Prosthetics and Orthotics International, 1981, 5, 11–18

Balance in lower limb child amputees*

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Abstract
Postural stability of five unilateral above-knee amputee children was measured when wearing the SACH and the experimental Child Amputee Prosthetic Project (CAPP) prosthetic foot. Excursions of the centre of pressure of the supportive forces were recorded via force platform during sustained weight-shifting forward, backward, left, right, and during normal standing. Visual proprioception effects on upright stance were also demonstrated with these child amputees. Total base of support did not differ for the two types of prosthetic feet, but the functional base of support for SACH foot was significantly larger than CAPP. Fluctuations of centre of pressure about a mean position in normal standing were less when children used CAPP foot. Focusing on a static target had no effect on postural stability in either anterior-posterior or lateral direction for CAPP foot conditions, but lack of visual target had a deleterious effect on lateral stability when SACH foot was worn.

Balance is one of the most difficult problems for a lower limb amputee (Hellebrandt et al, 1950; Moncur, 1969; Murdoch, 1969). The absence of part or all of a lower limb reduces the amount of proprioceptive information about the surfaces on which the foot is resting and the precise location of the prosthetic limb. While limited data have been reported on the balance and stability characteristics of adult amputees (Fernie and Holliday, 1978; Hellebrandt et al, 1950), information about balance of child amputees is almost non-existent. We have found only one report of the postural stability characteristics of a child amputee; Shambes and Waterland (1970) studied an 11-year-old quadrilateral amputee who had congenital Lisfranc amputations of both lower limbs, long above-elbow amputation of the left upper limb, and medium below-elbow amputation of the right upper limb.

The purpose of this study was to detail the postural stability characteristics for lower limb child amputees. In addition, the conventional SACH prosthetic foot was compared with the experimental Child Amputee Prosthetic Project (CAPP) foot for various postural tasks. The SACH foot (Fig. 1a) is usually constructed with a moulded polyurethane material which incorporates a heel cushion to allow some compression of the heel during heel strike in walking to simulate plantar flexion of a normal foot. The CAPP foot (Fig. 1b) is an experimental prosthesis undergoing development at the UCLA Child Amputee Prosthetic Project. It is designed to provide more knee stability during early stance phase during walking and also to respond to torsional loads occurring in the stance phase of walking. The heel projection of the CAPP foot is non-weight bearing and deflects upward at heelstrike. With the ground reaction forces shifted more anteriorly on the supporting foot there is an expected increase in dynamic knee stability during the stance phase of walking. While additional research is being conducted on the dynamic characteristics of the CAPP foot, the present study provides some preliminary information about the postural stability of child amputees using the experimental CAPP foot, as well as providing a comparison with the conventional SACH foot.

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*The research was supported in part by grants from U.S. DHEW (MCR-06004-11), USOE Bureau of Education for the Handicapped (AH 70536), UCLA Biomedical Research Support Grant, and the UCLA Academic Senate Research Committee.

