3 MATERIALS AND METHODS

3.1. Introduction

This study essentially consisted of three parts. First, a preliminary study undertook to find or develop a suitable and affordable instrument or method of 3-D input. This was required to obtain morphometric measurements and, in addition, to capture the topography of the weight bearing foot for future research and development of contoured foot beds for industry. Second, a multi-ethnic metric study was conducted, utilising the 3-D method developed during part one of the study. The metric study provided the means to compare specific measurements from a UK size 4 last and the corresponding foot measurements from a sampled population of size 4 foot length, in order to determine what percentage of women would fit the footwear derived from such a last. The third part of the study was a scaleable measurement comparison. In this final part of the study, a comparison of mean values was performed between data from participants of all sizes scaled down arithmetically to UK size 4 length, and data from actual size 4 participants. This was done in order to explore whether the set of mean measurements for size 4, occurring as it does near the lower end of the size range, was valid to be used to grade linear proportional measurements for participants whose sizes ranged from size 3 to size 9 in the South African female population.

3.2 Part one: Development of a 3-D method

Industry required the study to find a method that would capture the natural foot contours under a weight bearing foot, rather than measure the foot on a totally flat surface. Industry asked for this data to be a requirement of the study so as to pursue future developments in contoured foot bed technology. The ability to capture curves was the main reason why 3-D data input was needed, as opposed to conventional 2-D anthropometric methods that only capture linear measurements.

A basic understanding of 3-D principles is needed before it is possible to evaluate the challenge embodied in industry's request to develop a new approach within the 3-D realm.

3.2.1 3-D Measurement technology

The basic principle behind measurement and visualization in 3-D is to create a 3-D mesh from a real object. The mesh is composed of polygons linking points in space, each point distinct from the next in terms of its *x*, *y* and *z* co-ordinates. A grouping of these points will form a point cloud (Figure 3.1). Landmarks are specific *x*, *y* and *z* coordinates or points in space that can be placed on 3-D objects for the purposes of calculating the distances between such points. Some measurement systems provide for landmark data only, others for point cloud data. Point cloud data is required for one-to-one modeling of actual curves (Appendix I).

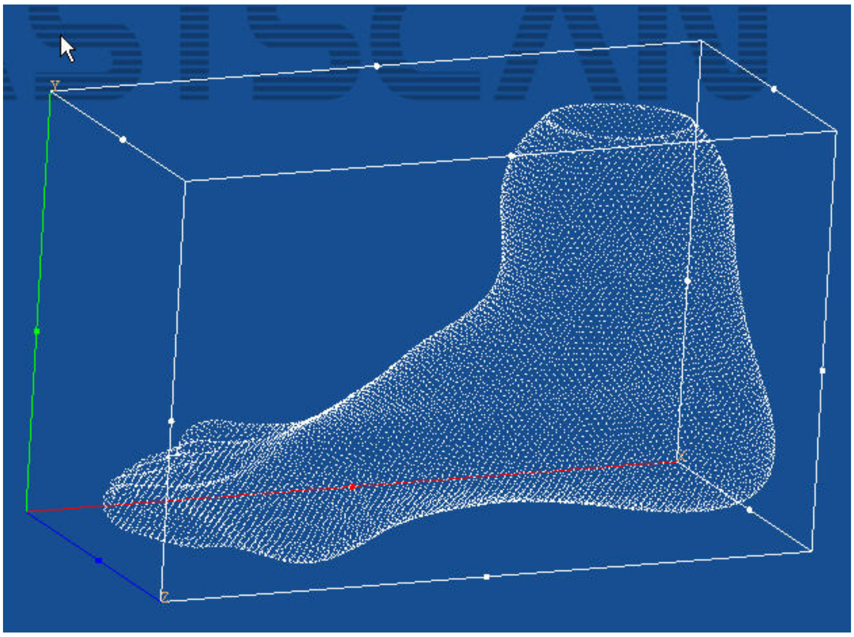

Figure 3.1 Point cloud data of a foot as measured in the study

Bearing in mind industry's future needs for contour data, the ability to capture point cloud data became an important criterion in the investigation to select a 3-D data input method.

