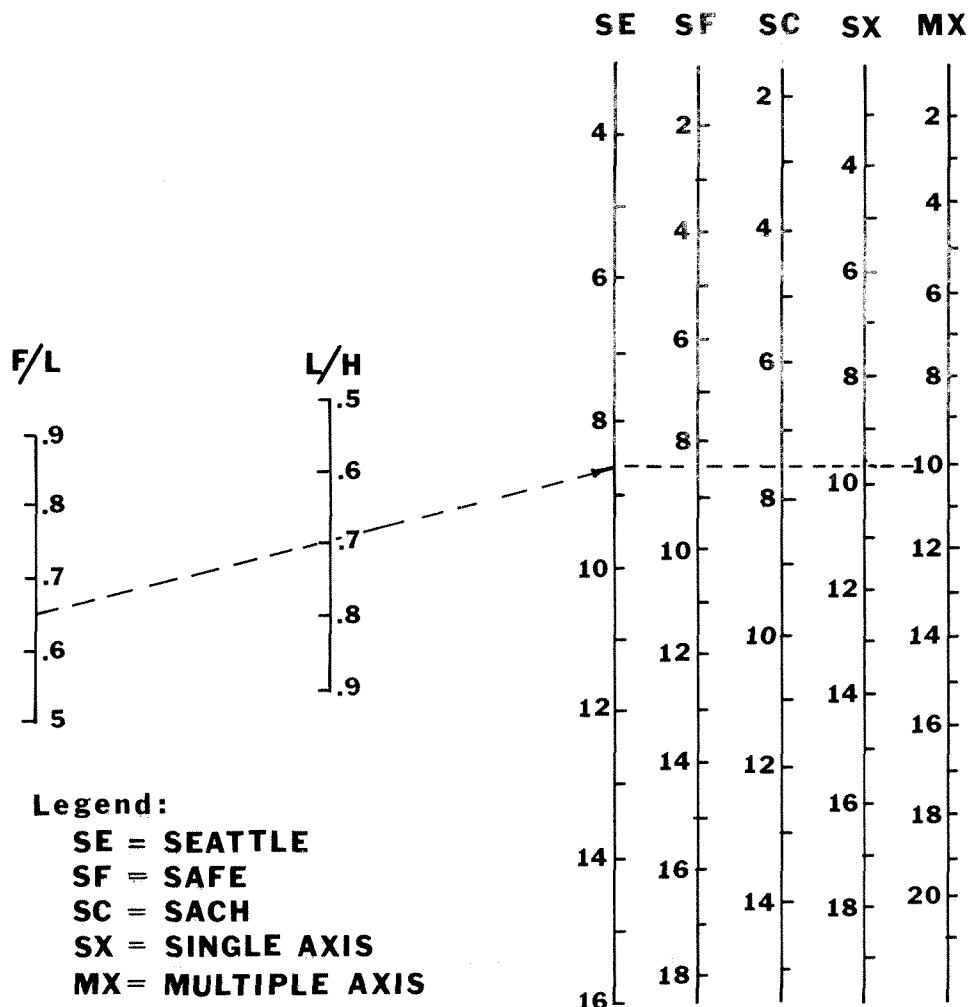


Figure 2. Nomograph for comparing shock among ankle-foot devices.

SEATTLE, SAFE, and SACH showed the lowest values, while the SINGLE AXIS and the MULTIPLE AXIS devices showed the highest. The dashed line illustrates use of the chart. By example, with $F/L = 0.65$ and $L/H = 0.7$, the resulting shock values are the following: SEATTLE = 8.6, SAFE = 8.3, SACH = 7.5, SINGLE AXIS = 9.7, and MULTIPLE AXIS = 10.0. The accuracy is about $\pm 1 \text{ rad/s}^2$. Comparison of magnitude of shock with subjective ratings showed that the device exhibiting the least shock corresponded to the subjective preference by the amputee.

Damping

The SACH, SAFE, and SEATTLE devices provided the highest damping for most subjects. Relative weight and relative length of residual limb determined which provided the highest damping for a given individual. Distinction between the three was possible by the following expression:

$$T = Wa/Wi + 0.095(RL)$$

where T is a threshold value. The boundary between SACH and SEATTLE was 1.9, meaning that if the value, T, was less than 1.9, then SACH provided the higher damping. The boundary between SEATTLE and SAFE was 2.2, meaning that if the value, T, was more than 2.2, then SAFE provided the higher damping (see **Figure 3**). The above correctly classified 17 of the 19 subjects.