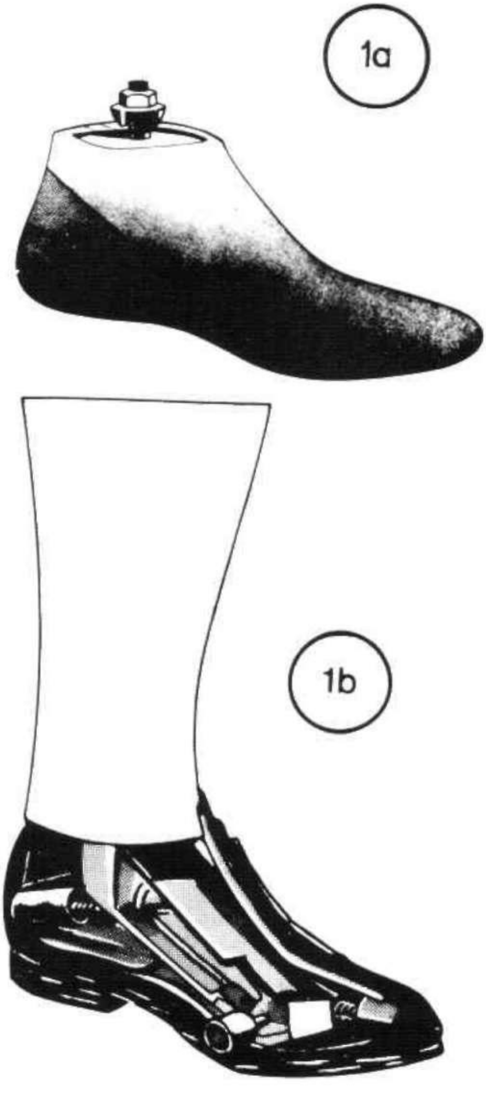

Fig. 1a. Conventional SACH foot. Fig. 1b. Child Amputee Prosthetic Project (CAPP) foot, see text.

Methods

Subjects

Five children, one boy and four girls, participated in the study. Their mean age was 11 yrs 3 months (±25·7 months), mean height was 139·2 cm (±6·2 cm), and average weight was 36·6 kg (±11·9 kg) when wearing their prostheses. The average weight of the prostheses with the SACH foot was 2·8 kg (±0·6 kg), while the mean weight of the prostheses with the CAPP foot was 2·7 kg (±0·4 kg). All the children were unilateral lower limb amputees who had worn a prosthesis for at least four years. Two of the children were above-knee (AK) amputees; one acquired the amputation as a result of an automobile accident and the other as a consequence of fibrosarcoma. The three remaining children were knee disarticulation (KD) amputees; etiologies were congenital, automobile accident, and gangrene. Two of the KD amputees wore prostheses with 4-bar modular knee units, while the other children had been fitted with constant-friction knee joints. Each child normally wore the SACH foot and was tested wearing first the SACH foot and then the CAPP foot on the same prosthesis. The evaluation of the prosthesis fit and function was done when each child was wearing his/her regular prosthesis.

Experimental procedures

Each child was asked to assume seven different positions while standing on a 40 × 60 cm force platform (Kistler 9261A) which was flush with the surrounding floor. The manoeuvres that each child performed were: (1) standing with eyes open with feet shoulder width apart and arms relaxed in a comfortable, dependent position at the sides, (2) from the initial position, weight-shifting forwards and holding, (3) from initial position, weight-shifting backwards and holding, (4) weight-shifting left and holding, (5) weight-shifting right and holding, (6) standing with feet together, medial borders touching, and (7) standing with feet together, medial borders touching and eyes focused on a target placed one metre from the child at eye level. All positions were maintained for ten seconds. The locations of the feet were the same for positions 1 through 5; similarly, foot placements for positions 6 and 7 were not changed.

The total base of support for each child was determined from the outlines of the child's shoes which were traced on graph paper taped to the surface of the force platform. The perimeter of the total base of support consisted of: (1) a line passing through the most posterior point of each heel, (2) a line passing through the most anterior point of each shoe, and (3) lines drawn along the lateral border of each shoe, thereby producing a quadrilateral. The intersection of the two diagonals (A) of the quadrilateral was defined as the geometric centre (GC) of the total base of support (Fig. 2).

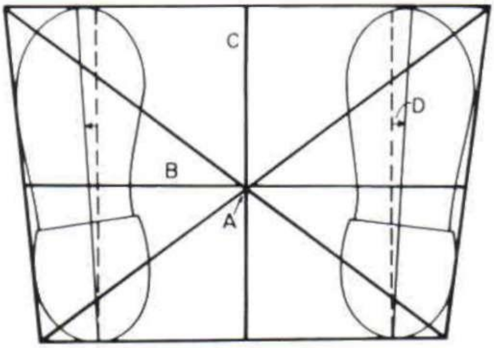

Fig. 2. Total base of support. Geometric centre (A), lateral width of base (B), anterior-posterior length (C), out-toeing angle (D).

The foot and stance dimensions for each child were calculated with respect to the GC of the total base of support. The anterior-posterior length of the total base (C) was determined by a line drawn perpendicular to the heel line, passing through the GC and intersecting the top and bottom of the quadrilateral figure; the angle of toe-in or toe-out (D) was measured relative to the line perpendicular to the heel line. The width of the total base of support (B) was determined by a line drawn parallel to the heel line, passing through the GC and intersecting both sides of the quadrilateral.

