1 Heading

2 Heading

3 Heading

3.1 Sub heading

3.2 Sub heading

3.2.1 Sub heading

3.2.2 Sub heading

3.2.3 Sub heading

3.2.4 Sub heading

3.2.5 Sub heading

3.2.6 Sub heading

3.2.7 Design of measurement platforms

In joint briefing and work sessions with Aclarus, the measurement stands were conceptualized and scale models constructed in balsa wood (Figure 3.37).

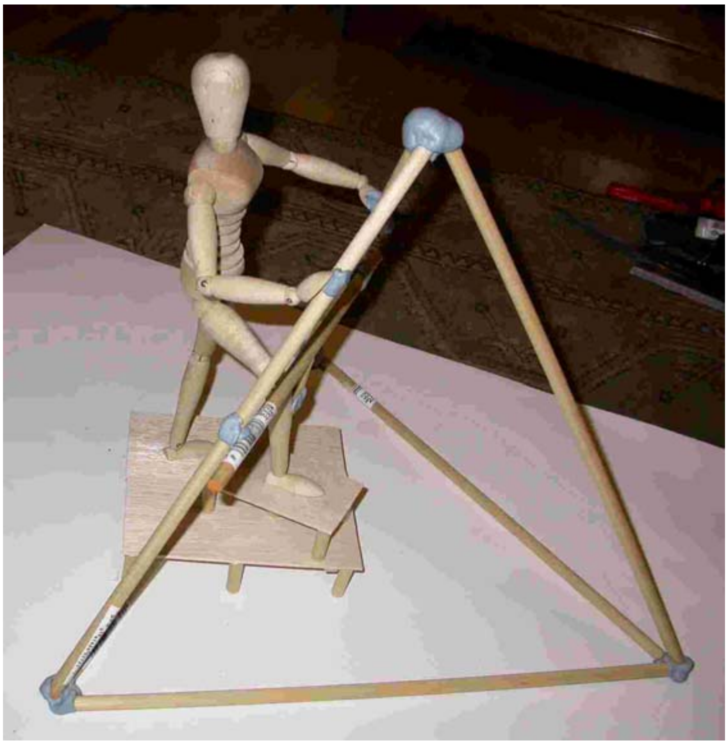


Figure 3.37: Balsawood and dowel model of the measurement stand.

3.2.7.1 Properties required of measurement pyramid pole material

Since the transmitter is a low frequency electro-magnetic device, any electronic "noise" in the environment would induce slight misalignment of successive scans. Therefore the environment itself, including the measurement stand, had to contain low electromagnetic "noise".

In considering the types of materials from which to make the measurement stand, the following properties were considered important:

- Corrosion resistance for durability
- Non-conductive thermally and electrically for safety
- Non-magnetic electromagnetic transparency
- Lightweight for portability
- High strength for durability
- Dimensional stability
- Low maintenance

Metal tubing such as lightweight aluminium was, therefore, unsuitable due to the limitations of electromagnetic transparency. Further investigation into such choices as polyvinyl chloride tubing, solid lightweight wood and hollow fibreglass tubing revealed that hollow fibreglass tubing fulfilled all the requirements, although not as lightweight as aluminium tubing.

The actual measurement stand used in the project (Figure 3.38) was constructed from custom designed and machined surgical steel fittings that connect hollow fiberglass tubing and a Manfrotto™ tube clamp plus Velcro™ padding. These were constructed in an original design that allowed articulation and dismantling of the entire assembly for transportation between data collection venues. The pyramid stand is light, portable, rigid and non-conductive.

In order to assist in maintaining static posture, the participant's lower leg, just distal to the knee joint, was strapped to a padded central stabiliser by means of Velcro™ fastening on a soft elasticated band.

The stand was used in conjunction with the laser scanning system to provide a sturdy support to steady subjects while being scanned (Figure 3.38).

Figure 3.38: Actual assembled measurement stand

3.2.7.2 Design of step up platforms

Because of the restrictions regarding use of metal, the base step up platform was made of wooden interlocking panels which needed to be sturdy but weighed 72 kilograms. In practice, this is a cumbersome weight to manage.

The second level step up was accomplished by means of wooden slabs, while the third level that supported the foot being measured, was made of formed acrylic.

The original design did not include the wooden slabs. It became evident during testing that, depending on certain participants' leg lengths (either very short or very long), the angle formed between the leg and the foot was not 90 degrees, as in relaxed calcaneal stance position.

Testing and trials resulted in wooden height adjustment slabs that were used according to the participant's height and, thus, the relative tibial length of each participant. Wooden height adjustment slabs were 16mm in thickness and were adjusted to the next height up when measurement fell halfway between one level and the next. Design could not incorporate a hydraulic or similar mechanism containing metal due to magnetic field restrictions.

In some instances of measurement, this resulted in an ankle flexion that was not exactly at 90 degrees from the vertical. Future studies should incorporate a method of measuring tibial length more accurately and a more accurate method of adjusting the height differences between the supporting surface for the foot not being measured and that of the foot being measured.

3.2.8 Design of custom scan procedure and custom software

Capturing an image of an extended limb is easy with free-form scanning, but capturing an accurate representation of a foot under load is more difficult. A special measurement approach incorporating the use of an impression material was invented to capture both the upper portion of the foot and the sole, while under load.

In this approach, the subject stepped onto a deformable foam block, and the upper foot and top surface foam were scanned by means of sequential "sweeps". The foot was then removed, and the resulting "negative" impression of the sole and the top of the foam were scanned with several sweeps. Combined and edited, these sweeps describe the plantar surface of the entire foot under load.

3.2.8.1 Sequence of scanning

After tests to develop the new method, the sequence of scanning became the following:

1. Capture the dorsal surface of the foot with several scan sweeps, utilising the wand.
2. Capture the dorsal anatomical landmarks (1-13) by means of the stylus marker.
3. Remove the participant's foot from the impression foam; then capture the plantar anatomical landmarks (14-22) by stylus marker.
4. Capture the plantar surface impression of the foot with several scan sweeps of the foam impression block.
5. Save the file as an .HLS file.

3.2.8.2 Sequence of processing post scanning

No method existed previously for post-processing. Beta testing and numerous trial methods resulted in the following sequence of processing post scanning:

1. Identify and flip selected sweeps corresponding to the plantar surface of the foot.
2. Clip the common plane data by the Point Separation method.
3. Edit regions (select and delete) to remove spurious data beyond the surface of the foot.
4. Generate Basic Surface (two objects, upper and sole).
5. Place the bounding box to clip at the ankle.
6. Generate RBF (Radial Basis Functions) Surface (combine two objects into a single object).
7. Save as .FSN file (retains both raw sweep and generated surface data).
8. Export as a .CSV stylus point file for Landmark Calculations (in MS Excel).
9. Export .OBJ file for Girth Calculations into Rhino software.

3.2.9 Restrictions to scan quality

One of the reasons that the Polhemus FastSCAN Cobra 3-D scanner was selected was because it allows free form scanning of any object, from any angle. However, this freedom of movement comes with some restrictions: the object must be in an environment free of magnetic fields, and must not move significantly between sweeps. To better understand this, it is necessary to describe the magnetic fields and the implications of their use.