Oscillatory frequency

The frequency of the shock oscillation averaged about 9 Hz and was governed more by characteristics of the individual than by the ankle-foot device. Among individuals, average frequency ranged from 6.5 to 11.0 Hz. The frequency f_s related to relative length of residual limb, RL expressed in percent height, and height H in cm, as follows:

$$f_s = 7.1 + 0.23(RL) + 0.054(178 - H)$$

This correctly expressed the frequency within 1 Hz in 14 of 19 subjects. The largest error was 1.6 Hz among the remaining five subjects.

General performance

The AP damped oscillatory angular acceleration or shock of the prosthesis after heel strike related linearly to the velocity of walking. The slopes of the lines of regression were all positive and differed for each device. Briefly summarized:

- a. Sensitivity to velocity, in r/s^2 per m/s: SACH = 5.47, SEATTLE = 5.90, SAFE = 8.35, SINGLE AXIS = 10.15, and MULTIPLE AXIS = 11.52.
 - b. Shock, in r/s^2 translated to velocity of 1.0 m/s: SACH = 7.9, SEATTLE = 8.8, SAFE = 9.0, SINGLE AXIS = 10.3, and MULTIPLE AXIS = 10.8.
 - c. Highest correlations were on the level surface and the lowest on the lateral incline.
 - d. Based on significance of correlation, SINGLE AXIS showed the least variability and SEATTLE the most.
- Results of the correlations are as follows:

Level

Values averaged from the three test speeds characterized performances on the level surface. All correlations were significant. The SEATTLE had the flattest slope and the MULTIPLE AXIS the steepest. The SACH, SAFE,

and SEATTLE developed the lesser AP shock while the SINGLE and MULTIPLE AXIS devices developed the greater. (Figure 4a).

Lateral incline

The lateral incline test condition was with the prosthesis on the “up hill” side. Results were more diverse than on the level surface. The SINGLE and MULTIPLE AXIS devices showed low correlations while SACH, SAFE, and SEATTLE were not significant. The SACH showed the flattest slope and the MULTIPLE AXIS the steepest. (Figure 4b).

Lateral decline

The lateral decline test condition was with the prosthesis on the “down hill” side. SACH and SINGLE AXIS showed good correlations while SAFE, SEATTLE, and MULTIPLE AXIS were not significant. (Figure 4c).

Up ramp

Slopes for SACH, SAFE, and SEATTLE were approximately the same. The SACH, SEATTLE, and MULTIPLE AXIS showed good correlations while SAFE and SINGLE AXIS were not significant. The slope for MULTIPLE AXIS was the steepest. (Figure 4d).

Down ramp

The down ramp performance were more diverse than up ramp. SAFE, SINGLE AXIS, and MULTIPLE AXIS

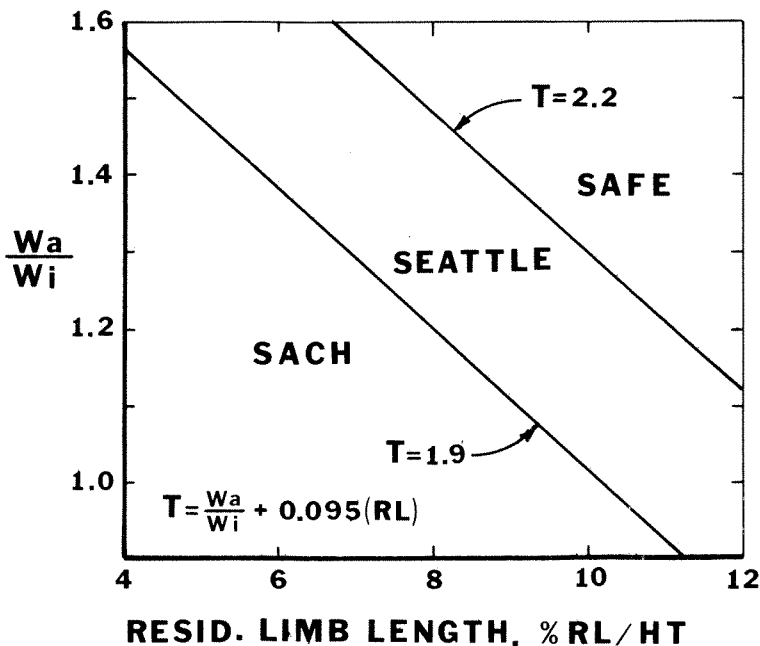


Figure 3. Boundaries delineating SACH, SEATTLE, and SAFE for highest damping.

