Prosthetics and Orthotics International, 1991, 15, 11–17

Clinical trial of a computer-aided system for orthopaedic shoe upper design

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Abstract
A trial has been conducted to produce the uppers for orthopaedic shoes using an existing commercial computer-aided design system. The aims of the trial were to confirm that a CAD system developed for the volume shoe trade (Shoemaster from Clarks Shoes) could be used for the upper design of orthopaedic shoes and to assess the contribution of professional shoe design on cosmesis and acceptability of these shoes. A small number of adult diabetic patients and children with foot deformities were selected, all of who had previously been prescribed and issued with special shoes. The existing lasts for these patients were digitised, and new styles developed on the CAD system over a 3D image of the last. Pattern pieces were cut automatically and the uppers closed. Lasting was done as normal at the two collaborating orthopaedic companies and the shoes supplied to the patients. The CAD system proved successful in coping with orthopaedic last shapes and shoe requirements. Professional design produced fashionable and cosmetically-pleasing styles within the constraints imposed by the underlying medical conditions.

Introduction

In orthopaedic footwear manufacture, advanced technology is very much less evident than in the volume shoe trade where it has been introduced widely over the past decade (Flutter, 1983). The introduction of computer-based techniques is however inevitable. Machining of foot shapes from digital information is demonstrated in Duncan and Mair (1983). Shape management technology for the generation and manipulation of last shapes is reported by Saunders et al. (1989). Investigations of surface modelling techniques for computer-representation of lasts have been conducted by Lord and Travis (1990). Staats and Kreichbaum (1989) have developed a system to design shoe inserts, in which the contours for a customised shoe insert are designed from the digitised information taken from a foot impression in a foam block. Several commercial companies claim to be using advanced technology in production. General issues raised by computer-aided design techniques are discussed in Lord and Jones (1989).

An ultimate goal for the application of advanced technology must be to automate the entire design process, from live shape scanning of the foot through to production of the last, the shoe upper and any shoe insert required. One stage in this chain, computer-aided design of the uppers, is already well developed for the volume shoe trade. Several commercial systems are available, and their use is being suggested for the orthopaedic industry. However doubt must exist initially about the suitability of these systems for this application.

The requirements for a CAD system in bespoke orthopaedic work are quite different from those in the volume trade. A range of lasts of abnormal shapes is encountered for patients with foot problems, and a question must be

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raised as to whether the commercial CAD system is sufficiently versatile to encompass this range. A second question can be asked about the benefits of using the CAD system. In the volume trade, the CAD system allows for rapid response to fashion, accurate pattern generation, and grading for size ranges. Of these, only accuracy of pattern generation initially appears to be of relevance to orthopaedic footwear, although CAD can be expected to make contributions to cosmesis through the availability of a range of styles on the system library.

The trial described below was conducted on the Shoemaster system* which has specially good capabilities for three-dimensional work. The trial was not intended to be a demonstration of how such a system might work in service. Rather, the more directed aims of the trial were to:

- confirm that an existing CAD system for shoe uppers is technically able to cope with orthopaedic shoe requirements, and
- assess the impact of professional design to produce fashionable and cosmetically-pleasing styles within the constraints imposed by the underlying medical conditions.

Procedure

Two research shoe designers from Shoemaster first visited the diabetic foot clinic at King's College Hospital and discussed with clinicians and patients their requirements for orthopaedic shoes. Constraints on style were that the final shoes would be suitable for the medical condition. The shoes would be mostly outdoor walking shoes with adequate instep fastening. The senior orthotist from each of the collaborating orthopaedic shoe companies (L.S.B. Orthopaedics Ltd. and J. C. Peacock & Sons Ltd.) selected subjects for the trial within the following constraints:-

a. Subjects should recently have been issued successfully with special shoes for which recent lasts were available. For children, if there had been growth since the last pair of shoes, the feet should be remeasured and the existing lasts modified accordingly.
b. Patients selected for the trial should have the ability to help in the design of the new shoes and be well enough to attend the clinic for consultation and fittings.
c. Any internal orthoses or modifications to the shoes to accommodate external orthoses could be included.
d. L.S.B. Orthopaedics Ltd. were asked to identify adult patients with diabetic foot problems, and J. C. Peacock & Sons Ltd. were asked to identify children with foot problems typical of spina bifida.

The patients' lasts were sent for digitisation and the surface of each last was captured with a stylus digitiser. Any cradle or insert allowance was added to the last before digitisation. Lasts which had previously been modified with soft additions or which had fairly rough exteriors, thus making their surfaces unsuitable for the stylus, were vacuum draped with thin thermoplastic before application of the digitising probe.