3.2.9.1 Magnetic field artifacts

The FastSCAN system precisely tracks the motion of the scanner (wand), stylus and receivers in space using magnetic fields generated by the transmitter. These fields are in the frequency range of 8 kHz - 12 kHz. The magnetic fields can be distorted by fields generated by other equipment such as cell phones, or by currents induced in nearby conductors such as metals and unshielded overhead lighting. Interference results in measurements that are not repeatable, or are misaligned.

Magnetic field artifacts result in sweeps that appear separated, or landmark points that are wrongly placed (Figures 3.39 and 3.40).

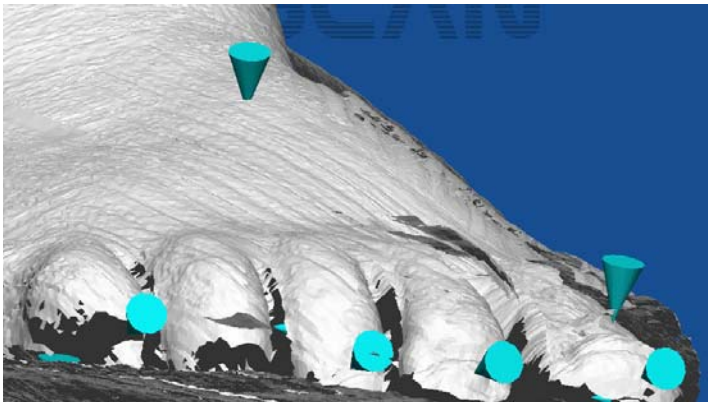


Figure 3.39: Misaligned sweeps over big toe.

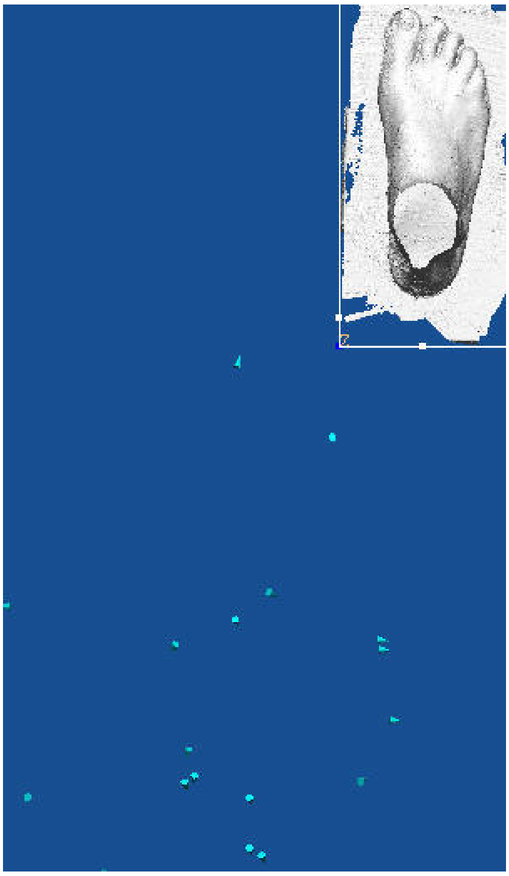


Figure 3.40: Magnetic field artifact affecting landmarks.

Field interference is generally uncommon as most commercial and consumer electrical equipment is shielded. More common is interference due to metal in the local environment. Metals are all conductive to some degree, and the more conductive a metal is, the more likely it is that currents can be induced in the metal, so distorting the magnetic field used by the tracker. Table 3.4 shows the resistive properties of various metals (the inverse of conductivity); the more resistive, the less effect the metal has on the scanning system:

Table 3.4. Resistive properties of various metals

Material	μΩ/cm
Silver	1.6
Copper	1.7
Gold	2.2
Aluminium	2.7
Nickel	6.9
Iron	10.1
Stainless Steel	75

Surprisingly, stainless steel is quite resistive to electrical currents. Acrylic sheet, fiberglass, wood and surgical stainless steel are all acceptable materials for equipment near the transmitter.

Predetermined index landmarks were used to check for distortion. The coordinates for these points had to be the same for every session. It was decided to use three landmark points on the surface of the acrylic measurement platform (landmarks 20 to 22). This validation of instrumentation is further described in 3.3.2.5.

The interaction with metal made it necessary to ask participants about implants, pins and other metal artefacts such as those from past surgery.
It was also important to be aware of unseen sources of metal near the measurement area such as, for example, pocket change, jewellery, cell phones and steel reinforcement bar in the concrete floor slab.

Testing showed that it was necessary to keep the receiver and scanner as close to the transmitter as possible to maximize data capture as free from interference as possible. An important consideration was to always ensure that nothing was placed between the transmitter and the scanner except the foot to be scanned.

3.2.9.2 Movement artifacts

Movement generally falls into two categories: a whole object can move as a unit, or portions of an object can move relative to other parts of the object. The FastSCAN system can track and scan whole moving objects with the use of additional receivers attached to the object, but when an object such as a foot (attached to a live person) is scanned, involuntary muscle movement can introduce registration errors.

A complete scan comprises several layers or sweeps (Figure 3.41) and the processing software that merges sweeps into a smooth surface works best when the layers touch each other and are contiguous. When part of an object moves, the next sweep becomes misaligned (Figures 3.39 and 3.42), because the surface is no longer where it was. The software compensates for this through a process of interpolation.

Figure 3.41: Successive sweeps of a scan.

If layered sweeps were too far from each other, interpolation errors were introduced, and the software might not be able to produce a surface. The process of merging sweeps is called "Generate Basic Surface". If a basic surface was generated and produced a crystalline surface, this indicated that successive sweeps did not touch (Figure 3.42).

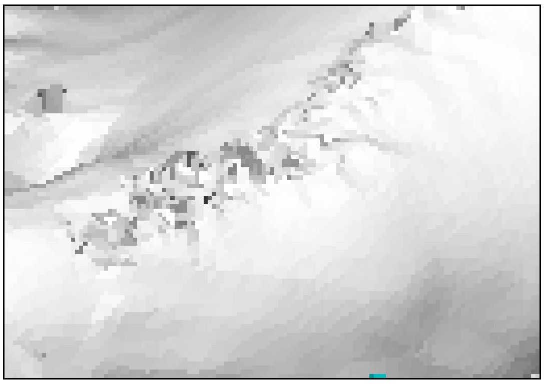


Figure 3.42: Crystalline surface caused by misaligned[a] sweeps.
[a] Misalignment formed by the big toe twitching during scanning.

It became evident that it was necessary to sweep areas prone to involuntary muscle movement first and to do so quickly. To minimize errors induced by fatigue in the subject, sweep areas furthest away from the transmitter had to be done first, as errors were reduced the closer the wand was to the transmitter. In scanning a foot, and assuming the transmitter was at the heel, the first sweep was across the toes. More time could be taken with the sole or inverse impression since the foam was immobile (no fatigue factor).