Centre of pressure (COP) excursions within the base of support resulted in calibrated voltage variations in the force platform which were recorded on a polygraph (Grass 7B). The analogue records of the rectangular co-ordinates of the COP were manually digitized with a Hewlett-Packard programmable calculator and digitizer (HP 9830 and HP 9864). Measurements were taken at 100 ms intervals during the 10 sec that each position was maintained. A printer (HP 9862) plot of the absolute excursions of the COP was also produced by the calculator programmes. The relationship between the excursions of the COP in the base of support was determined by overlaying the printer plots on the footprint tracings. Scatterplots and mean locations of the COP for normal standing and forward, backward and lateral leans were plotted on the footprints. Locations of the various mean positions were quantified as polar co-ordinates (r, θ) as shown on Figure 3.

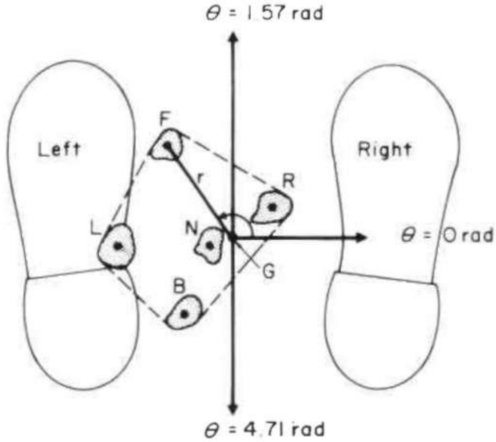

Fig. 3. Functional base of support for a right amputee. Excursions of centre of pressure (COP) for normal standing (N), leaning forwards (F), leaning backwards (B), leaning left (L), and leaning right (R). Geometric centre (GC) of functional base (B).

The per cent of the area of the functional base of support in relation to the total base of support was calculated for the five amputee children. The functional base of support was defined by the perimeter of the excursions of the COP made while the child stood normally, leaned anteriorly, posteriorly, and laterally. Perimeter of the functional base of support is shown as a dashed line (–·–·–·–·–) in Figure 3. The distance (r) from the average excursion of the COP from the GC was determined by drawing a line from the GC to the mean location. The angle (θ) of the average excursion of the COP about the GC was measured counterclockwise from a right ray which originated at the GC. Note that any COP position that was *between* 1·57 rad and 4·71 rad fell to the *left* of a sagittal line through the GC of the base of support, while any COP position at an angle *less than* 1·57 rad or *greater than* 4·71 rad fell to the *right* of the centre line. The four corners of the quadrilateral figure were digitized along with the perimeter formed by the excursions of the COP from the five standing positions. A computer programme calculated the areas.

The variation in the positions of the COP about the mean position was used as a measure of postural stability of the amputee child when standing with the medial borders of his/her feet together and focusing and not focusing on a target. Therefore, the standard deviation of the COP excursions about a mean position was used to compare the amputee stability with and without a specific visual target.

Results

The absolute dimensions of the total base of support for the child amputees were not significantly ($p>0{\cdot}05$) different when standing with the SACH versus CAPP foot for either feet apart or feet together. Unless specifically noted, all significance tests were done with Student's *t* test for paired observations (Marascuilo, 1971). The mean anterior-posterior length of the base was 24·5 cm ($\pm 2{\cdot}1$cm) and was simply a function of the children's shoe sizes. The lateral dimensions of the base of support were related to the positions of the feet, feet approximately shoulder width apart versus feet together. The mean base widths for the SACH foot with feet apart (26·9 cm$\pm$3·8) and feet together (15·3 cm$\pm$1·2) were only 0·1 cm wider than the respective mean dimensions when using CAPP foot. The mean foot angles also showed no significant differences ($p>0{\cdot}05$) between the CAPP and SACH conditions: (1) during normal standing with the SACH foot, the average toeing-out angle was 0·209 rad ($\pm$0·126 rad) and with the CAPP it was 0·220 rad ($\pm$0·143 rad), and (2) while standing with feet together, the SACH condition average toeing-out was 0·185 rad ($\pm$0·122 rad) versus the CAPP condition with 0·129 rad ($\pm$0·059 rad).

