Forces Under the Hallux Valgus Foot Before and After Surgery

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Surgery for hallux valgus is intended to give long-term relief of pain and to correct the deformity of the forefoot. A good result gives unimpaired function of the foot in the patient's chosen shoes and a good cosmetic appearance. Over 100 surgical treatments for hallux valgus have been described. Although the failure rates of these procedures are usually well documented, the causes of failures are not well understood. This makes the selection of a treatment for a particular patient more difficult.

The results of operations for hallux valgus have been measured in terms of anatomic correction, the patient's return to normal activity, clinical tests of range of movement of the great toe, presence of callosities, and radiographic evidence of the conditions of the bones and joints.[2,3,6,13] Common causes of failures of operations have been metatarsalgia, march fractures and formation or worsening of callosities as evidence of overloading of the lesser metatarsals. This overloading has been associated with failure of the great toe to bear weight. Henry and Waugh[4] drew attention to the finding of Moynihan[8] that arthrodesis of the first metatarsophalangeal joint usually relieved or prevented metatarsalgia.

In this study we concentrated on measuring forefoot loadings in walking. The distribution of load on the forefoot was measured pre- and postoperatively in patients undergoing operation for hallux valgus (Keller's operation or first metatarsal shaft displacement osteotomy). Measurements were compared with those from 64 healthy subjects who gave no history of pain in their feet, or of foot treatment. Other comparisons were made with measurements of patients after arthroplasty of the first metatarsophalangeal joint with the Swanson implant.[11] This operation has been performed either for hallux valgus or for hallux rigidus.

MATERIALS AND METHODS

Patients walked at their own comfortable walking speed along a walkway 7 meters long.[9] About halfway along the walkway was a force plate 144 mm by 400 mm which was divided into bands each 12 mm by 400 mm (Fig. 1). The vertical force

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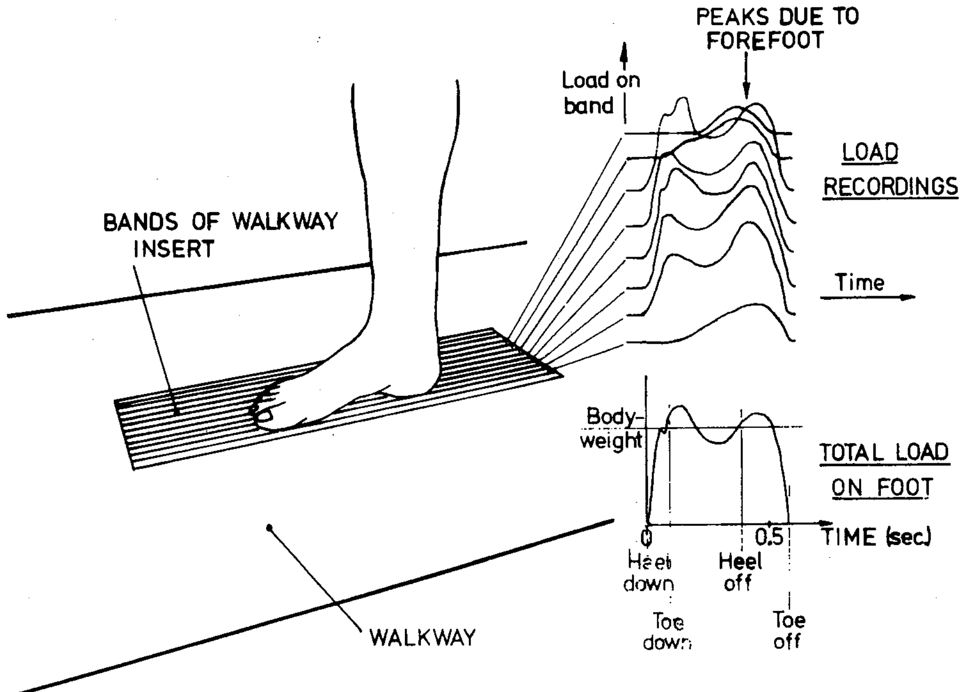

FIG. 1. The load measuring insert on the walkway in its longitudinal configuration. (Reprinted with permission from The Chiropodist [London] 32:6, 1977 [Fig. 1].)

on each band was measured by means of strain gauges. These gave signals which were amplified and recorded on a 12-channel U.V. recorder. Thus when a patient stepped on the force plate, a recording was obtained of the loads on bands of the foot each 12 mm wide (Fig. 2). The location of the force plate was disguised by means of a polyvinylchloride-covered cloth painted the same color as the walkway surface. The underside of this cloth was inked to give a footprint on a piece of paper placed between it and the force plate. This footprint allowed the recorded forces to be attributed to known areas of the foot. During preliminary walks a starting position at one end of the walkway was established for each patient so that a particular foot would land on the force plate.