Conventional laser surface scanners generally incorporate a rigid laser/camera assembly. This assembly is usually stationary, meaning that it is fixed in 3-D "space" and the object being scanned is rotated around it on a mechanical platform. Alternatively, the object can be fixed and the laser camera or assembly is moved mechanically around or along it. This movement usually takes the form of a rotation about one axis (contained within the object) or translation in one direction (along the object, such as along a track parallel to the object).

Unless the object being scanned is a simple surface where every point on its surface can be "seen" by the scanning apparatus in the course of a complete scan, a fixed-axis scanner is unable to measure the complete surface of an object in one scan orientation (Figure 3.2). This presented a significant limitation when scanning a complex object such as a foot. Foot arches, curves and indentations are unlikely to be visible when a scanning device follows a fixed predetermined path.

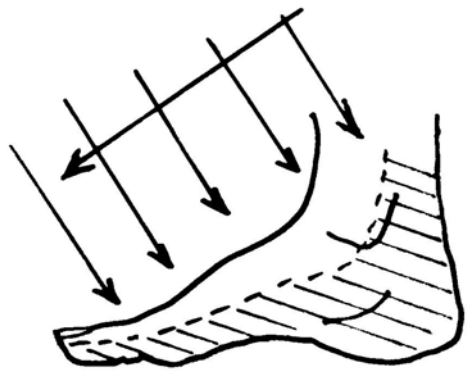

Figure 3.2: Single fixed path foot scanning fails to capture all details.

The study investigated not only fixed path systems but also portable 3-D systems. Portable 3-D scanning methods appeared to offer a means to overcome the limitations of fixed path or stationary scanning systems in capturing the complexity of the human foot.

3.2.2 Selecting and working with technical collaborators

Investigation through local academic and commercial engineering and laser design sources failed to find an existing locally available or locally represented portable 3-D scanner.

The study undertook to find international suppliers of 3-D hardware and software by assessing the technical merits and costs of each system. Considerations in selecting a 3-D data input method for the study included an investigation into specifications, lead time for design and manufacture of a prototype, lead time for supply if commercially available, technical collaboration, training, budget and funding.

Internet investigation and email communications revealed that custom foot scanning devices existed in various other countries. However, in every instance, these systems captured the weight bearing surface of the foot as a flat profile because the foot is placed on a flat surface such as glass or steel.

What the study envisaged was a 3-D means of digitally capturing plantar load bearing contours of the foot in as detailed a way as that captured by podiatrists in a clinical setting, who employ orthopaedic foam or gypsum impression casts of the foot.

Since no local representation existed for any of the scanning devices that had been located through the internet, it became necessary to look beyond South Africa for technical collaboration. Further detailed technical enquiries with potential suppliers of such 3-D scanning solutions were necessary to find out whether a commercially available system could be modified to serve the purposes of this study. The footwear industry assisted the study in selecting a systems integration specialist in the United States to assist with the follow up investigation into these 3-D systems.

A summary of a portion of the initial part of the investigative process may be found in Appendix I.

As will be seen in 3.2.3, once a 3-D portable system was found that best met the requirements for the study, the systems integration specialist from Aclarus Corporation provided the means of coordinating the overseas technical collaborators with the efforts of the study.

A detailed background into all the technical collaborators may be found in Appendix II.

3.2.3 Selection of a portable 3-D data input device

The FastScan hand held scanner selected for this study overcame fixed axis limitations and disadvantages. It is portable and this was a considerable advantage over other fixed site installations as sampling could take place in different parts of the country. It provided not only a portable but a hand-held means and method of scanning an arbitrarily located and oriented foot with the scanner components also being arbitrarily located and oriented in space.

This substantial freedom of movement is achieved by the use of a transmitter that emits a small alternating current electromagnetic hemisphere. Intersection of the magnetic field by both the laser beam and the camera yields triangulated data that the software can process into *x*, *y* and *z* coordinates in space. As long as the transmitter remains fixed and the object being scanned (namely the foot) also remains in a fixed position once scanning begins, the other two components (the laser beam and the camera) are free to move in space around the object (Figure 3.3).