During normal standing the average COP with the CAPP foot had a tendency to be located closer to the GC of the total base of support than the mean COP for the SACH foot; however, statistically this difference was not important ($p>0{\cdot}05$). The relationship between the mean COP to the GC for normal standing was 39 per cent of the distance of the COP from the heel line for the SACH foot and 43 per cent of the distance for the CAPP foot.

During normal standing and during leaning forward and backward, the children always favoured their normal side (Table 1); for a right amputee the COP was located to the left of a sagittal line through the geometric centre and in left amputees the effect was in the opposite direction. When the children were volitionally weight-shifting to the left or to the right, the COP moved to the side of the shift, regardless of the side of amputation. The SACH foot appeared to permit a greater weight-shift backwards, left, and right than did the CAPP foot.

As expected, with the almost identical absolute dimensions of the total base of support, the mean area of the total base of support for the

Table 1

Polar co-ordinates of centre of pressure locations[a]

	SACH			CAPP		
Direction	r	Right amputee θ	Left amputee θ	r	Right amputee θ	Left amputee θ
Normal	3.7(1.4)[b]	3.71(L)[c]	0.46(R)	3.9(1.9)	3.35(L)	0.91(R)
Forward	6.4(1.2)	2.08(L)	1.10(R)	7.2(1.6)	2.39(L)	1.06(R)
Backward	6.8(1.2)	3.74(L)	5.75(R)	5.5(2.8)	3.77(L)	6.23(R)
Left	9.1(2.9)	3.24(L)	2.60(L)	6.6(1.9)	3.58(L)	1.98(L)
Right	6.7(1.4)	6.21(R)	0.18(R)	3.9(2.5)	0.83(R)	0.82(R)

[a]The distance (r) in centimetres of the mean position of the centre of pressure from the geometric centre and the angle (θ) in radians of the mean position (see Figure 3 for example).

[b]Mean value with ± 1 standard deviation in parenthesis.

[c]Note that the letter in parentheses, L (Left) or R (Right), refers to a mean centre of pressure location to the left or right of a sagittal line through the geometric centre of the base of support.

SACH foot did not significantly differ from that of the CAPP foot ($p > 0.05$). The mean area of the base with the SACH foot was 689·9 cm^2 (± 121.2 cm^2) and 704·7 cm^2 (± 182.3 cm^2) for the CAPP foot. However, the functional base of support for the SACH foot was significantly ($p > 0.01$) greater than the CAPP. The mean area of the functional base of support was 83·4 cm^2 (± 30.8 cm^2) for the SACH foot and 40·4 cm^2 (± 12.0 cm^2) for the CAPP prosthesis. Thus the amputee children wearing the SACH foot used 12 per cent of their total base of support compared with those same children wearing the CAPP foot who used only six per cent of the total base of support available to them.

During each task of standing or sustained weight-shifting, the COP constantly fluctuated about the mean position (Table 2). The standard deviation of the COP fluctuations about the mean position provided a measure of stability during weight-shifting. Although the variability of the anterior-posterior excursions were always greater than in the lateral directions, no significant ($p > 0.05$) differences were demonstrated between the SACH and CAPP conditions for any of the postural tasks during normal foot placement.

When the amputees stood with their feet placed together, with differing visual conditions, they consistently had greater stability with the CAPP foot than the SACH foot in both anterior-posterior and lateral directions (Table 3). Even with the small number (4) of comparison conditions, i.e., Anterior/Posterior and Lateral with and without target for SACH versus CAPP, there still was less than a 25 per cent probability (Sign Test; Marascuilo, 1971) that the consistently larger SACH COP fluctuations were due to chance alone.