The force plate could be turned through 90° in the walkway to give a recording of loads on bands of the foot either longitudinal or transverse to the direction of walking (Fig. 2). Of particular interest were the maximum loads imposed on the forefoot. The maximum loads on longitudinal bands under the forefoot were automatically selected (by specially built electronic circuits) and plotted in the form of a "peak loading diagram." This showed how the peak loads were distributed across the forefoot. Statistical comparisons were made between these diagrams by extracting a single parameter, the position of their center of area (centroid). This was expressed as a distance (ℓ) from the medial border of the forefoot and given as a proportion of its width (Fig. 2). This parameter can be considered as giving an effective midline of action of the forefoot, indicating the extent to which the medial side of the forefoot was loaded during walking.

The maximum load imposed on the toes was measured from the recordings made with the bands of the force plate transverse to the direction of walking. In this configuration the front 3 or 4 bands of the force plate carried most of the toes. (The fifth and sometimes the fourth toe rested on bands which also supported part of the ball of the foot.) The resulting measure of the maximum load on the toes was a useful indicator of the activity in the flexor musculature and of the loading imposed on the metatarsophalangeal joints in walking.

Since successive recordings from the same foot were not identical, several recordings were taken from each foot to give average values for each parameter. Three longitudinal and 2 transverse recordings were found to give adequately accurate values.[9]

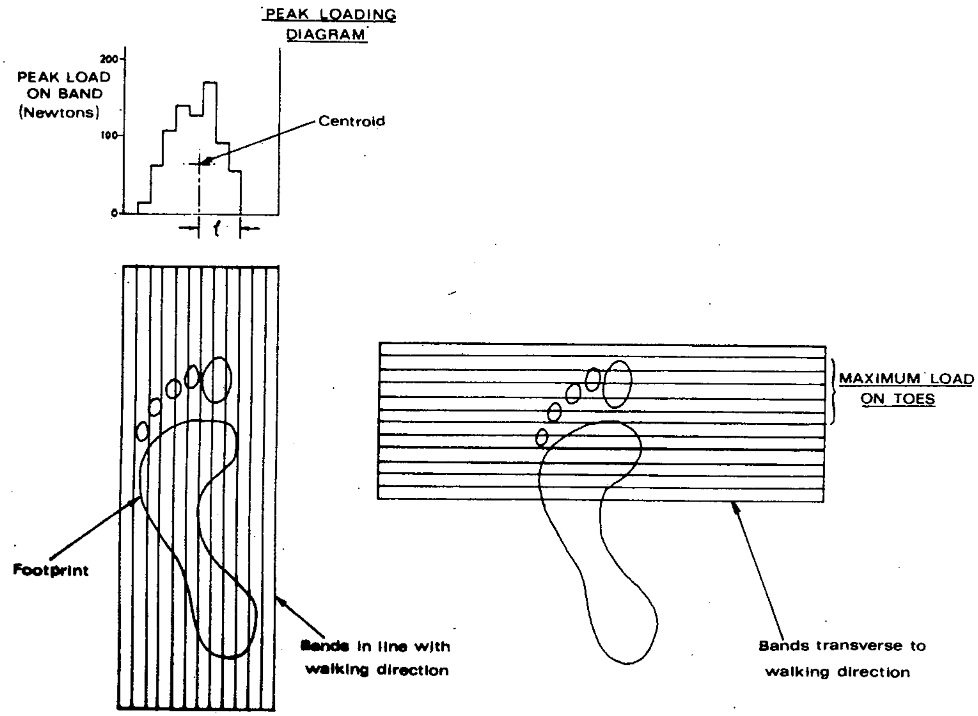

FIG. 2. The subdivided force plate in the walkway in its 2 configurations, showing how the parameters of loading on the forefoot were obtained.