Crystalline artifacts were an indication that the sweeps were too far apart, which required raising the smoothing parameter. The larger the smoothing facility was set at, the more tolerance was created for misaligned scans, and the smoother the resulting surface. The cost of greater tolerance was surface accuracy; if successive sweeps were separated by several millimetres, then the resulting surface would only approximately capture the true volume of the object. The parameters in Table 3.5 served as guidelines for the sweep smoothing:

Table 3.5: Software parameters for sweep smoothing.

Sweep Quality	Smoothing	Decimation (Accuracy)
Good (no layering)	1.5 mm	1 mm
Normal	2.5 mm	2 mm
Poor (layering)	3.5 mm	3 mm

The objective became to overlap the sweeps so that these could be processed for a basic surface (Figure 3.43) with the lowest smoothing parameter, without resulting in artifacts. The dialog box in Figure 3.43 shows the typical values. "Surface Simplification" had to be turned on or enabled, to reduce the number of points generated and so reduce the processing time for the next step of generating a Radial Basis Functions (RBF) surface.

A brief explanation of Radial Basis Functions follows in 3.2.9.3.

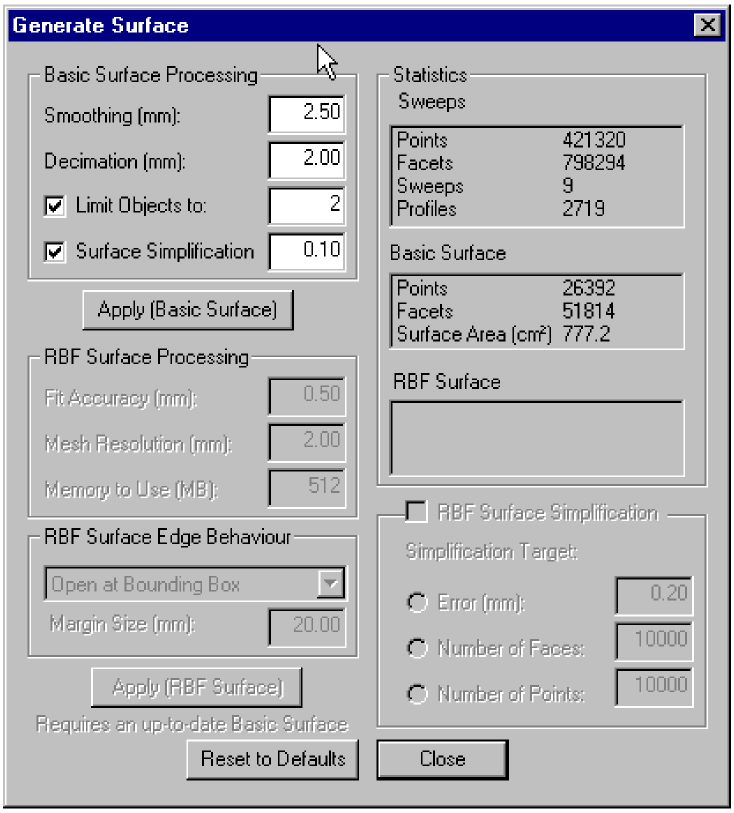


Figure 3.43: Parameters to generate a basic surface.

As a result of the extensive work carried out in this study for beta testing, ARANZ subsequently made a registration utility available in a further version of software to help better merge misaligned sweeps.

3.2.9.3 Application of Radial Basis Functions

The objective in any scanning session was to completely cover the foot with as few sweeps as possible. Too many sweeps increased processing time and increased the chance of misalignment; too few sweeps created "holes" in the data which could lead to interpolation problems (Figure 3.44).

Creating a surface from multiple sweeps was a two-step process. The first step was to create a 'Basic Surface', which merged sweep data into a continuous surface. If two or more discrete objects were formed, such as an upper foot surface and the surface of the sole, these surfaces could also have gaps, where the sweeps did not cover.

To eliminate gaps and join two or more objects, ARANZ developed advanced software to smoothly interpolate scattered 3-D data by a mathematical concept known as Radial Basis Functions (RBF). RBF interpolation forms smooth surfaces from irregular, non-uniformly sampled data. An RBF surface was generated from the Basic Surface, to fill in holes and join the upper and sole data.

RBF processing relies on reasonably contiguous data – so if large parts of the data are missing, it will seek the nearest surface for a join. If the edge of the nearest surface is too far away, it will balloon out to join with it (Figure 3.44).

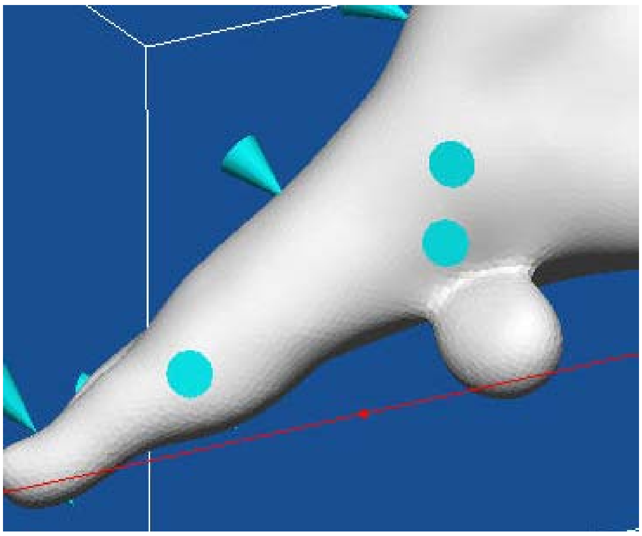


Figure 3.44: A balloon is the result of missing data.

Missing data under the arch is the reason for the result in Figure 3.44. Data missing under toes would lead to bulbous, elongated toes that engulf the landmark point at the tip of the toe.

Too much missing data would result in the RBF software creating surfaces that did not actually exist, in effect creating a surface model that was an inaccurate representation of the original object. This proved to be a good feature to help discard poor data.

Spurious data (unwanted data that was not deleted in the Clip step; see 3.2.10) had the same potential to create fictitious bridges between the foot and this data. This meant that the clip step, even though time consuming, had to be well executed.

Special attention had to be paid to obscured areas. When scanning the foot, these were usually under the toes and under the arch. The scan had to come up the ankle to the malleoli – if the sweep was not high enough, there was insufficient data to truncate cleanly at the ankle, leading to a "clubbed" effect where the data ended (Figure 3.45 see A).