Figure 3.3: Spatial freedom of movement of FastScan laser and camera

The scanner captures three dimensional surfaces by smoothly sweeping a hand held visible laser and a charge-coupled device (CCD) camera assembly over an object - in a manner similar to spray painting. An accurate 3-D image of the object is captured in real time. Several overlapping sweeps are combined in software to create an accurate 3-D surface model. The three-dimensional data can then be saved in industry-standard formats for loading into other programs. Since the scanner is lightweight and portable, this was considered useful for the study's physiological scanning application since the device allows free form scanning with no mechanical constraints.

The scanner comprises three main sub-systems; the *positioning hardware* to sense the location of the hand-held-scanner; the scanner *laser system* to sense the surface being swept; and *software* to capture and smooth the data obtained from the scanner (Polhemus, 2004).

By means of development work that was carried out in conjunction with the Department of Mathematics University of Canterbury, Applied Research Associates New Zealand (ARANZ) produced advanced software for processing various types of 3-D data sets. In working with sampled data, this software smoothly "fills in" scattered 2-D and 3-D data by a mathematical concept known as Radial Basis Functions (RBF).

The collaboration with ARANZ in the current study resulted in the development of a custom made extension of this software, with several additional modifications to join the sole underside data, and to process the data that was gathered by the laser system. The software was used to merge sweeps, join objects, and smooth surfaces into one contiguous 3-D object (Figure 3.4).

Beta testing, report back and modifications were ongoing while part two of the study was being prepared and coordinated. The study provided feedback on features and performance to the team at ARANZ. In turn, the ongoing study coped with twenty six versions and upgrades of the software, some of them entailing changes in file format and data features/characteristics.

Figure 3.4. A foot scan rendered via RBF modeling.
(Polhemus, Fast Scan promotional CD-Rom, 2005)

3.2.3.1 Integration with 3-D modelling and visualisation

The FastScan software that was developed for the study supports data export into other software by means of a number of industry standard 3-D software formats such as 3-D Studio (.3ds), AutoCAD (.dxf), IGES (.igs), Inventor (.iv), Matlab (.mat), STL (.stl), VRML (.wrl) and Polyworks Scan (.psl).

The data could thus be exported to an industry-standard 3-D software modelling package, Rhino 3-D (sourced from Robert McNeel & Associates, Miami, USA) to facilitate understanding of the data by visual means. Rhino software is compatible with many design, drafting, Computer Assisted Modelling (CAM), engineering, analysis, and rendering software packages, and directly outputs STL, the computer language of 3-D printers and rapid prototyping systems for foot last manufacture.

An advantage of the modeling software is that it can convert 3-D scans into visual material that can be used by small "start up" manufacturers who are not yet computer enabled, in order to enable them to share in the same knowledge as more technologically advantaged manufacturers.

3.2.4 Selection of heel elevation for 3-D measurement

In consultation with industry designers (Metior, 2004; Vandenheede, 2004), it was decided that this study measure the foot in a natural flat weight bearing position without heel elevation. This would permit subsequent comparisons to other studies (Hawes *et al.*, 1994:194; Anil *et al.*, 1997:85; Houston, 2002:47) and provide a baseline for future studies. It was decided that subsequent studies could focus on foot morphology at different heel elevations such as 35mm and 60mm.

3.2.5 Assessment of plantar impression materials

Once it was determined that ARANZ could provide a version of software that would "stitch" a dorsal surface to a positive (inverted negative) impression of the plantar weight bearing surface, it became necessary to find a suitable impression material. The material had to produce a detailed foot impression or "footprint" on loading with the weight of the leg; it had to deform to the same degree for each participant; it had to be suited for infection control, either by coating with some disinfectant medium or by fresh replacement for each participant.

3.2.5.1 Sea sand

The degree of definition of the footprint was found to be unsuitable with dry sea sand. Definition improved on damp sand, but was again lost on sand that was too damp. Various methods were tried to control and quantify the amount of water to produce a suitable wet sand footprint. Oil was also tried as a wetting medium but this proved messy.

Issues such as how to control for the particle dimensions of the sand; how to control the moisture factors as well as factors concerning infection control became too time-consuming and further investigation into this medium was abandoned.