Measurements from non-weight-bearing antero-posterior X-rays of the patients' feet were also made. The angle of the first metatarsophalangeal joint, the angle between the first and second metatarsals and the length of the first metatarsal were measured by the method of Lundberg and Sulja.[5]

GROUPS OF PATIENTS AND CONTROLS

Sixty-four healthy subjects of both sexes between 15 and 65 years of age were studied, giving results for 128 feet.

Five patients (7 feet) were studied between 10 months and 7 years after a modified Keller's procedure involving a Silastic joint spacer.[11] Six patients (6 feet) who had this operation for hallux rigidus were also studied. This provided an interesting comparison, since the deformities of the foot seen in hallux valgus were not apparent in these feet.

Fifteen patients between 12 and 35 years of age (27 feet) were studied before an oblique displacement osteotomy of the first metatarsal. This was performed as described by Wilson,[12] except that a metal screw was used to fix the divided sections of the bone in a corrected position. Ten patients (18 feet) returned between 21 and 35 weeks postoperatively for the measurements to be repeated.

Thirteen patients (22 feet) were studied before and after Keller's operation. The follow-up was between 14 and 29 weeks after operation. Preliminary results of the investigation have already been published,[10] and are included along with new results for comparison. These patients were between 51 and 82 years of age, except for one boy who was 16. The patients were considered to be representative of those treated by Keller's operation. About one third of the proximal phalanx was removed at surgery. Postoperative immobilization was by dressings only; wire fixation was not used.

RESULTS

HEALTHY FEET

Among the 64 healthy subjects there were roughly equal numbers of men and women, and a wide range of ages. There was considerable variability in the measurements of

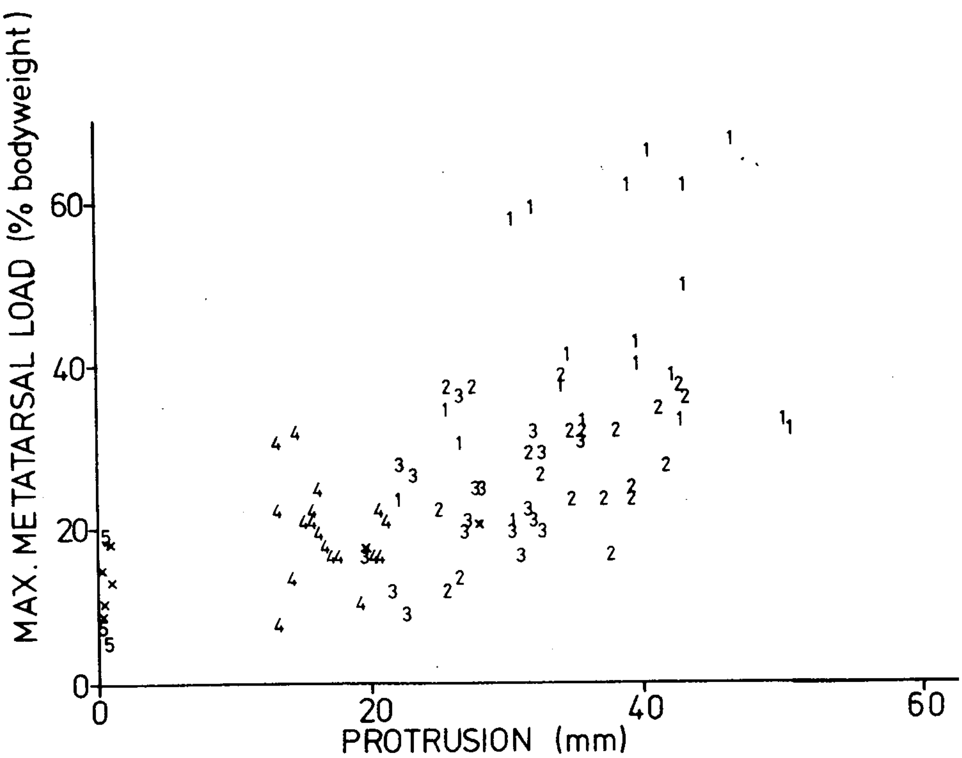

FIG. 3. The peak load on each ray plotted against its relative protrusion beyond a line through the fifth metatarsal head and perpendicular to the direction of walking. The graph was drawn from results for 10 healthy subjects for whom a-p X-rays were available. (1—1st ray *etc.*, x—2 superimposed points.)

loading on the foot, so before comparisons were made with the patients' feet, an attempt was made to explain this variability. However, the measurements used here (maximum toe load, and the position of the centroid of the "peak loading diagram") were apparently not related to the age, weight, height, sex, or walking speed of the subject, nor to combinations of these such as bodyweight expressed as a multiple of the average weight of a man or woman of the same height.