The shoe designers brought the CAD system to the patients at the two clinics, where the designer and patient together sketched the shoe style on-screen over the three-dimensional view of one of their own lasts (Fig. 1a). The orthotist and orthopaedic last-maker were on hand for consultation. The preliminary designs produced on the computer in the clinic were later completed for that shoe. The final design was then mapped over the last shape for the other foot and the two shoes harmonised as a pair (Fig. 1b). For example, where there was one short foot, the shoe styling lines were managed in such a way as to make a proportioned *pair* of shoes.

After the design was completed, the 2D pattern pieces corresponding to the 3D image were engineered on-screen to include the correct cutting allowances etc. Leather was cut by computer controlled machinery and subsequent closing was performed in the factory. This included the use of automated decorative punching and stitching to achieve the special effects called for in the design. The closed uppers (Fig. 1c), together with the original lasts were dispatched to the orthopaedic shoe makers where the shoes were lasted and finished (Fig. 1d). The children's shoes were trial fitted before final finishing because of the possibility of growth. Shoes were issued to the patients with care being taken to assess fit and solicit reactions to cosmesis. Follow-up assessments were made to check that

*Shoemaster, Clarks Shoes, 40 High Street, Somerset, England BA16 0YA.

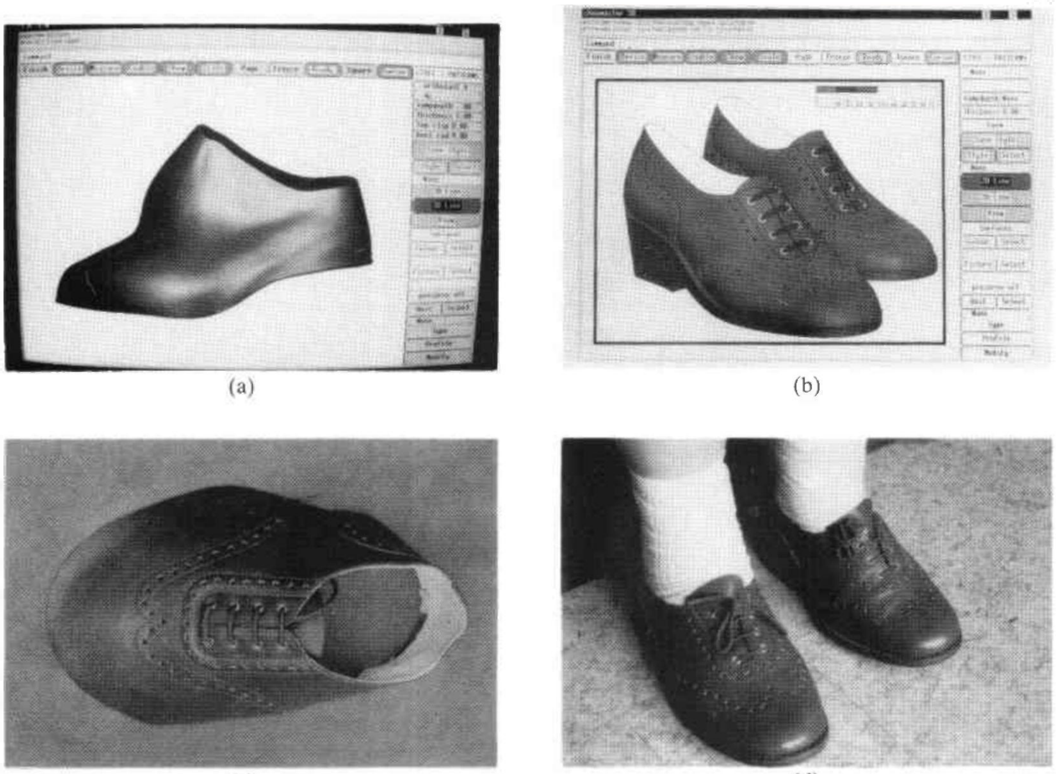

Fig. 1. Example of a design process (a) screen view of an orthopaedic last. (b) completed design as a harmonised pair. (c) closed uppers (d) completed shoes.

the patient had been caused no problem by the footwear, for fit after wear, to seek the subjects subjective views on style and fit and to observe the state of the shoes after they had been worn.

Results and observations

The list of subjects, their background medical condition, the condition of their feet, and the CAD shoes made for them is shown in Table 1. The six children typically had very deformed feet with bulky midfoot areas, mostly resulting from spina bifida. In two cases orthoses extending above the ankle were worn. The four adult subjects were all diabetic; two pairs of feet were intact but prone to lesions, one man had undergone a forefoot amputation, and another lady had very sensitive and swollen feet following a recent operation since which she had not worn shoes at all.