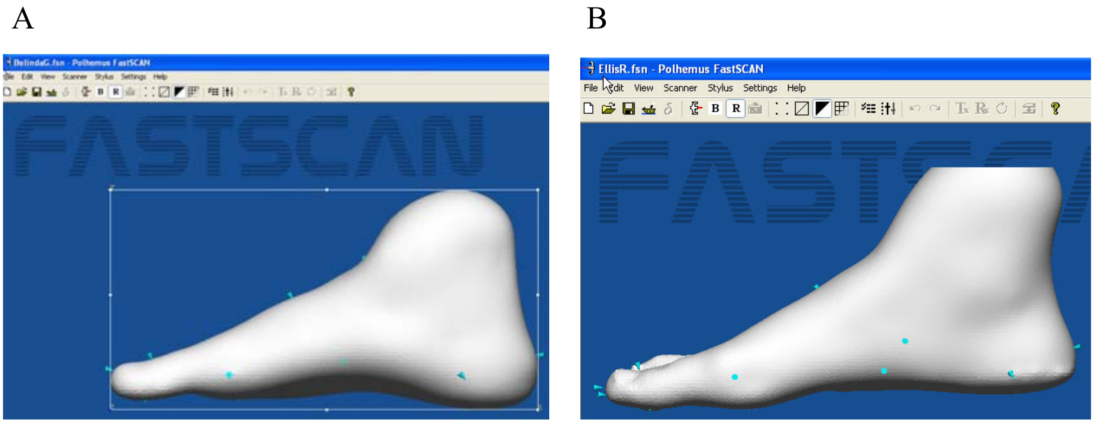


Figure 3.45: Ankle truncation effect. A = Without truncation, B= With strap truncation.

A black Velcro™ strap to demarcate the upper limit of the sweeps above the ankle was used. The camera would not detect the laser beam on a black surface. Thus the boundary of the strap became visible in the data, and points above the line could be deleted (Figure 3.45 see B).

To set the RBF parameters (Figure 3.46), a fit accuracy was specified at 0.2 mm, but this could be increased to 0.3 mm if some crystalline artifacts were present. Mesh Resolution performed best if kept at 2 mm. It became advisable to increase the memory to enable function of the software.

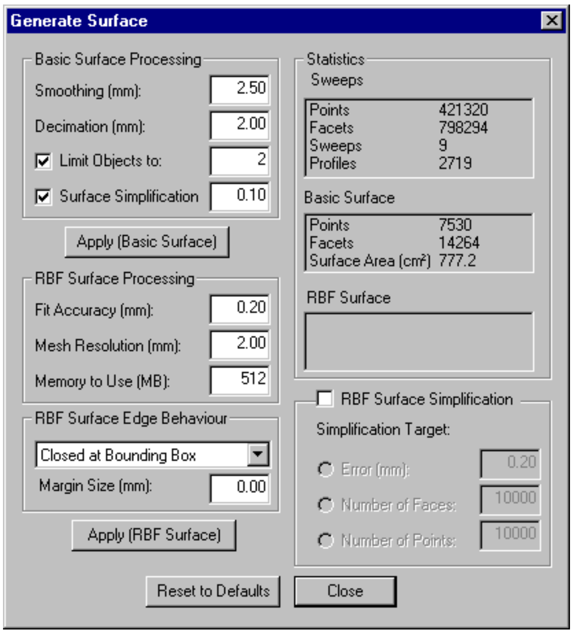


Figure 3.46: Parameter to process RBF surface.

The command "Close at Bounding Box" was only effective if a bounding box to clip the data was specified (see 3.2.10). To truncate the top of the ankle sharply, the foot image had to be turned to a side view, and "Set Bounding Box to View" used.

3.2.10 Clipping: creating a solid model

The scanner captured both point cloud (*x, y, z*) and vector (direction) information, so the sweeps over the sole (because they were made from the concave impression of the foot in the impression material) appeared as if they have been taken from "inside" a transparent foot, from a viewpoint normally obscured.

While the point data for this was correct, the vector data had to be reversed or inverted; otherwise the bottom surface could not be used to join to the top surface and create a solid 3-D object. This inversion of the point of view of the scanner was done by the Sweep List dialog box (Figure 3.47). Only selected sweeps would be flipped by using the Flip Sweep button. To see the affected sweep, the “Selected Sweep Transparent” option was developed.

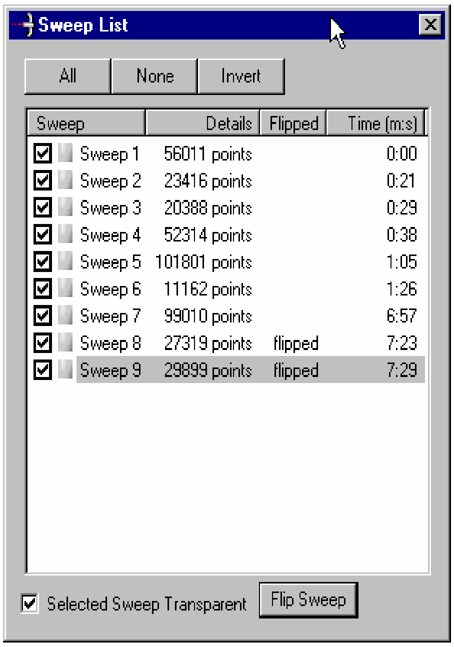


Figure 3.47: Sweep List dialog box to reverse or “flip“sweeps.
(Enables the creation of a positive from a negative sole impression)

This dialog box was useful to quickly check that all sweeps were useful. By clicking on each sweep, the sweep area is highlighted in red against the previous sweeps. Those with few points in relation to others are suspect and can be assessed, deleted or re-done.

The result of data capture and processing was a series of sweeps that enclosed a foot, as taken from various viewpoints above and below the foot. This model of the foot had two surfaces that were not needed: the top surface of the foam block around the actual foot (taken when the foot was scanned) and the same surrounding surface, now inverted, taken when the sole impression was scanned. It is important that these surfaces were the same, because the technique used to discard this surface relies on this concept. If, after clipping, segments of this surface are noticed to be remaining, it meant that the sweep data for this surface did not overlap properly.

Two algorithms to clip the unwanted data off the edges of the object were developed, and both worked well in tests. The first method, “Clip by Baseline”, required the use of an initial baseline reference sweep of the foam block before other sweeps began.

The second method, Clip by Point Separation (Figure 3.48), is simpler (fewer sweeps) and was found to be best for most circumstances.

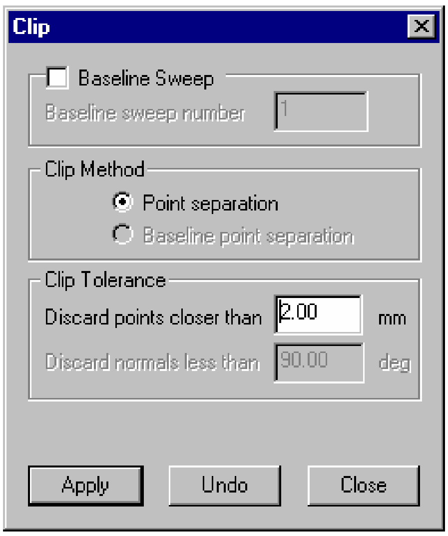


Figure 3.48: Clip by Point Separation Screen

The algorithm for this method is:

> Discard any point P on a top sweep that is within a distance D of any point on a bottom sweep;
> discard any point P on a bottom sweep that is within a distance D of any point on a top sweep.

Point separation relies on the concept of overlapping sweeps (common surface is removed) but only if data exists for both the top sweep and the bottom sweep.