The "toe-out" angle was also measured by taking a line through points half way across the heel and the forefoot, and measuring its angle to the direction of walking. This did not appear to be related to the measurements of loading on the forefoot, except when combined with measurements of the relative protrusions of the metatarsal heads on a-p X-rays. Among the 10 subjects for whom X-rays were available, there was evidence that the share of load carried by the first and second metatarsal heads was related to the protrusions of these bones measured relative to the direction of walking (Fig. 3). This finding was just statistically significant ($p < 5\%$).

The results from the normal subjects showed that a large proportion of bodyweight is imposed on the toes in walking (around 40%). The peak of loading is of short duration, and occurs just before the foot leaves the ground. This load results from activity in the toe flexor muscles, and depends on the toe joints being able to sustain the high reaction forces which are developed. The results also demonstrated the

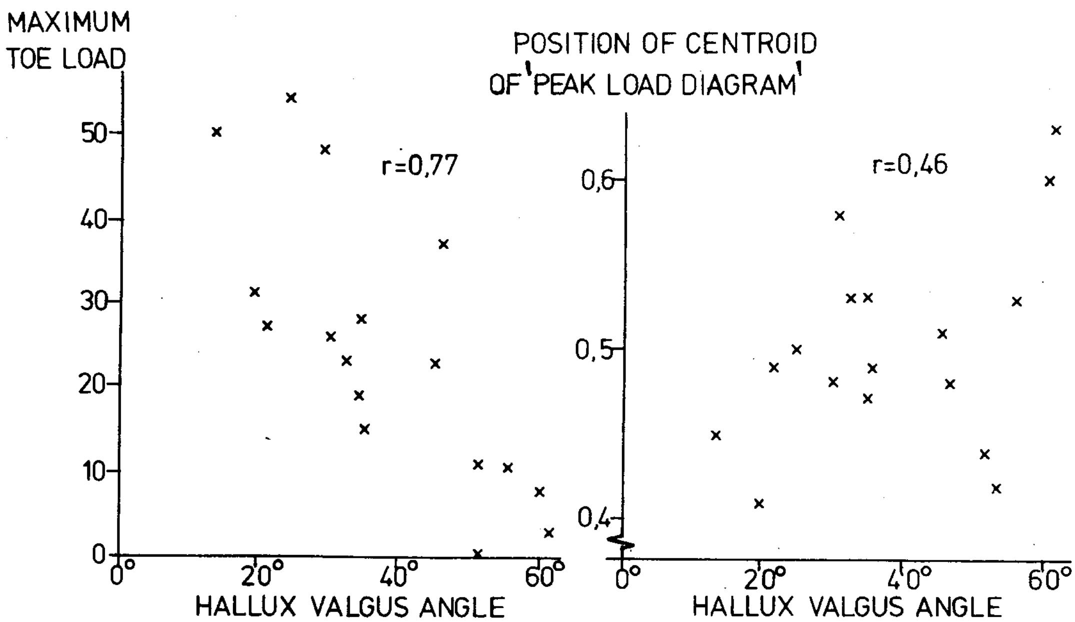

FIG. 4. Correlations found between 2 of the parameters of loading on the forefoot with the angle of valgus deformity among patients before Keller's operation. Maximum toe load is expressed as a percentage of bodyweight, and the "peak loading diagram" centroid was measured from the medial side of the foot. Only the correlation with the maximum toe load is statistically significant.

importance of the medial side of the forefoot, which nearly always carries the greater loads in the healthy foot, as shown by the position of the centroid of the "peak loading diagram."

Preoperative Measurements

The older patients with more severe hallux valgus who were treated by Keller's operation were found to have abnormal feet preoperatively. They imposed significantly lower loads on the toes in walking than the "normal" group of subjects, and they carried more load on the lateral as opposed to the medial side of the forefoot (Table 1). Both abnormalities correlated with the degree of the deformity, measured as the angle between the first metatarsal shaft and its proximal phalanx on antero-posterior X-rays (Fig. 4).

