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Foot loading in amputee stance

M. LORD and D. M. SMITH

Bioengineering Centre, University College London.

Abstract

A survey has been carried out to establish information on foot loading in amputee stance. The parameters measured are percentage body weight and the positions of the centres of pressure under each foot.

The data was collected in a clinical environment by the use of a Double Video Forceplate (DVF), a tool developed at the Bioengineering Centre. The objective of the survey is to provide background information for the use of the DVF in static alignment of lower-limb prostheses.

Results are presented from a number of patients attending the Roehampton Walking Training School, and for a small group of patients attending the Bioengineering Centre for delivery of an experimental below-knee prosthesis. Scattergrams and averaged results provide normative data which can assist in interpretation of DVF displays during individual alignment.

Introduction

The pattern of foot loading under a lower limb prosthesis will in most cases reflect features of the alignment of the limb components. Based on this premise, a clinical tool has been designed to aid static alignment by rapid collection and display of foot loading parameters during stance at the time of fitting of a prosthesis (Smith et al, 1983; Smith and Lord, in press). A background of comparative data is required to interpret the significance of individual loading patterns seen in clinical assessments, and it is to provide such information that this study was initiated.

In symmetrical rest stance of a normal subject, the loads on each foot are dictated by anatomy, posture and balance. The loading under the feet of a lower-limb amputee is determined also by constraints imposed by amputation and fitting of a prosthesis. There has been to date little study of foot loading of the amputee in stance and its dependence on prosthetic considerations.

Ground loading can be expressed in terms of the foot-to-floor reaction force occurring at the support surface. For the whole body, the origin of the reaction force at the support surface is commonly defined as the Centre of Foot Pressure (CFP). The CFP corresponds to the projection of the body's Centre of Gravity onto the support surface averaged over a period of several seconds standing. The location of the CFP with respect to the foot positioning has been the subject of limited study. Carlsoo (1972) describes the location of the CFP by reference to a vertical line passing through the body's centre of gravity, stating that this "line of gravity passes 2–5 cm ahead of the movement axis of the talo-crural joint, which itself passes through the lower tip of the lateral malleolus". Hellebrandt et al, (1938) found the average location of the line of gravity to fall 50.8 mm in front of the ankle joint, but noted a wide range in this parameter.

In prosthetics, the location of the centre of pressure for an individual foot is of relevance, indicating the line of the limb loading at the foot. This line may be strongly influenced by the alignment of the prosthetic limb components. No studies have been identified that quantify the location of the centre of pressure for each foot individually (referred to hereafter as the ICFP). If it is reasonable to assume that a normal subject can stand symmetrically on request, the position of the ICFP under the left foot will be a mirror image of that for the right foot; then it can be deduced that the anteroposterior location of both ICFPs are the same as that of the CFP. However for amputees or other subjects with disabilities of the spine or lower limbs, the stance cannot be assumed to be symmetrical.

All correspondence to be addressed to Dr. M. Lord, Bioengineering Centre, University College London, Roehampton Lane, London SW15 5PR.

There have been many studies of the small movements of the CFP occurring in the support plane during postural sway (Thomas and Whitney, 1959, De Wit, 1972) which have been analysed as indicators of disturbed postural balance (Njiokiktjien et al, 1978). It is widely reported that for normal adult subjects standing still for periods of less than a few minutes, sway movements of the CFP are confined within a few tens of millimetres of the mean position. The majority of the power is in the bandwidth of 0.1 to 10Hz, and therefore a mean location of the CFP can be described by averaging over ten seconds or more.

In the amputee population, it is anticipated that a greater variation in the anteroposterior location of the ICFP will be seen, dependent on the type of limb, level of amputation, hip complications, residual anatomy and muscle function. It might be anticipated, for example, that the meean location of the ICFP under a prosthesis with a patellar-tendon-bearing socket will be anterior to that expected in the normal subject, reflecting the anterior placement of the load at the knee. Conversely, the ICFP may be abnormally posterior under the prosthetic limb on an ischially-seated above-knee amputee. The ICFP on a remaining natural limb may be shifted in a compensatory response. However these variations should correspond to physical factors within a consistent framework of alignment and prosthetic fitting.