With the CAPP foot, the presence or absence of a static visual target had no significant ($p > 0.05$) effect on either anterior-posterior or lateral stability. With the SACH foot, however, the lack of a specific focusing point in the field of view had a pronounced influence on lateral stability. Without a target, the COP lateral

Table 2
Average standard deviations (mm) for amputees—feet apart

	SACH		CAPP	
Standing	A/P	Lat	A/P	Lat
Normal	6.1(3.2)	3.5(0.6)[a]	6.5(4.2)	4.6(2.9)
Forward	8.3(3.5)	5.1(2.4)	8.9(6.4)	5.9(4.4)
Backward	6.1(2.2)	5.9(3.7)	5.1(2.9)	4.5(3.6)
Left	6.1(2.3)	5.4(2.4)	3.4(1.9)	4.2(1.5)
Right	6.1(4.2)	5.3(1.8)	3.7(2.1)	4.8(3.4)

[a]Standard deviation of the values about the mean are given in parentheses.

Table 3
Average standard deviations (mm) for amputees—feet together

	SACH		CAPP	
Visual condition	A/P	Lat	A/P	Lat
Target	5.1(6.5)[a]	6.4(5.6)	2.9(1.2)	3.2(1.6)
No target	4.9(3.9)	7.4(5.4)	3.1(0.9)	3.4(0.8)

[a]Standard deviation of the values about the mean are given in parentheses.

variations for the children with the SACH foot (7·3 mm, Table 3) were significantly ($p>0·05$) greater than all other conditions examined. No significant ($p>0·05$) effects were observed in any other pairs of the tested conditions for standing with feet together.

Discussion

Postural stability is affected by the overall size of the base of support. There were no practical or statistical differences between the SACH and CAPP prosthetic feet in the width, length, or out-toeing angles for their total base of support when standing with feet apart; the amputee children maintained the same total base of support when wearing either prosthetic foot.

The functional base of support is a good indicator of the area over which the child could move and still maintain her/his balance. Thus, during normal standing, the COP may be expected to be positioned equally between both feet and near the middle of the base of support. Murray et al, (1975) found that the mean location of the COP for normal men was 43 per cent of the fore-aft distance of the base of support. The amputee children wearing the SACH prosthetic foot had a smaller per cent distance (39 per cent) than did the normal men, but while wearing the CAPP foot, the children had the same percentage of the distance (43 per cent) as the adult men. Thus, with the SACH foot the children tended to shift the COP closer to the heels during normal standing.

During volitional weight-shifting, the children wearing the SACH prosthetic foot were able to lean further backward, left, and right, while the CAPP prosthetic foot allowed greater movement forward than the SACH. Because of the construction of the CAPP foot, i.e., a non-weight supportive heel which focused the weight at the ball of the prosthetic foot, the child may not have felt that he/she was stable enough to move in a direction where there was a lack of support. The SACH foot provided the support in the heel necessary for stability during backward shifting, while the CAPP foot provided support in the anterior portion of the prosthetic foot.

COP locations for the amputees were affected by the side of amputation; the amputees favoured their normal side. In contrast, Murray et al, (1975) found that with normal adult men, the mean position of the COP did not relate to the side of the dominant upper limb. There were no comparable data for normal children.

A large functional base area will allow the amputee a greater range of movement over which he/she can maintain balance. The SACH and CAPP prosthetic feet had smaller functional base areas, 83·4 cm^2 and 40·4 cm^2 respectively, than normal men (Murray et al, 1975) whose functional base area was estimated to be 96·3 cm^2. As a percentage of standing height, the functional base area of the SACH foot was 60 per cent and the CAPP foot was 29 per cent, while the functional base area to the total height for the normal men (Murray et al, 1975) was 55 per cent. The SACH prosthetic foot allowed twice the functional base over which movement and balance could be maintained than did the CAPP prosthetic foot. The large difference between the SACH and CAPP feet was probably related to the familiarity that the children had with the SACH foot, the one they normally used.

Even though the actual sizes of the functional bases of support were significantly different between the CAPP and SACH feet, it was interesting to note that there were no significant differences in the amount of COP fluctuations (steadiness) at the extremes of the shifted positions. Comparable steadiness was found in each of the weight-shifted positions for both CAPP and SACH feet. The magnitude of the COP fluctuations may provide important information to the child about the degree of unsteadiness permitted to safely maintain balance.