The younger patients with less severe hallux valgus (who were treated by the osteotomy) had these abnormalities to a lesser extent (see Table 1). No significant correlations were found relating the loads on these patients' feet to skeletal measurements from X-rays.

Postoperative Measurements

The abnormalities of loading seen in the feet with hallux valgus preoperatively were generally found to be increased after both Keller's operation and the osteotomy. Among the 40 feet studied pre- and postoperatively there were only 2 instances of an increase in the maximum toe load, and 10 instances of a shift of load towards the medial side of the forefoot. The patients who were treated with the Silastic implant provided an interesting comparison. Among those treated for hallux valgus there was some evidence that the loading on their feet was less abnormal compared with the conventional Keller's procedure, although this finding was not statistically significant in the

TABLE 1. Parameters of Loading on the Forefoot in Walking for Groups of Patients and Controls

	Preoperative						Postoperative					
	Maximum Load on Toes			*Position of Centroid of "Peak Loading Diagram" from Medial Side of Foot*			*Maximum Load on Toes*			*Position of Centroid of "Peak Loading Diagram" from Medial Side of Foot*		
	Min.	*Mean*	*Max.*	*Min.*	*Mean*	*Max.*	*Min.*	*Mean*	*Max.*	*Min.*	*Mean*	*Max.*
Control group	15.0	37.06	61.0	0.348	0.463	0.594						
Swanson procedure for hallux valgus							5.0	15.93**	31.0	0.345	0.472	0.544
Swanson procedure for hallux rigidus							8.0	30.57	60.0	0.450	0.511*	0.561
First metatarsal osteotomy	15.0	32.02*	52.0	0.381	0.466	0.580	7.0	16.75**‡	30.0	0.413**	0.515‡	0.588
Keller's operation for hallux valgus	1.0	23.6 **	54.0	0.369	0.486	0.635	1.0	15.0 **††	40.0	0.339**	0.509†	0.609

* Significantly different from "Control" group ($p<5\%$)
** Highly significantly different from "Control" group ($p<1\%$)
† Significant postoperative change in group ($p<5\%$)
‡ Highly significant postoperative change in group ($p<1\%$)

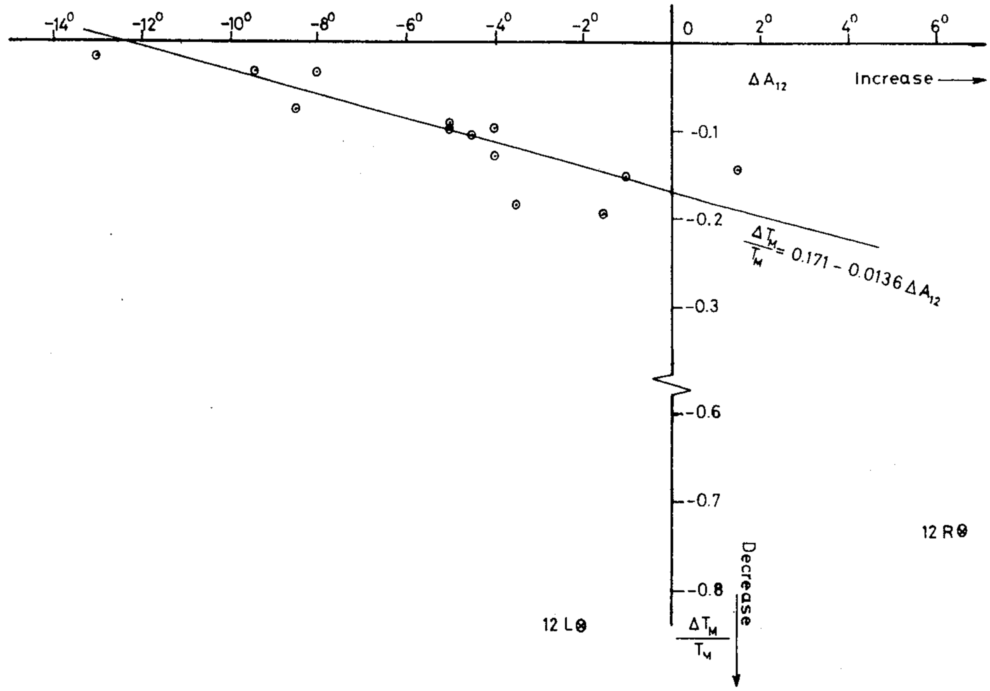

FIG. 5. The relationship (omitting patient 12) found between the proportional change in the maximum toe load (T_M) and the change in the intermetatarsal angle (A_{12}) among patients after first metatarsal osteotomy. Patient 12 had pain and inflammation on both forefeet when seen 6 months after surgery, and was the one patient in the group who was dissatisfied with the operation.

small number of patients studied here. However, the patients who were treated with the implant for hallux rigidus were found to have more normal foot function (see Table 1).