For amputees the magnitude of the limb load on the amputated side may not reach 50%. It is predictable that the natural limb should be favoured in the majority of cases where there are no severe complications of the remaining natural limb. However, failure to place a reasonable load through the prosthetic limb may reflect an undue lack of confidence, a short prosthetic limb, pain (stump, knee or hip) or some alignment factor. Data on magnitude of load may establish criteria for satisfactory weightbearing on the prosthesis.

In this study, the locations of the CFP, ICFPs and magnitude of load were recorded. The range and variability of loading parameters for the lower limb amputee are investigated, with an attempt to seek consistent trends.

Methods

Technique

A research prototype of a DVF (Double Video Forceplate) was used to assess groups of amputee patients and non-amputee subjects. The DVF consists of a pedestal with a separate forceplate for each foot, an output display for monitoring, a printer and a controlling microprocessor (Fig. 1). An additional facility of this device permits the projection of the reaction force line against the limb in the lateral view, although this was not explored in this study. Each patient was asked to stand in his customary footwear on the pedestal, which places the feet in a known orientation by reference to medial and rear guides (Fig. 2). The guides place the subject's feet with heel midpoints approximately

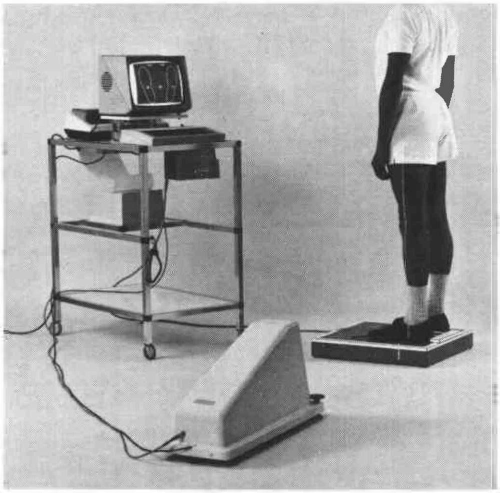

Fig. 1. The DVF equipment. A facility to project a laser line against the lateral aspect of the limb (shown in the foregound) was not used in this study.

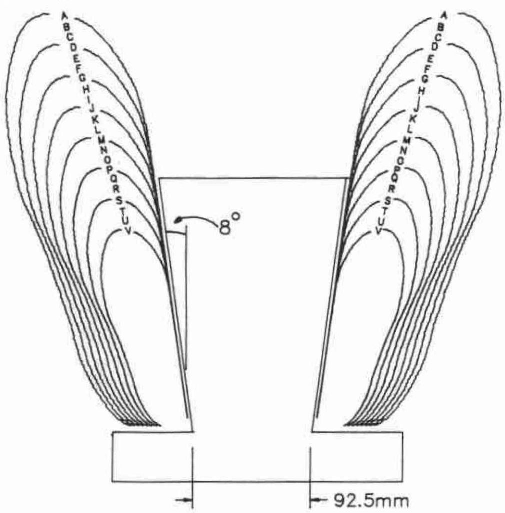

Fig. 2. Foot placement markings on the DVF pedestal.

150 mm apart and with 30° included angle between their midlines (bisectors of the angle between the medial and lateral tangents to the shoe outline). The foot outline corresponding most closely to the patient's shoe was selected by its letter code, and this size of outline is used subsequently for display and printout.

The patient was asked to stand as evenly as possible for 15 seconds, after which a printout of the time-averaged loading was produced (Fig. 3). During the recording period, the patient could not see the screen display of loading. Care was taken to ensure that the patient remained facing squarely forward without visual distractions.