Throughout many sessions of testing, it became essential to maintain a flat, precisely positioned foam block between upper and lower sweep sessions. The foam had to be precisely machined so as not to move in the holder. The material composition (see 3.2.5) was important, as the friable foam had to crush and not rebound.

Proper placement of the foot had to be ensured at a controlled rate, so as not to deform the edges of the impression. The foot placement and depth was based on the researcher's skill as a podiatrist, according to the clinical standard for relaxed calcaneal stance position, and minor variations were considered to not affect the result greatly, unless the foot was depressed too far to obtain useful curvature data around the toes. In such instances, the foam was discarded and foot placement re-done on a fresh foam block.

Clip parameters involved setting "Discard Points Closer Than" to 1 mm, with a choice to increase the setting if it was seen that foam surface remained. A larger setting increased the gap (Figure 3.49) that the RBF software had to bridge to join the upper and lower foot surfaces. By experimentation, it was found that 2 mm was optimal, 3mm was typical for poor scans, and any number larger than this could lead to distorted surface fitting results, in the form of a "band" around the foot. If the band covered curved toes areas, this would distort results. It was necessary to try new parameters after each clip run to find the optimal parameter (Figure 3.49). Once this was accomplished, it was then possible to remove the spurious overlapped data.

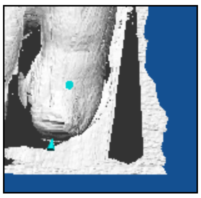
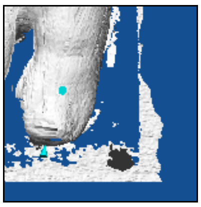
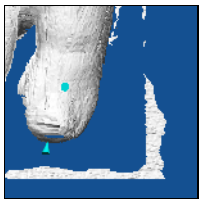
 Not Clipped	 2mm Separation	 3mm Separation

Figure 3.49: Results of differing clip parameters. (Close ups of the big toe.)

3.2.11 Summary of new data capture and processing method

Beta testing over a period of five months through versions 1 to 27 was conducted to provide ongoing feedback to refine the method.

In order to provide a quick understanding of the method developed, the following is a listed summary of the steps developed to capture and process data for each participant.

1. Raw data files in Hand Laser Scanner format were formed by capturing the surface of the foot with several sweeps of the scanner.
2. Anatomical landmark stylus point data were captured by touching the foot with the stylus marker.
3. Sweeps were edited, clipped and joined to generate a 3-D surface.
4. The 3-D surface exported to an object file format.
5. The landmark points exported to a comma separated value file.
6. Use of Microsoft (MS) Excel to import comma separated value file.
7. Use a macro written in MS Excel to calculate planes and distances between landmarks.
8. Use Rhino modeling software to import object format file.
9. Within Rhino, create a cross-section of the tread girth circumference.
10. Collate measurements into master workbook, ready for statistical analysis.
11. Print upper, side and cross section views of rendered object format files, to be used in SMEE's "library" of outputs for future reference (training manuals).
12. Import the group averaged object format file(s) into CADCAM for 3D print into mother model last(s).

Whereas data collection averaged fifteen minutes per participant, post processing takes between thirty five to forty five minutes per participant because, although conducted on a computer, this is not an automated process.

3.3 Part two: Multi-ethnic 3-D metric study

The focus of the second part of the study was to gather foot anthropometric data on a representative sample of the South African female adult population. This was necessary to determine what percentage of the population would fit the shoe and thereby answer the primary research question. In addition, the Industrial Partners required that the sample be representative not only of ethnic strata but represent potential purchasers of a future footwear product to result from the anthropometric study data, namely working women and active retirees.

In order to produce a sample that was representative of the larger shoe purchasing population, it was necessary to consider the features of size and bias as shown in 3.3.1.6 and 3.3.2.3 (Melville & Goddard, 1996:30). Certain other considerations were necessary such as adequate representation or stratification of age groups, as well as the deciding on the demographics in which possible clustered groups could be located and sampled within the constraints of time and convenience.

3.3.1 Materials for the multi-ethnic 3-D metric study

3.3.1.1 Ethnic, tribal and sub group participant selection

It was requested that all ethnic or tribal groups in the South African female population be represented in the study. This required an approach that incorporated a degree of sensitivity.

Governmental census in South Africa continues to classify people by population group, in order to monitor progress being made by groups in moving away from discriminatory practices of the past. Membership of a population group is now based on self-perception and self-classification, not on a legal definition (Statistics South Africa, n.d.). This self-classification also incorporates a distinction based on home language of which there are eleven official home languages in South Africa (Table 3.6).

Since previous studies concentrated primarily on the white African female population (Pratt, 2001; Wilson, 2005), it was decided to adopt the guidelines of Statistics South Africa (the national census body) and ask participants to identify themselves culturally and linguistically according to the definitions used by Statistics South Africa (Table 3.6).

Distribution of ethnic groups varies from province to province (Statistics South Africa, n.d.) and this precluded selecting any one statistical distribution for either a province or an economic group above that of another. In consultation with Industry and since the study was to establish the core of a national database to which data would be added on an ongoing basis, it was hoped to measure comparatively equal numbers of participants from each ethnic group as per Table 3.6.

Table 3.6: Classification groups used by Statistics South Africa, 2004.

National Census: Ethnic groups	Official Home Languages
Black African White African Asian/Indian Coloured	Afrikaans English IsiNdebele IsiXhosa IsiZulu Sesotho Setswana Sepedi Siswati Tshivenda Xitsonga

3.3.1.2 Age group selection

Various sources state that cessation of growth in the female foot occurs in the teen years. Volpon (1994:83) states it is by age 12 while Whitaker, Rousseau, Williams, Rowan and Hartwig (2002:385) state that female osseous maturity occurs from age 12 years and six months onwards. Some authors such as Anil *et al.*(1997:80) assume female foot maturity at age 17, while Tachdjian (1990:63) states that complete osseous and soft tissue maturity of the female foot is reached between the ages of 20 and 21.

In consideration of the above, and in view of the fact that possible poor nutrition in childhood could somewhat delay skeletal maturity (Lewis *et al.,* 2002:732), an adult female foot was defined as age 21 and older for the purposes of this study.

Since the footwear industry considers their primary market in adult female footwear to be active adult women aged 21 to 69, this was requested as the age range for the study.

It was planned to collect data from participants across five age group intervals until sampling of the intervals approximated the percentages supplied by industry, as shown in Table 3.7.

Table 3.7: Age group intervals.

Interval	Percentage
21 – 29 years	20%
30 – 39 years	30%
40 – 49 years	20%
50 – 59 years	15%
60 – 69 years	15%
	100%

3.3.1.3 Recruitment and sampling of participant groups

In order to save time and to enable clustered convenience sampling, it was decided to recruit groups of participants rather than one person at a time. Through facilitation by the University of Johannesburg with other institutions and organizations, prospective concentrations of active participants were located (see Table 3.8). Investigation showed that people at these organizations did represent all age group intervals and ethnic groups. These groups also fulfilled the required trait or characteristic of being active women who could be purchasers of leather shoes.