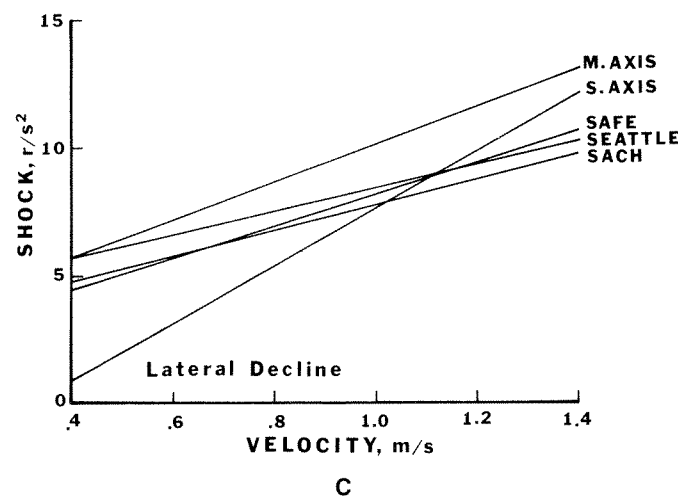
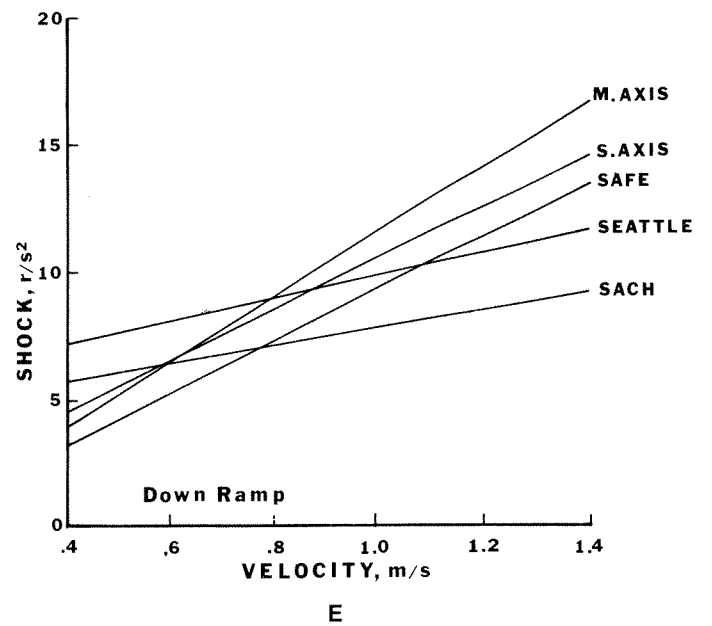
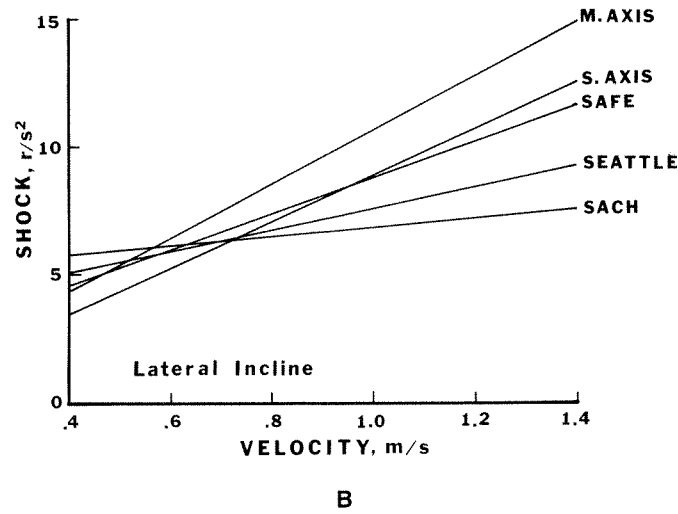
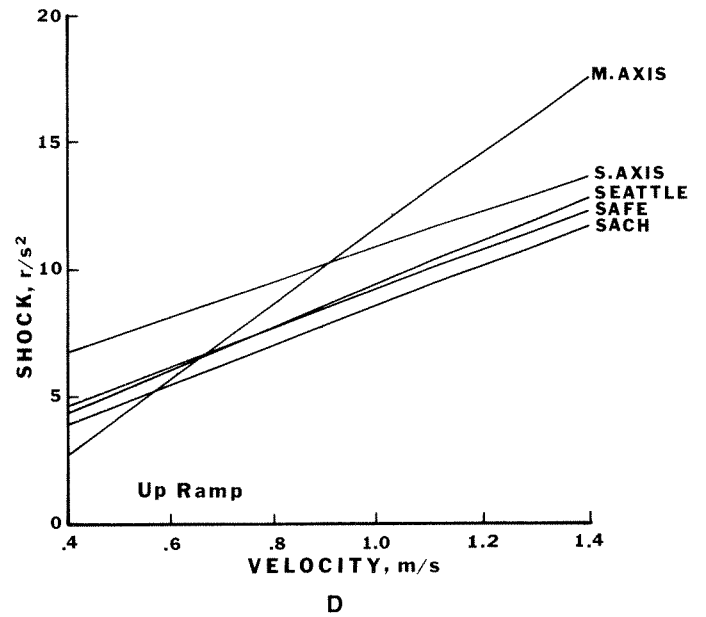
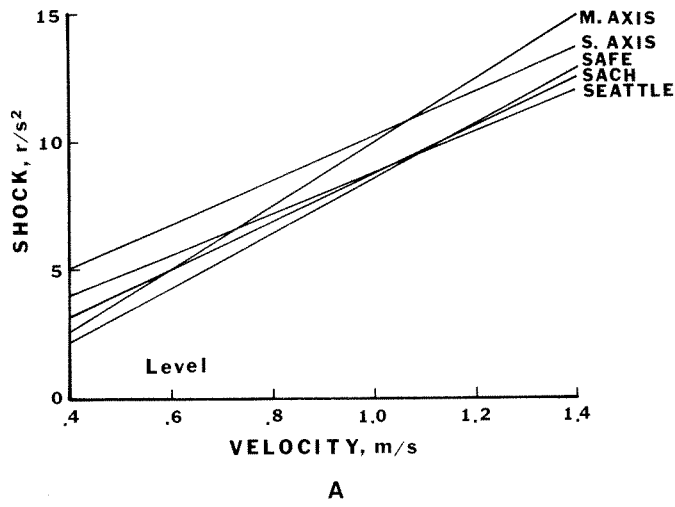