Changes in the loadings imposed on the forefeet of these patients might be attributed to destruction of the first metatarsophalangeal joint and shortening of the toe (in the case of Keller's operation), to shortening of the first metatarsal (in the case of the osteotomy) or to failure of the operation to correct the coexisting deformity—metatarsus primus varus. However, no correlations were found with measurements from X-rays to explain the changes in loading on the forefoot. The only significant correlation (among the osteotomy patients) was between the change of load on the toes and the reduction in the angle between the first and second metatarsals brought about by the operation ($r = 0.87$, $p < 2\%$). A large reduction in the angle between the first and second metatarsals produced the smallest decrease in the load on the toes (Fig. 5).

Most of the operations were successful in relieving painful symptoms. One patient in the osteotomy group was a notable exception. When she returned 5 months postoperatively for measurements to be repeated, she had pain and inflammation under the lateral metatarsal heads of both feet. Recordings from the walkway showed a marked fall in the peak toe load (Fig. 5), and above average changes in the "peak loading diagram" indicating a shift of load to the lateral side of the forefoot. Union of the first metatarsal after surgery had resulted in the great toe being slightly dorsiflexed in the rest position, and there was an increase in the intermetatarsal angle on the one side, with only a small decrease in the other foot.

DISCUSSION

Results from the healthy feet demonstrated the high loadings which are imposed on the toes in walking, and a concentration of load on the medial side of the forefoot. (A centroid of the "peak loading diagram" in the medial half of the forefoot demonstrated that the highest loads were on the first and second metatarsals, which occupy the medial half of the forefoot.) However, it was usual to find that the lesser metatarsals, including the second, were carrying load out of proportion to their size. The finding that the load on the metatarsal heads is related to their relative protrusions supports the suggestion of Morton[7] and is in agreement with the measurements of Barnett.[1] However, these writers did not take into account the angle made by the foot with the direction of walking. This factor was found to be important in the relationship we found.

The feet with hallux valgus were loaded abnormally, to an extent dependent on the degree of the deformity. The increases in the abnormalities after surgery are difficult to explain, but are apparently not a reaction to pain (as the preoperative abnormalities might have been) since the patients had relief of pain after treatment.

Loading of the great toe in walking depends upon activity of the flexor muscles, and on the ability of the joints of the toe to sustain the resulting reactions. The flexor activity is evidently reduced in established hallux valgus, and does not recover following treatment whether by Keller's operation or with the Silastic implant: it is in fact further reduced postoperatively. The relative lengthening of the flexor tendons which results from shortening of the toe in both operations may be partly responsible. In contrast, the Silastic implant carried near normal loads in the patients treated for hallux rigidus, but did not take on this function in patients treated for hallux valgus. In light of these findings, it would be interesting to find whether the pseudoarthrosis formed after the treatment of hallux rigidus by the conventional Keller's procedure also carries the high loads characteristic of healthy feet. Although the treatment of hallux valgus by the first metatarsal osteotomy left a relatively intact joint, there was no improvement in the load-carrying capacity of the first metatarsal, possibly because the shortening of the metatarsal places it in a less favorable position to carry load, according to the idea of Morton[7] that the more forward the position of the metatarsal head, the higher its share of the load.

No trends were found relating the postoperative changes to follow-up time. This suggests that the measurements had been repeated after an adequate time for healing, and for the patients to become accustomed to the effects of the surgery. In a study of patients treated by Keller's operation and by first metatarsal osteotomy for hallux valgus, Bonney and McNab[2] found that the pattern of success and failure had become established within one year, although results were generally not so good when the follow-up was after more than one year.