3.2.5.2 Floam

Floam is an American product composed of a mixture of fine polyethylene powder and oil, commercially supplied in a sealed vinyl pack. The vinyl original pack was too thick to retain a detailed impression of the foot, so the mixture was removed and placed between two thin sheets of polyethylene film. This only worked if the starting depth of Floam was > 60mm and provided that the covering film lining was smooth to begin with, to prevent wrinkles caused by displacement. Deep impressions were difficult to scan due to the alignment of the scanner's camera and laser beam. It was also unacceptably messy to have to manually reform the material and replace the film sheet for infection control before each subsequent scan. Floam was rejected as an impression material for these reasons.

3.2.5.3 Modelling clay

Commercially available terracotta modelling clay was experimented with. Good results were obtained by adding additional water to the ready mixed clay. However, in practice, it proved too difficult to control moisture levels and prevent the clay from drying out. Clay was also rejected as an impression material.

3.2.5.4 Phenolic foam

Phenolic foam is commonly used to capture orthopaedic impressions for such applications as manufacture of orthoses and prostheses (Figure 3.5). Phenolic foam has no memory characteristics, will hold an impression and can be "dented". It cannot be re-used and thus also served the purpose of infection control in the study since individual blocks could be discarded after single use.

Figure 3.5: Phenolic foam[a].
[a]Conventionally supplied in a retaining box for othotic manufacture.

3.2.5.5 Assessment of plantar impression force

Strain gauge testing and comparison of scans of feet under varying loads determined that forefoot spread (maximum displacement of the heel and ball of the foot in the transverse plane) would occur commencing at one-tenth of body weight, exerted as pressure in raising one's foot as if to climb a shallow step.

This lead to the concept that, if a participant were to place the foot to be scanned on a higher step, this would not only spread the foot to maximum as when fully weight-bearing (thereby fulfilling the requirement for a weight-bearing measurement) but also permit the researcher more room to maneuver the scanner beam (between the ankles) to capture the medial or inner border of the foot.

3.2.6 Defining the measurement parameters

Comparison of various texts for the shoe industry and those in the medical field revealed terminology that differed for certain common measurement concepts. It became necessary to explore and define the terms to facilitate communication and mutual comprehension with industry.

3.2.6.1 Search for common terminology

Some examples of terminology differences between industry and podiatry for the same concepts are listed in Table 3.1. and illustrated in Figure 3.6.

Table 3.1: Examples of differences between industry last and podiatric terminology

Last Descriptive	Podiatric Descriptive
Heel seat	Heel pad or calcaneal pad
Joint girth or Ball girth	Circumference of the metatarsophalangeal (MTP) joints
Ball joints	Metatarsophalangeal joints
Inner joint	Medial border of the first MTP joint
Outer joint	Lateral border of the fifth MTP joint
Waist girth	Least circumference of mid foot at the medial longitudinal arch
Instep girth	Maximum circumference of mid foot over the dorsal arch formed by the articulations of the navicular, cuneiforms and metatarsal bases.
Tread	Plantar line joining the mediolateral borders of the 1^{st} MTP and 5^{th} MTP Joints

Further, an illustration of some of the last descriptives listed in Table 3.1 is shown in Figure 3.6. Also notable in Figure 3.6 are internal measurements that translate into geometry and internal proportions of foot morphology.