The DVF is a live interactive device and on occasions the patients were asked to transfer load fore and aft or from the inside to outside border of the foot with reference to the screen display. This enabled the range of motion of the ICFPs to be observed. The ICFP positions can be determined from the DVF printouts to an accuracy of ±7, mm, and the weight distribution determined to within 1% for adult subjects.

Patients

Two groups of patients have been studied. One group comprised all A/K and B/K patients attending the Walking Training School at the Roehampton Limb Fitting Centre during a fixed period, who did not have prosthetic or medical complications. Data was collected by a physiotherapist collaborating on this project. The age range of the patients is not available.

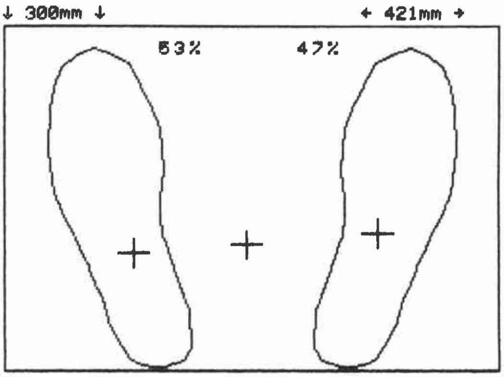

Fig. 3. A typical printout from the DVF, showing the loading pattern averaged over 15 seconds. Crosses indicate ICFPs and CFP, and the figures indicate the percentage weightbearing on the left and right foot respectively. The dimensions within arrows indicate the dimensions of the box drawn around the foot outlines. The DVF screen display is similar to the printout, but gives instantanous results.

The second group consisted of patients attending the Bioengineering Centre for fitting of an experimental vacuum formed thermoplastic socket PTB limb (Davies and Russell, 1979). These limbs were all similar, and fitted by the same prosthetist. The data was recorded at final fitting prior to delivery, either by the prosthetist or researcher. The age range of the patients was 20–78: mean age 47.

Non-amputee comparison

A group of non-amputee asymptomatic subjects was also studied. This data was collected in the same location, by the same researcher following the same procedure as with the second group of amputees. (Age range 16–72: mean age 42).

Analysis

From the DVF printouts, the position of the ICFP under each foot was measured in terms of its percentage length and width in the anteroposterior and mediolateral directions respectively (Fig. 4). A statistical investigation of CFP and ICFP positions indicated that representation of the range of distribution of the group averages by a standard deviation would not be meaningful because of the apparent non-Gaussian nature of the distribution and small sample sizes. Therefore the results for sample groups are presented visually in the

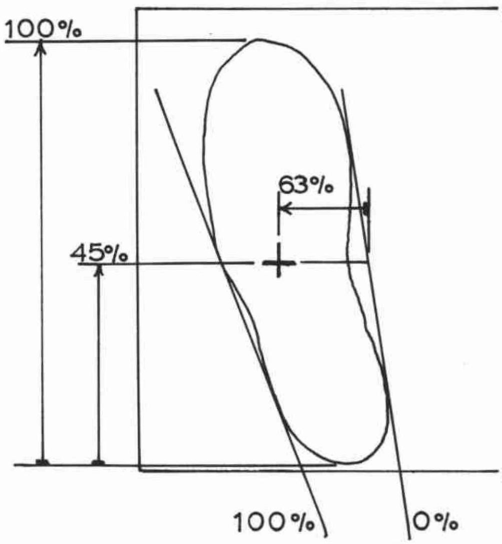

Fig. 4. Conversion of ICFP position to percentage length and width points. Construction for the right foot is a mirror image of that shown for the left foot.

unprocessed form of scattergrams. Each scattergram comprises the overlaid printouts for the individuals in the group, normalized for foot size. The numerical data represents group averages of mean ICFP positions and magnitude of limb load.