Table 3.8: Planned participant demographics
Universities – administrative staff, faculty academics and students
Retirement villages and centers
Airline crew
Administration and sales staff of a national broadcaster
Factory administration staff

Although this sampling method embodied aspects of probability sampling, it would only be representative of the sub populations from which it was drawn and would not be used for strict inferential statistics on the greater population (Healey, 1993:143).

3.3.1.4 Demographics of participants

Further to the requirements stated in 3.3.1.1 the study had to consider that planning, time, administration and travel costs would increase with each additional province to be sampled.

A further consideration was that of support structures for the duration of the study since, although the University of Johannesburg is located in Gauteng province, both industry partners for the study are located in the province of Kwazulu Natal.

Data collection was thus planned for the two most densely populated provinces of the country (Statistics South Africa, n.d.), namely Gauteng and Kwazulu Natal, specifically in the cities of Johannesburg and Durban. All participants were urban residents.

3.3.1.5 Exclusion criteria

Non ambulatory female participants were excluded, since it was considered that these did not fit the profile of a potential footwear purchaser.

Recipients of metallic implants such as pacemakers or prostheses were excluded from the study due to possible magnetic field interference from the laser scanning equipment (see 3.2.8.1).

3.3.1.6 Sample size

Statistical literature states that a minimum sample size of 30 is required to reliably apply large sample methods for estimating statistics such as the mean (Melville & Goddard, 1996:66). Based on previous study models (Hawes, Nachbauer, Sovak & Nigg, 1992:22; Hawes *et al.,* 1994:191), at least 100 participants per ethnic group or size interval were required in order to obtain statistically meaningful data.

A suggested calculation for sample size was thus: 30 participants x 5 age groups x 4 ethnic groups = 600 participants.

Subsequently, a reference was found to the study conducted by Sokolowski (1999) which reported non linear relationships between sloper segments (see 2.2). Since the shoe industry uses two different gradings for length and width, it became apparent that the entire sample could be used for a linear measurement comparison. All data in the entire sample could be scaled and/or graded from whatever size up or down to the industry model size 4 in order to find whether linear relationships existed. Thus the sample size was finalized at 500 participants to allow for 4 ethnic groups of at least 100 participants per ethnic group plus a margin for errors and discarded data.

3.3.2 Method for the multi-ethnic 3-D metric study

3.3.2.1 Opportunity to collect data for future study

The data collection method selected was planned to allow for the collection of more data than was needed to answer the deceptively simple research question in the present study. The logistical nature of population measurement studies is such that they are typically conducted over intervals of a number of years. It was, thus, necessary to think in a broader context to allow for data collection that would permit subsequent exploration and analysis of the data to address more areas of future research that were considered to be beyond the scope of this study.

3.3.2.2 Body Mass Index

It was necessary to collect data on participant stature and body mass, in order to quantify and qualify the data for an industry that has to take into consideration the body mass characteristics of its market in the production of a footwear product. Collection of this data would also enable comparison to previous and similar studies (Thompson & Zipfel, 2005: 22).

3.3.2.3 Sample and researcher bias

Although early plans for participant recruitment included use of public media such as radio (see Appendix VII), this could result in skewing of data since it was possible that too many biased participants with "problem" feet would come forward to be measured. Since a previous study showed that eighty percent of South African women report foot pathology due to ill-fitting footwear, obvious "problem" feet could not be excluded from a group of this nature, since this might create an opposite bias.

In spite of random participants being asked to volunteer, the sample may still have included biased or interested participants. By random convenience sampling of work groups such as staff members at a common place of work, it was hoped to eliminate most of the sample bias.

The information sheet (Appendix VIII) made provision for participants to withdraw from the project at any time.

3.3.2.4 Validation of intra operator repeatability

Prior to the collection of data, and in order to test whether the amount of error associated with any landmark variable was greater or less than the natural variation in the variable, a reproducibility study was undertaken. Nine landmark measurements were placed on six participants and the landmark placement was repeated on six rotations of sequential measurements to determine intra-observer error.

Basic descriptives and visual tools were used in order to check the repeatability of the test.

The results of the replication testing for Major foot length are shown in a basic descriptive manner together with a visually evident table (Table 3.9) and a graph (Figure 3.50) displaying that there is little change over the means across the 6 rotations of measurements, thus indicating that the measurements are indeed consistent.

Table 3.9: Replication test results on major foot length measurement

	Statistic			
	Mean	95% Confidence Interval for Mean		Std. Deviation
		Lower Bound	Upper Bound	
Major Foot Length 1	237.67	219.96	255.37	16.872
Major Foot Length 2	237.83	220.38	255.29	16.630
Major Foot Length 3	238.17	220.39	255.94	16.940
Major Foot Length 4	237.83	220.26	255.41	16.750
Major Foot Length 5	238.00	219.80	256.20	17.344
Major Foot Length 6	237.83	220.57	255.10	16.449

In the replicate testing, the mean derived displayed a 95% confidence interval. A confidence interval is defined as a range of values, based on the sample mean, that, with a designated likelihood (in this case the 95% confidence level), includes the population mean (Hays, 1994:221; Welkowitz, Ewen & Cohen, 1982:93).

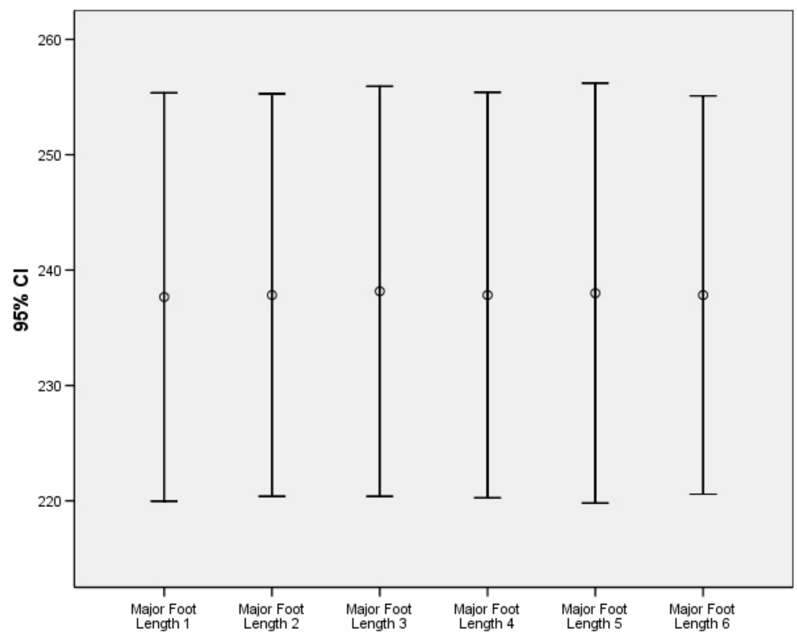


Figure 3.50: Means-on-spokes for results of replication testing of Major foot length. (95% confidence interval; *x*-axis represents means of replicate tests, *y*-axis indicates mean measurement in millimetres, replication accuracy was within 1 millimetre).