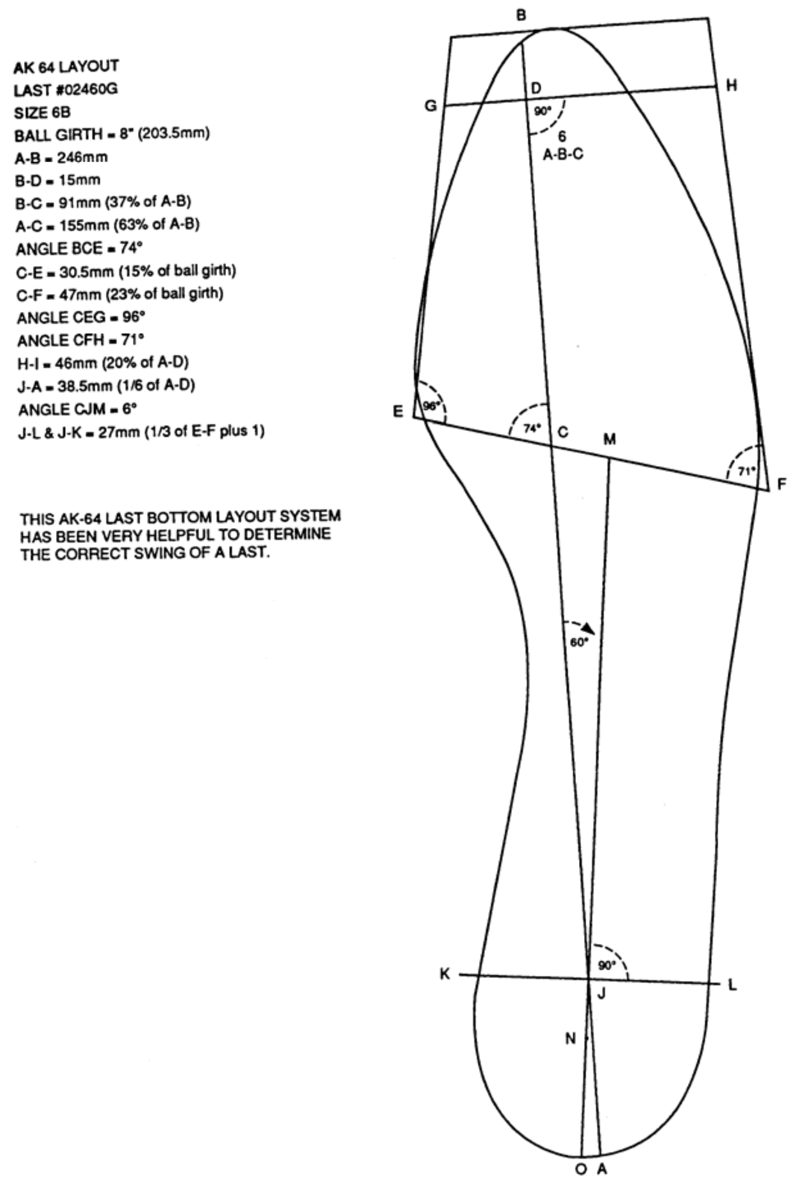

Figure 3.6: American last bottom pattern (Adrian, 1991:3)
E to F: Tread width, K to L: Heel seat width position

3.2.6.2 Selection of measurement parameters

A literature review of available resources revealed a number of previous studies of foot anthropometry. The measurement parameters considered important for investigation in these studies are listed in Table 3.2.

Table 3.2. Measurement parameters in previous studies	
Measurement Parameter	Reference
Foot length	Baba, 1975; Hawes and Sovak, 1994; Anil *et al.*, 1997.
Ball width	Baba, 1975; Hawes and Sovak, 1994; Anil *et al.*, 1997; Houston, 2002.
Ball girth	Hawes and Sovak, 1994; Anil *et al.*, 1997; Baba, 1975; Houston, 2002.
Heel to ball length at 1st MPJ	Hawes and Sovak, 1994; Houston, 2002.
Heel to ball length at 5th MPJ	Hawes and Sovak, 1994.
Heel to Hallux length	Hawes and Sovak, 1994; Houston, 2002.
Heel to 2nd toe length	Hawes and Sovak, 1994.
Heel to 3rd toe length	Hawes and Sovak, 1994.
Heel to 5th toe length	Hawes and Sovak, 1994.
Waist girth	Houston, 2002.
Instep girth	Houston, 2002.
Heel width	Hawes and Sovak, 1994; Houston, 2002.
Hallux height	Houston, 2002.

3.2.6.3 Anatomical landmark definitions

Anatomical landmarks can be defined as "biologically meaningful loci that can be unambiguously defined and repeatedly located with a high degree of accuracy and precision" (O'Higgins and Johnson, 1988:149-170).

Anatomical landmarks were chosen so as to produce the measurements that were considered important both for the comparison in the present study as well as for subsequent last development and manufacture.

Landmark numbers 1 to 13 were placed on the dorsal surface of the foot (Figures 3.7 to 3.25) while landmarks 14 to 19 were placed on the negative impression of the plantar surface of the foot as captured in the impression material (Figures 3.26 to 3.31). Landmarks 20 to 22 were placed at precise points on the impression stand to facilitate calculation and verification of planes (Figures 3.32 to 3.34).