Figure 4. Regression lines of shock versus velocity for ankle-foot devices, a) level, b) lateral incline, c) lateral decline, d) up ramp, and e) down ramp.

showed good correlations while SACH and SEATTLE were not significant. The slopes for SACH and SEATTLE were the flattest and for MULTIPLE AXIS the steepest. (Figure 4e).

Velocity versus age

Average velocity V_a in m/s of walking experienced under different test conditions varied inversely with age A , in years. The relation was the following:

$$V_a = 1.36 - 0.009A$$

The relation may be seen in Figure 5.

F/L and L/H interdependence

The magnitude of shock related to two derived variables, F/L (stride frequency to stride length ratio) and L/H (stride length to height ratio). These variables offered insight into the effect of age on locomotion control strategies involving trade-offs between stride length and stride frequency, when accommodating changes in speed and in walking on unlevel surfaces. Performance characteristics of the nominally younger and older subjects tended to differ in a number of respects.

Younger. To manage the slow speed of walking on a level surface, stride length usually increased and stride frequency decreased. In accommodating the incline-decline surfaces, a comfortable F/L ratio was maintained to achieve

a "usual" speed. In walking up the ramp, the comfortable F/L ratio was maintained, but the stride length was decreased. In walking down the ramp, the F/L ratio was increased and the stride length (L/H) was decreased.

Older. The older subjects' performances showed less ordered relations between stride frequency and stride length. Many test subjects over 50 years of age demonstrated an increased F/L ratio at the "slow" speed. In accommodating the unlevel surfaces, L/H was reduced and the F/L increased drastically. Moreover, considerable scatter in F/L and L/H relations occurred in the four tests involved with walking on unlevel surfaces.

Miscellaneous

Harmonic ratios, which indicate degree of bilateral asymmetry, were in the order of 1.7 and ranged in isolated cases from about 0.9 to 4.4. By comparison, the harmonic ratios of healthy individuals are in excess of 3.0. Harmonic ratios did not correlate with angular accelerations of the prosthesis. Moreover, no significant relations were found between the harmonic ratios and subjective ratings by the amputees.