In order to visually appreciate these results, the confidence intervals have been inserted as described into a means-on-spokes graph (Figure 3.50). It can be seen that the average as well as the confidence intervals hardly deviate, suggesting but not proving that the measures were accurate, in the sense of being consistent, across the six tests. Consistency of measurement was placed within the nearest one millimeter.

Similar consistent results were found in the remaining eight measurement parameters selected for replicate testing and are shown in both tabular and graphic form in Appendix III.

Placement of landmarks on the last did not require replicate testing as the landmarks corresponded to points inherent in the design of the last and were marked before scanning.

3.3.2.5 Validation of instrumentation

In order to check validity of the instrument, prior to commencement of each data collection session, a blank 3-D scan was made of the foam block resting on the measurement platform (without a foot resting on it). The stylus marker was lightly touched on the top surface of the foam, as well as on the three reference points on the platform. The three reference points were exported to MS Excel to check for variance.

The normal average validation co-ordinates for the three reference points are:

20. x = 0, y = 0, z = 31 (Acceptable deviation x = 0.1, y = 0.3, z = 0.0)
21. x = 8, y = 350, z = 30 (Acceptable deviation x = 0.1, y = 0.2, z = 0.0)
22. x = 163, y = 352, z = 26 (Acceptable deviation x = 0.3, y = 0.3, z = 0.1)

Each day's data collection only proceeded once validation of the instrument had been carried out in this way.

3.3.2.6 Ethical approval and recruitment

Approval was granted by the Faculty Research and Ethics Committee of the Technikon Witwatersrand (now University of Johannesburg) Faculty of Health Sciences (see Appendices IVa and IVb). Standard protocol was followed in requesting permission to inform and contact staff to volunteer (when approached) at the various institutions (Appendices V, VI, VII, VIII and IX).

Recruitment by radio was prepared (Appendix XIII) but was subsequently discarded because of equipment security concerns for a public venue and because the sample would not be large enough to minimize skewed data in what would have been a non-structured sampling method.

3.3.2.7 Data collection venues and logistics

Data collection venues were conference venues or similar rooms at each participating organisation, with the proviso that no metal furniture be present in the room as this could interfere with readings from the small magnetic field generated by the scanning equipment.

Logistics were resolved so that a regular number of subjects presented themselves for measurement at fixed time appointment intervals throughout the measuring days, in order to facilitate the optimum number of subjects measured in the least time available, as well as the least time away from their work duties.

3.3.2.8 Data collection process

Data collection consisted of two parts: the first part measured participants and the second part measured the selected last.

3.3.2.8.1 Measurement process for participants

On arrival at the data collection venue, the participant was asked to read the participant information sheet (Appendix X). The purpose of the study was explained to each participant, in addition to a short explanation of the type and duration of the examination. Assured of safety and anonymity, each participant was also asked whether there were questions regarding the examination.

Signed consent was obtained from each participant before data collection took place (Appendix XI)

The participants were assisted to remove their shoes and hose, being given a fresh disposable pair of theatre booties to place on their feet. At that point, participants were questioned by the assistant regarding metallic implants and advised to remove their jewellery, cellular phones and keys from their person and place them in the safe container provided. On questioning, those participants who were found to be bearers of metal implants such as pacemakers and joint replacements were thanked for their willingness to participate, but excluded from the data collection.

The assistant allocated the next participant number to the participant's Data Recording Form and participants were asked to fill in their age and indicate language and cultural self identification on the blocks provided on the Data Recording Form. The participant was then assisted to step onto the digital scale to measure body mass. The mass in kilograms was then entered by hand onto the Data Recording Form (Appendix XII). The participant was helped down from the scale onto the floor, at which point the participant's height in metres was measured by means of the portable digital stadiometer. The participant's forefoot girth measurement was then taken by means of a standard new (not stretched) last measurement tape. This latter measurement was the only manual foot measurement in the study and served as a cross check to the digital one subsequently obtained from the modeling software (3.2.11 item 9).

The participant was helped to step on to the measurement platform. The participant stood erect on the platform, with the right foot resting at an elevated position in such a way that the sole of the foot was flat on the impression foam, with the ankle joint at approximately ninety degrees. A wide (40mm) black Velcro™ strap was used to anchor the leg of the foot being measured to a stability bar attached to the measurement platform. The bar end was padded to avoid possible discomfort from resting against a pole. A shorter (40mm) black velcro strap was placed in position around the ankle to produce a clean edge of the sweeps at the ankle area. Note: Black absorbs light (including laser light) and therefore a totally black surface will not register in the scan). The participant was given a pair of Dalloz™ safety spectacles to protect against any possible laser beam scatter.

Once the scanning was complete, both Velcro™ straps and the spectacles were removed from the participant, the bootie replaced and the participant assisted off the platform.
The remaining landmark placements on the impression foam were then completed, followed by the scanning sweeps of the foot impression in the foam.

3.3.2.8.2 Measurement process for the last

Because the surface of the last is a green semi-translucent plastic that absorbs the red wavelength of the laser beam (making it less visible to the camera), it was prepared by coating with white acrylic paint. Once dry, the prepared last was placed on the impression material. Firm, even pressure was applied to partially embed the last in the impression material. Scanning and landmark placing continued in a similar way to that conducted on the foot but as defined in 3.2.6.4 and 3.2.6.5.

3.3.2.8.3 Discarded data

A total of fifty seven HLS and/or CSV data files (11.17 %) were discarded, leaving a remainder of four hundred and fifty three data files suitable for further processing.

Some files were discarded because the HLS (scanning) component was missing due to extraneous interruptions. For example, height and stature were measured but the scanning portion was not completed.

Some discarded CSV files contained data that had been distorted by environmental factors only discovered (or searched for) once files had been semi-processed and the distortion became apparent.

Figure 3.51 shows an HLS image in which all the landmark points have been distorted in magnetic space by metallic interference (landmark points are not on the surface of the foot where they were placed). In this example, it was subsequently found that the participant had been wearing an under wired (metal) brassiere.

Figure 3.51: Total[a] distortion of landmark points. ([a]No landmark on the foot)

Figure 3.52 by contrast shows an HLS image where landmark points have been partially distorted in magnetic space by metallic interference (dorsal landmarks are undistorted but the plantar landmark points are not on the surface of the foot impression where they were placed). In this example, subsequent investigation revealed that the participant, after stepping off the measurement platform, had retrieved a cellular phone and keys. The participant then placed the metallic items in a pocket and then strolled back out of curiosity to closely watch while the operator completed the scan and landmarks of the plantar impression, thereby introducing metallic interference.