All of the six children were successfully fitted. Both children and parents were very pleased with the 'high-street' appearance of the shoes. Three of the four adults were happy with the shoes provided. The fit was poor for the fourth adult, mostly due to lack of communication about the depth of special insole to be provided. This prevented the shoes being issued, but the patient was pleased with the style and at her request another attempt will be made to obtain a fit when a small lesion noted at the fitting visit has healed.

There were no major obstacles in the design or lasting process although several points which require attention emerged during consultation between the coordinators, the orthopaedic companies and the staff at Shoemaster. Detailed observations at the various stages of the process are given below.

The design process

Patients generally came with a clear idea of what they would like in broad terms of style and functional requirements. Two of the boys wanted their new shoes to look like trainers and

Table 1. Details of the patients on the trial, and the shoe styles developed for these patients

Subject	Sex	Age	Medical condition	Description of feet	Type of CAD shoes made
EMS	Female	75 yrs	Diabetes NIDDM (7 yrs)	L large dorsal tuberosity at 1st MP joint.	Yellow Derby style lace up.
WW	Female	69 yrs	Diabetes IDDM (33 yrs)	Neuropathy, unsteady gait.	Red lace ups. D buckle and U shaped closure.
KH	Female	64 yrs	Diabetes/oedema NIDDM (recent)	Surgery for equinus feet Buckled toes Hypersensitive feet.	Lace up. Reddish/brown with fancy laces.
DW	Male	52 yrs	Diabetes/ischaemia IDDM (10 yrs)	Amputation R toes 1–5 Amputation L 1st toe.	Black lace-ups.
DH	Female	14 yrs	Congenital left club foot with short leg and foot.	Equinus left foot, history of surgery.	Brown brogues with subject's punch design.
AH	Male	14 yrs	Congenital club feet.	History of surgery. Pronated feet.	Trainer type. Blue and yellow.
CE	Female	10 yrs	Congenital spina bifida, neuropathy and muscle wasting.	Needs to accommodate thermoplastic AFOs. Pronated feet.	Clarks "Hectik" purple suede shoes – T bar and buckle.
AG	Male	9 yrs	Congenital left club foot.	History of surgery, short left foot with varus forefoot.	Grey Clarks "Hardware" with yellow lace.
MP	Female	6 yrs	Congenital equinus feet.	Recent surgery, pronated and abducted feet.	Patent purple shoes with flower applique.
RP	Male	3 yrs	Congenital lymphoedema (Milroy's disease).	Feet very oedematous but with normal bone structure.	Black and white trainer type shoes.

one of them had come with a previously prepared coloured diagram (Fig. 2). The other children were encouraged to select from current Clarks styles which were displayed on example shoes. Three did this (Fig. 3). The designers brought a selection of patterned laces, fasteners, buckles etc. all of which could be used on the final shoes. They also suggested other features, such as a soft top edge used for the pair of laced walking shoes requested by one lady (Fig. 4). This proved to be a particularly beneficial exercise as the subjects had not previously considered the possibilities for these important styling additions.

The time taken with the designer and patient together for sketching one of the proposed shoes onto the computerised last shape was in the order of an hour to an hour and a half. For current Clarks styles, the pattern was called up from the library and mapped over the individual's last, which took far less time to achieve. The designers needed subsequent additional time to tidy the design, to map it over the other last and except for the existing styles, to do the essential pattern engineering (add lasting allowances etc.). The balancing of

Fig. 2. The design brought in as a free-hand sketch and magazine cut-out, and the corresponding design on the CAD system.

Fig. 3. A Clarks design was mapped over the orthopaedic lasts to produce these custom shoes.

Fig. 4. An example of a screen view and the completed shoe, showing a soft-top feature on a lady's walking shoe.

left and right shoe for odd-sized feet took some time.

Lasting the shoes

The orthopaedic companies undertook lasting the closed uppers and finishing the shoes which had been produced from large ranges of leathers available to Clarks. The special requirements and the working with some of these unusual leathers such as patent or soft leather did not present great problems although some of the standard orthopaedic procedures such as soaking puffs and stiffners and coating the lasts with talc were found not to be suitable. Adults' shoes made from fairly 'solid' leather were machine lasted and the soft leather adults' shoes and the children's shoes were hand lasted.

The lasting allowances were found to be even but could have been slightly greater to allow for the orthopaedic manufacturing processes. The uppers fitted snugly to the lasts indicating that the patterns were accurate. The linings were slightly short and had to be "pulled" to make sure they reached around the bottom of the last.

The design of the soles on the computer was an 'artists impression' but in reality, the orthopaedic shoemaker used his discretion and skill in finishing the shoes to give a balanced appearance and correct heel heights etc. This provided in general to be a successful technique.