External work of locomotion varied both among and within subjects. Among subjects, the work ranged from about 0.35 to 0.7 J/Kg-m walked. Within subjects, work ranged about ± 20 percent attributable to the effects of

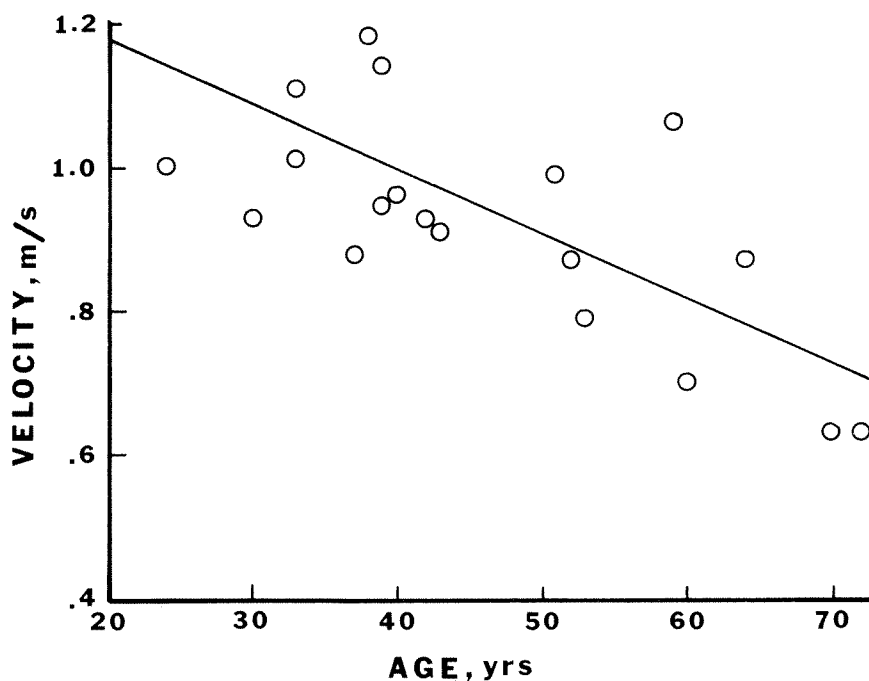


Figure 5.
Relation of walking speed to age.

ankle-foot devices. Correlation between subjective ratings of the different prosthetic feet and numerical values for work was not significant.

DISCUSSION

Not surprisingly, subjective responses varied considerably. This could be expected because of variation among the subjects such as age, physical characteristics, experience with prostheses, influence of personal prosthesis, and differing abilities to verbalize distinctions among the devices tested. However, these responses were invaluable in the effort to determine which measured variables served to discriminate performances in a manner consistent with opinions expressed by the amputees.

The subjective rankings of the ankle-foot devices led to distinctions among the devices by virtue of age, weight, length of residual limb, and ratio of stride frequency to stride length. These results may be due partly to design by the developers of certain components (1,2) and partly by age, physical condition, and attitude of the amputee. Regarding the older subjects' reactions to the SAFE and SEATTLE devices, one might conclude that older people don't want to be hurried! While it is beyond the scope of this report to try to delineate cause and effect for these observations, the observations should serve as additional guidelines in the prescription of ankle-foot devices.

Inferred from the amputees subjective responses was that the mechanism producing the least shock represented the preferred device. One exception was the SACH. The SACH demonstrated lower shock and higher damping values than others in many cases, yet many subjects rated the SACH as inferior. Written commentaries suggested that the SACH was not as well suited for activities such as running or dancing. While vigorous activities were not on the test protocol of this project, the subjective observation should serve as a prescription guideline.

Presumably the amputees perceived shock as merely a perturbative impact even though shock consisted of three elements: amplitude, frequency, and rate of damping. The effect of shock on the residual limb, as defined in this report, is the product of torque and time, known in mechanics as impulse. Neither the magnitude of the initial angular acceleration nor the rate of damping are adequate by themselves to characterize impact. Both intensity and duration are required. The choice was made to calculate the magnitude of the oscillatory acceleration at 8 percent into the gait cycle. The choice of 8 percent was purely arbitrary.

Proceeding beyond the initial foot strike provided the means to register the effects of the magnitude of the initial acceleration, the degree of damping, and a time relation to quantitate the perturbation.

Damping of shock is not a simple issue. Damping occurs during the period when the stump seats into the socket and is partly due to the characteristics of ankle-foot device and partly due to the progressively increasing coupling of the prosthesis to the stump. The reason that comparisons between devices could be made was because the socket and suspension remained the same for each individual for each of the five ankle-foot devices. Hence, differences could be attributed to the effect of a given ankle-foot device on each individual.

A trend noted was that shock frequency increased with length of residual limb. This may be partly attributable to the longer limb developing a longer lever arm (purchase) and thereby increasing the "stiffness" of the system.