Our finding of the increase of the load on the lateral side of the forefoot after surgery suggests that these patients were at risk for metatarsalgia. It appears from our results that repair and realignment of the first metatarsophalangeal joint is not sufficient to restore normal forefoot function to patients with hallux valgus. It seems that while it may be essential to realign the first metatarsal, this bone should not be shortened and must be kept in a good position relative to the other metatarsal heads in order to carry load. Such measures will restore good foot function and shape, and they are more likely to produce a normal distribution of load on the sole of the foot.

Hallux valgus is associated with a significant reduction in the loading imposed on the toes and the medial side of the forefoot in walking, compared with healthy feet. This abnormality is related to the degree of the deformity, and was found in both a group of adolescent patients and an older group of patients.

Increases in the abnormalities of forefoot loading were found when patients were seen around 6 months after either Keller's operation or a first metatarsal wedge osteotomy. In most cases it was not possible to relate these changes to changes in the geometry of the foot. However, in the case of the osteotomy a large reduction in the angle between the first and second metatarsals was associated with the smallest reductions in the loading on the toes.

There is a large variability in the distribution of loading on healthy feet. Evidence was found that the distribution of load between the first and second metatarsals is dependent on their relative protrusions measured against the direction of walking. Thus a prominent metatarsal head is more likely to receive high loads in walking.

The Swanson design Silastic implant used in a modified Keller's operation is not subjected to very high loadings when used to treat hallux valgus. When it is used for hallux rigidus, the great toe, and hence the metatarsophalangeal joint and implant, carry near normal loadings.

SUMMARY

Abnormalities in the hallux valgus foot and changes after surgery were investigated by measuring the distribution of load on the foot in walking. Hallux valgus was associated with reduced load imposed on the toes, and on the medial side of the forefoot, compared with a large sample of healthy feet. Abnormalities correlated with the degree of the deformity. Both Keller's operation and a wedge displacement osteotomy of the first metatarsal not only failed to restore normal loading but increased the abnormalities of loading seen preoperatively. A large decrease in the angle between first and second metatarsals as a result of surgery minimized this increase. A silastic arthroplasty did not carry high loads when used to treat hallux valgus, but near normal loads were imposed on it when used for hallux rigidus. Considerable variability was found in the loading distribution on the healthy feet. The distribution between first and second metatarsal heads was partially dependent upon their protrusions, relative to the direction of walking. The changes in the relationships between the loadings on the forefoot and skeletal shape in response to surgical operations are important for our understanding of treatment of the hallux valgus foot.

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REFERENCES

1. Barnett, C. H.: The phases of human gait, Lancet 2:617, 1956.
2. Bonney, F. and McNab, I.: Hallux valgus and hallux rigidus. A critical survey of operative results, J. Bone Joint Surg. 34B:366, 1952.
3. Cleveland, M. and Winant, E. M.: An end result study of the Keller operation, J. Bone Joint Surg. 32A:163, 1950.
4. Henry, A. P. J. and Waugh, W.: The use of footprints in assessing the results of operations for hallux valgus, J. Bone Joint Surg. 57B:478, 1975.
5. Lundberg, B. J. and Sulja, T.: Skeletal parameters in the hallux valgus foot, Acta Orthop. Scand. 43:576, 1972.
6. McBride, E. D.: A conservative operation for "bunions." End result and refinement of technique, JAMA 105:1164, 1935.
7. Morton, D. J.: The Human Foot, Chapter 22, New York, Columbia University Press, 1935.
8. Moynihan, F. J.: Arthrodesis of the metatarsophalangeal joint of the great toe, J. Bone Joint Surg. 49B:544, 1967.
9. Stokes, I. A. F., Stott, J. R. R. and Hutton, W. C.: Force distributions under the foot—a dynamic measuring system, Biomed. Eng. 9:140, 1974.
10. ———, Hutton, W. C. and Evans, M. J.: The effects of hallux valgus and Keller's operation on the load-bearing function of the foot during walking, Acta Orthop. Belg. 41:695, 1975.
11. Swanson, A. B.: Implant arthroplasty for the great toe, Clin. Orthop. 85:75, 1972.
12. Wilson, J. N.: Oblique displacement osteotomy for hallux valgus, J. Bone Joint Surg. 45B:552, 1963.
13. Wrighton, J. D.: A ten year review of Keller's operation. Review of Keller's operation at the Princess Elizabeth Orthopaedic Hospital, Exeter, Clin. Orthop. 89:207, 1972.