In assessing the total anterior-posterior base of support available, it was determined from Murray's data that normal men used 54 per cent of the total fore-aft direction possible. The children amputees wearing either prosthetic foot were not able to move over as large a portion of their anterior-posterior base of support as normal men. The per cent area in the fore-aft direction was approximately the same for the right and left amputees wearing the SACH foot, 40·2 per cent and 36·6 per cent respectively. The values for the right and left amputees wearing the CAPP foot were 30·5 per cent and 28·4 per cent respectively.

The dynamic nature of upright balance is such that the COP underfoot fluctuates incessantly during each of the sustained positions. Apparently the movements of the COP result from contractions and relaxations of the supporting muscles and the shifting of the masses of various body segments. Musculoskeletal proprioception is an important factor in the control of upright posture, but the potent effect of visual proprioception should not be underestimated. The effect of an absent or available target provided evidence for the importance of specific visual proprioception in the control of stance for amputee children. A static planar target failed to affect significantly the postural deviation in the anterior-posterior direction for the amputee children; this finding was similar to that reported for normal children (Zernicke et al, 1978). By comparison, Lee and Lishman (1975) reported a significant decrease in anterior-posterior trunk sway as adults focused on a static nearby object, as opposed to looking at more distance surrounds. A dynamic visual reference system has also been demonstrated to be a potent influence on anterior-posterior postural control for both infants (Lee and Aronson, 1974) and adults (Lee and Lishman, 1975). The strong effect of visual proprioceptive information, however, was evident in the lateral deviations of the COP. There was a significant decrease in lateral sway when the amputee children, with the SACH foot, and the normal (Zernicke et al, 1978) children focused on a target. The target had no comparable effect on lateral sway when the amputee children wore the CAPP foot; with the CAPP foot, fluctuations of the COP were small with or without the target.

Both normal and amputee children have specific postural stability needs which are not simply scaled down characteristics of adults. Prostheses for amputee children, therefore, should be designed to incorporate the biomechanical characteristics of normal children, not normal adults. The CAPP prosthetic foot was designed to provide increased stability during dynamic weight-support in walking or in static weight-support during standing. Our initial postural tests with the new prosthetic foot have provided some unique information about children amputees' stability in general, and about the SACH and CAPP prostheses specifically. A next stage of testing would be to define the alignment criteria to use when the CAPP foot is worn in conjunction with existing prosthetic systems or when the new foot is aligned with a total prosthetic limb specifically designed for the CAPP foot. Amputee children should then be allowed an extensive familiarization period with the new prosthesis, to experience fully its limits and functional characteristics. Clinical tests on a larger child population may also result in more definitive assessment of the prosthesis; differences and similarities in stability between the two prosthetic feet would then either be proved generalizable or shown to be non-inferential and strictly applicable to only these five children and their immediate situation.

Conclusions

On the basis of the data collected on these unilateral child amputees, the following conclusions were warranted: (1) There was no significant difference in the absolute dimensions, foot angles, or areas of the base of support in normal standing with the SACH versus the CAPP prosthetic foot. (2) During normal standing and during forward and backward weight-shifting, the COP of the supportive forces was always shifted toward the normal limb, regardless of the type of prosthesis. (3) The functional base of support for the SACH foot was significantly greater than for the CAPP foot; the children used 12 per cent of their total base of support compared with those same children who used only six per cent of the total base of support available to them when wearing the CAPP foot. (4) When standing with feet together, medial borders touching, the children consistently displayed less COP fluctuation while wearing the CAPP foot than with the SACH. (5) Visual proprioception had a significant effect on lateral stability when the children were wearing the SACH foot. Focusing on a target did not significantly alter the anterior-posterior or lateral stability when the children were using the CAPP foot.

Acknowledgments

We wish to express sincere appreciation to Dr. Yoshio Setoguchi, Ruth Rosenfelder, Carl Sumida, Wally Sumida, Darrell Baldes, and Melissa Hoy for their assistance and support.

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