Results

Reproducibility of results from any one individual on repeated testing is obviously an issue to consider. In previous tests, 14 healthy young men were recorded on the DVF sequentially in shoes, barefoot, barefoot and in shoes (Smith and Lord, in press). The difference in position of the ICFPs between the first and last shod test was less than 20 mm in the anteroposterior direction in all cases. This represents approximately 7% of the average male shoe length. Preliminary tests repeated during a session with a few volunteer amputees indicated that a similar reproducibility of anteroposterior ICFP location could be expected. The other measures were similarly repeatable to better than 7%.

Scattergrams of the normal population are shown in Figure 5. On average, the weight bearing is close to the expected 50% on each limb. ICFPs lie in the range of 32% to 51% of shoe length in the anteroposterior direction and 34% to 63% of shoe width in the mediolateral direction. In contrast, the loading of the above-knee amputees (Fig. 6, top) is approximately 40% of body weight on the prosthesis, and the range of locations of the ICFPs under the prosthetic foot are from 23% to 71% anteroposteriorly, and 37% to 58% mediolaterally. Results of below-knee amputees from the second group of patients are also presented (Fig. 6, bottom), showing a similar pattern of decreased loading and increased scatter of ICFP locations under the prosthetic foot.

The locations of the ICFPs averaged by group are shown in Table 1, further grouped by

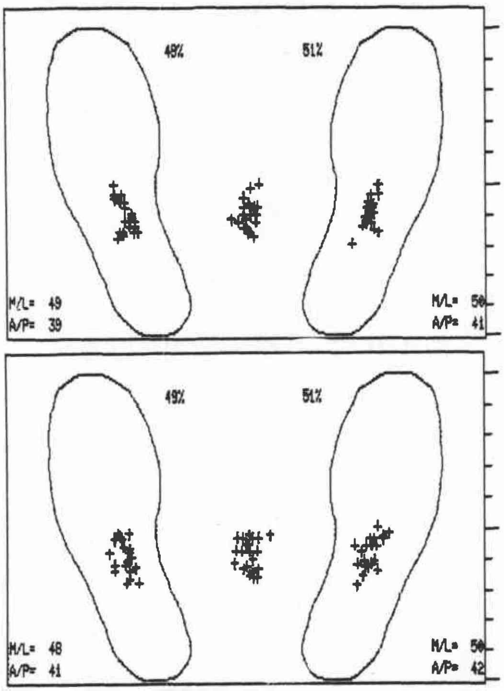

Fig. 5. Scattergrams of 42 non-amputee subjects, split randomly into two groups for clarity. For scattergrams the individual data is first normalized as shown in Figure 4, and then superimposed on a standard size footprint. The figures in the lower left and right hand corners are the average percentage positions of the left and right foot ICFPs.

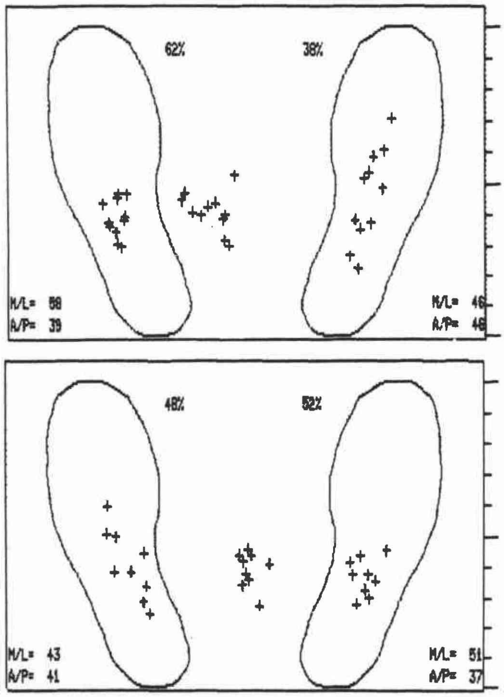

Fig. 6. Top, scattergram from 11 right above-knee amputees, wearing a variety of different limbs. Bottom, scattergram from 9 left below-knee amputees, wearing PTB prostheses with polypropylene sockets.