The ratio F/L (stride frequency to stride length ratio) was sensitive means to note subtle changes in the strategy of accommodating challenges to locomotion. In unhampered walking, where no threat to stability is posed, both F and L are usually modulated almost equally to change velocity. Molen (4) noted this by referring to the s/n ratio where s was step length, and n was step frequency. Under circumstances where the walker perceives a threat to stability and intends to maintain velocity, the stride length is often shortened and the stride frequency increased. Applied to a younger person walking at "usual" speed, the minimum momentum of the body is large enough to assure safe movement through midstance despite any small disturbing impulse. An older person, on the other hand, whose "usual" velocity is slow, may perceive a threat to stability from a similar small disturbing impulse because of low momentum. That individual may: 1) shorten stride length and widen base of support; 2) increase stride frequency; and, 3) increase the double support period. These trade-offs were seen among all the subjects, particularly as they descended the ramp. The younger amputees, whose reaction times were presumed to be faster than those of the older subjects, demonstrated the lesser increase in F/L ratio. Subjects less sure of their security made pronounced increase in their F/L ratio in both ascending and descending the ramp.

SUMMARY

The effect on gait of five commonly prescribed ankle-foot devices was measured. The five devices were: SACH, SAFE, SEATTLE, ARTICULATED SINGLE AXIS, and MULTIPLE AXIS (Greissinger). Locomotion testing was conducted in a laboratory setting which provided testing on a level surface, surfaces with a lateral incline and decline, and up and down ramps. The principal objective measurements were angular acceleration of the prosthesis and forward velocity of the body.

Subjective ratings by the amputees served to resolve which physical variables determined the preference of a given ankle-foot device. The four physical variables were: 1) age; 2) ratio of actual to ideal weight; 3) relative length of residual limb; and, 4) the ratio of stride frequency to stride length. Thresholds were established which optimally classified devices preferred by the subjects.

Distinctions in performances were derived from analyses of the anterior-posterior angular accelerations occurring in the prosthesis immediately following heel strike. The accelerations were characterized as a damped oscillatory waveform. The principal factors serving to discriminate performances were amplitude and rate of damping. These findings, when related to the subjective rankings, showed that subjects preferred devices which developed the least shock and the greatest damping.

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GLOSSARY

Correlation coefficient. A measurement used to express the degree of association between two variables.

Fourier coefficient. A number prefixed as a multiplier to a given sine or cosine component used in quantitating a periodic waveform. The magnitude denotes the relative contribution of that component to the total waveform.

Fourier series. The expansion of a periodic function into a series of sines and cosines.

Harmonic. One of the component frequencies characterizing a waveform and is an integral (whole number) multiple of the fundamental frequency. In gait, the fundamental is the stride frequency. Harmonics are integral multiples of the fundamental such as two times, three times, four times, etc.

Harmonic analysis. The analytical procedure of breaking a periodic function into components, each expressed as sine or cosine function and determining the relative contribution of each harmonic to the total waveform.

Harmonic ratio. The harmonic ratio is the quotient derived from dividing the sum of the absolute values of the even harmonics by the sum of the absolute values of the odd harmonics. Applied to this gait study, the higher the harmonic ration, the more symmetric the gait.

Impulse. Product of force times time in a linear system. Product of torque times time in a rotatory system.

Kinematics. Characterization of motions without consideration of what caused the motions.

Kinetic energy. Energy by virtue of a body in motion. Energy is the capacity to do work.

Kinetics. Consideration of causes of motion, hence the consideration of forces and energies.

Momentum. Product of mass times velocity in a linear system. Product of moment of inertia (for mass) about its axis of rotation times angular velocity.

Newton. The newton is the amount of force which imparts to a mass of one kilogram an acceleration of one meter per second per second. One newton is approximately 0.225 pounds.

Periodic waveform. A repetitive waveform, such as may be found to recur from gait cycle to gait cycle.

Potential energy. Energy by virtue of position. A raised weight has potential energy.

Regression analysis. A means to determine how two or more variables relate to each other.

Root mean square. The square root of the average of the sums of the squares of a variable. While the root mean square (rms) is almost the same as the arithmetic average, it allows for irregularities, in particular when numbers range above and below zero.

Significance level. Significance, also called the rejection level, is a value used to judge the probability of two variables not relating to each other. The symbol used to express the probability is "p." The smaller the "p," the less likelihood that the relation is pure chance.

Waveform. Shape of a wave as a function of an independent variable such as time, percent gait cycle, or other convenient base.

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