Fitting and review of the shoes

No special problems with fit or wear related to the CAD system were noted. Very positive comments on cosmesis related to the *normality* of the appearance, whether for an original design or for the three cases where a Clarks style was adopted. The balancing of odd-sized shoes for some of the children was particularly successful, it being hard to determine on first inspection the larger foot.

In several cases the shoes were found on review to be wearing rather better than those normally supplied, and in one notable case, the shoes had withstood a period of three times normal without requiring the usual frequent toe-capping. This did not correlate with a heavier weight of leather being used.

On the whole, the CAD designs had more stitching than would normally be used. Some of the stitching was decorative. Care was taken to avoid stitching in locations which could be problematic, and this did not give rise to any problems of abrasion. Indeed the construction with more pieces contributed to the better holding of the shape over the forefoot, where the orthopaedic shoes were prone to crease on the uppers above the metatarsal break (Fig. 5).

Discussion

This trial has brought together the expertise from two quite different manufacturers of shoes in order to transfer knowledge both of new advanced techniques and of the cosmetic styling so readily developed on the system. In order to make use of the CAD system and the expertise of the designers, it was necessary for the orthopaedic side to appraise the fashion designers of the medical and functional constraints on style. Also the pattern engineers needed to appreciate the methods of lasting which would be employed, quite different for the one-off orthopaedic shoe than for the fashion shoe. This exercise in communication has produced very positive results.

Fig. 5. Comparison of the conventional orthopaedic shoe and trial shoe worn for a similar length of time. The trial shoe has held its shape better, which is thought to be a function of the styling.

In a service situation, a CAD system would not be efficiently employed in the manner of this trial. However this trial confirms that an existing CAD shoe upper system has the technical capability to design patterns for at least some categories of orthopaedic shoes. The system generated patterns which were a good fit to the orthopaedic lasts. Minor problems such as that which arose with lining allowances can easily be rectified in future. The system could also benefit from minor developments for orthopaedic use, for example to expedite balancing. These will be discussed fully in a separate detailed evaluation of the technical factors.

In the investigation of the contribution of artistic design into surgical shoes for the improvement of cosmesis it was noted how up-to-date fashion in colour, materials, patterns of stitchings and punchings and in the style of accessories such as lacings, fastenings and eyelets etc may be incorporated into special shoes. This was shared by both sexes. Several children wished to copy their friends in having trainer-style footwear, which is accepted by most state schools for everyday wear. The design input was not able to influence shape of the shoes which was pre-determined by the orthopaedic lasts. However, it was possible to use design style lines and other features to minimise abnormalities in shape and to suggest an alteration in the perceived appearance of the finished orthopaedic shoes. Good design also minimised the perceived differences between odd-sized feet.

The three cases where current Clarks designs were used are particularly significant. The psychological impact for children to have the same style as those available to their peer groups cannot be overestimated. This procedure of using a library style is the obvious mode of operation for a service scenario, and the CAD system showed that it was entirely feasible to map such a style over an individual last within a reasonable time scale and with good results in terms of the pattern pieces which were generated, attributable to the CAD system for these patients, who were typical of two major groups of consumers of orthopaedic shoes. Although none of the deformities were gross — such as would absolutely necessitate the taking of a cast — these feet could not be accommodated within normal shoes without problems. Extension of the findings to cover other major consumer groups, e.g. patients with arthritic conditions, is not automatic, although the team could see no technical reasons why this should not be possible. The functional requirements and medical problems should first be investigated to give the designers direction for possible styles, but the last shapes would not be grossly different to those already encountered.

It was noted by the orthopaedic shoemakers and by the patients that the leathers used in this trial were of a very high standard and had a large range of colours and textures. This is due to the large quantities a volume manufacturer is able to buy, and is one of the benefits which might be available from more centralised production of shoe uppers than is presently common in the UK. This incidental observation from the trial has cost-implications related to repair and replacement for the active patient.

Conclusion

This trial has indicated that the computer-aided design system tested has the capability to design for a range of orthopaedic shoe uppers. The system enabled current high-street styles to be duplicated for some patients, and for others very acceptable original styles were designed.

Acknowledgements

This project was partly supported by a development grant from the British Diabetic Association with medical collaboration from Dr. M. E. Edmonds of King's College Hospital, London. We acknowledge the considerable contributions of design engineers P. J. Smith, H. Bishop and E. Duffey and B. Holley of Clarks Shoes Ltd, B. Holback and S. Lloyd of L.S.B Orthopaedics Ltd. and C. Peacock and P. Charlton of J. C. Peacock and Son Ltd. (Director and Senior Orthotist of each company respectively). We particularly thank the Directors of Clarks Shoes for permission to use the Clarks styles.

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