Table 1. Group averages of ICFP positions, expressed as a percentage of foot length and width. For amputees, the figures are given for left amputees, with those for right amputees in brackets. For the non- amputees the figures are averages for right and left natural limbs.

		Walking Training School A/K	Walking Training School B/K	Bioeng. Centre B/K	Non-amp. group
		n=12 (11)	10 (14)	9 (6)	42
Anteroposterior ICFP position (% from rear)	Prosthesis	36% (46%)	48% (45%)	41% (42%)	
	Natural limb	44% (39%)	37% (36%)	37% (33%)	41%
Mediolateral ICFP position (% from medial)	Prosthesis	46% (46%)	39% (42%)	43% (39%)	
	Natural limb	52% (58%)	54% (51%)	51% (51%)	49%

amputation level and side where relevant. Overall the measures vary considerably between the groups and for left and right amputees. Two points worthy of note are the anterior placement of the ICFP on the prosthetic side compared to the remaining natural limb for all B/K patients; and the medial location of the ICFP under all the prostheses with a lateral shift out on the natural side, compared to the non-amputee group.

Discussion

The study revealed some trends in the loading patterns of amputees although the results show a great deal of variability. The latter could be a reflection of the variability of the physiological condition of the patients, and the range of different prostheses worn by the various patients. However, it may reflect the fact that static alignment is not well standardized.

A constraint imposed by the DVF is the placement of the feet in standardized locations. The orientation shown in Figure 2 was tested for suitability for amputee use at the Walking Training School at the Roehampton Limb Fitting Centre. The stance was sometimes not the one that the amputee would normally assume in the rest position but was reported to be comfortable, except for bilateral amputees who needed a wider base of stance. Standardization of foot position has the advantage of removing one of the variables affecting standing balance, and aids comparisons between repeated measures on the same patient or between the individual and normative data.

The screen display and printouts refer to a standard foot outline, which is only matched in length to the patient's footwear. The position of the foot within the shoe is not estimated in any way, and variability in the toe space in different styles of shoes undoubtedly leads to ambiguity in the relation of the foot anatomy to the shoe outline. This is especially true in the case of high-heeled shoes, but these were not too common in the amputee population.

Repeated measures on a sample of both amputee and normal subjects have shown that reasonable repeatability of results can be expected provided that posture was controlled. Important points were voluntary maintenance of a constant pelvic orientation and head forward position.

Inspection of the individual results did not show any obvious correlations between the positions of the ICFPs and the type of limb worn. For example, above-knee patients with ischial seating sockets produced both the most anterior and posterior of the ICFP locations. It was suspected, but could not be proved within this study, that the anteriorly placed ICFPs were to be found on patients who made little use of the ischial seating. Further study on larger groups of patients is needed to correlate ICFP positions with such factors of socket fit, alignment, stump flexion etc.

It was found useful to express the location of the ICFP in terms of the percentage of foot length and width, in order to facilitate comparisons of patients with different foot sizes. As a result of the system adopted (Fig. 4) and the foot placement in toe-out, a saggital movement of the ICFP would lead to changes in both the percentage of foot length and width. Voluntary gross forward sway was typically accompanied by a reduction in percentage foot width position of the ICFP i.e. the ICFP moved medially.

Conclusion

Normative data on foot loading has been collected from amputees and normal subjects, and this has allowed differences between the two groups to be established. The chief findings are that amputees favour their natural limb with approximately 60% of bodyweight, and that the load is placed medially on the prosthesis with a compensatory lateral shift on the natural foot. Of particular significance is the large scatter in the anteroposterior location of ICFPs for amputees, which did not correlate clearly with the type of prosthesis and socket. It is possible that this variability was due in part to variations in the alignment of the limbs.

Whether static alignment expressed in terms of these foot loading parameters is of clinical significance is a question beyond the scope of this normative study, and remains to be established.

Acknowledgement

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