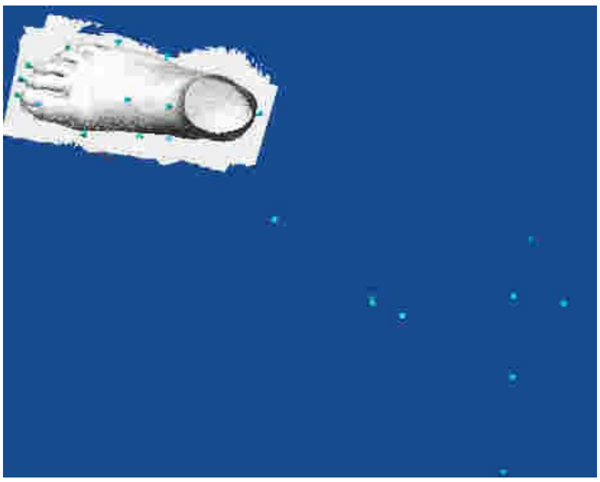


Figure 3.52: Partial[a] distortion of landmark points.
([a]Only dorsal landmarks on the foot)

3.3.3 Data analysis of the multi-ethnic 3-D metric study

Statistical analysis is necessary in order to interpret results and bridge the gap of knowledge between the data gained from a sample or subset of a population to the much larger (unmeasured) population. It is also necessary to understand and to compare results with professional literature that, in turn, is also based on statistical analysis (Welkowitz *et al.,* 1982:4).

Descriptive statistics are used to order, describe or summarize the characteristics of raw data in a clear, convenient manner, while inferential statistics allow one to draw statistical inferences, extrapolations or conclusions about what is present in a population, based on what is observed in the sample data. (Welkowitz *et al.,* 1982:6; Healey, 1993:146; Melville & Goddard, 1996:47).

Analysis of data for the metric study was undertaken in collaboration with Statkon, University of Johannesburg and consisted of basic descriptive statistics such as measures of central tendency, frequency distributions and measures of dispersion.

The descriptive statistics were followed by inferential analysis by examining the sampling distribution, determining measures of variability and bivariate Pearson correlation analysis.

3.3.3.1 Calculated new variable

Before statistical analysis began, Body Mass Index (Height squared divided by mass as endorsed by the World Health Organisation [WHO] in 1998) was calculated for each participant and constituted a new variable.

3.3.3.2 Descriptive statistics

The most common techniques used in descriptive statistics are measures of central tendency, frequency distributions and measures of variability or dispersion (Welkowitz *et al.,* 1982:18).

3.3.3.2.1 Measures of central tendency

Of the three measures of central tendency (mode, median and mean) the best measure of central tendency is the average or mean, designated by μ (Welkowitz *et al.,* 1984:46). The mode is generally used for nominal data and denotes the most common value, while the median represents the value at the exact centre of a distribution of scores or values from least to most and is most commonly used for ordinal data (Healey, 1993:68).

The mean is used when working with interval-ratio data because it is generally more consistent than the median or the mode and is required for more advanced inferential statistics. Another important characteristic is that the mean is affected by every value in the distribution so that, if the distribution contains some very high scores, there will be a positive skew and the mean will have a greater numerical value than the median. If the distribution has some very low scores or values (a negative skew) then this will be reflected in a mean having a lower value than the median. The mean is preferred with interval data since it is more powerful in the statistical sense, using a greater amount of information about the data set than does the median or the mode. This makes it a better summary of data if extreme values should be present (Healey, 1993:72; Melville & Goddard, 1996:51).

3.3.3.2.2 Frequency distributions

Data is made more understandable by listing every possible score value in order, and next to that score value the number of times that the score (frequency) occurs. A frequency therefore consists of the count or representation of the number of cases or classes having each score or value (or range of values) of a variable. A frequency distribution is a listing of a set of classes with each class paired with a number that represents its frequency or f (Hays, 1994:77).

Frequency distributions were thus used to determine the physical number of counts representing a particular value of a foot measurement that would relate to acceptable or poor shoe fit, according to pre-determined limits (Table 3.10).

In the study, the score values were those of the last measurement, so that an immediate comparison to the last would be obtained by referring to the frequency distribution summary.

For example, assuming a last tread width measurement of 83mm, and if two value ranges are set for the frequency distribution, namely, “Less than or equal to the last measurement” and “Greater than the last measurement”, the frequency table would reflect how many participants reflected measurements that corresponded within the last measurements (would fit the shoe) and how many had greater measurements than the last (that would then constitute a poor fit).

Frequency tables and summaries were conducted for every variable measured.

The value ranges applied for each variable in the frequency distributions (in order to find whether all foot measurement variables would fit within the last measurement variables and whether any would not) are shown in tabular form in Table 3.10.

Table 3.10: Value ranges for frequency distributions.
* 10mm allowance for heel seat curvature, ** 2mm allowance as fit allowance.

Variable	Value range = acceptable fit	Value range = poor fit	
Minor foot length	Less than or equal to the last measurement	Greater than the last measurement	
Toe height	Less than or equal to the last measurement	Greater than the last measurement	
Tread width	Less than or equal to the last measurement	Greater than the last measurement	
Heel seat width*	Fits last measurement with 10mm margin either side	More than 10mm larger than last measurement	
Heel to ball 1 **	Fits last within 2mm margin on either side	More than 2mm smaller than the last	More than 2mm larger than the last
Heel to ball 5 **	Fits last within 2mm margin on either side	More than 2mm smaller than the last	More than 2mm larger than the last
Tape forefoot girth **	Fits last within 2mm margin on either side	More than 2mm smaller than the last	More than 2mm larger than the last

3.3.3.2.3 Measures of variability or dispersion

By themselves, measures of dispersion are not sufficient to fully describe a distribution of data, and must be accompanied by measures of dispersion that provide an indication of the amount of variety, how scattered or "spread" the values are within a distribution (Healey, 1993:101).

One measure of dispersion is the variance; in the case of a population, variance is denoted by σ^2. This is defined as the average squared deviation. Another measure used to indicate the "spread" or dispersion of data about their mean is the standard deviation. Standard deviation is the (positive) square root of the variance of the data. Thus, while the mean represents the "average" value, the standard deviation represents a type of "average variability" by taking the average of the deviations of each score from the mean (Welkowitz *et al.,* 1984:56).

In a normal distribution, 68% of cases fall within one standard deviation of the mean ($\mu - \sigma$ and $\mu + \sigma$) and 95% of cases fall within two standard deviations. For example, if the mean (μ) age is 45, with a standard deviation (σ) of 10, then 95% of the cases would be between 25 and 65 (two standard deviations) in a normal distribution (Melville & Goddard, 1996:65). The minimum value, maximum value and standard deviation (designated by s for samples and σ for populations) were the measures of dispersion used in this study.

3.3.3.2.4 Normality of distribution

Just as the concept of probability is inherent in statistical tests, the most common probability distribution for a continuous random variable is the normal sample distribution, usually depicted as a bell curve shape (Melville & Goddard, 1996:63). A normal distribution has two parameters, namely, its mean and standard deviation.

In order to move from the sample distribution (which exists and is known) to make inferences about the population distribution (which, while it does exist, is not known), inferential statistics make use of theories based on the laws of probability to create a sampling distribution, for which shape, central tendency and dispersion can be deduced.

The Kolmogorov-Smirnov test for "goodness of fit" was used to test normality in the study. This tests whether a data sample is compatible with being a random sampling from a given distribution and is expressed as:

$$D_N = \max \left| S_N(x) - F(X) \right| \text{over all } x$$

where the value D_N is calculated to compare a data sample of N events whose cumulative distribution is $S_N(x)$ with a hypothesis function whose cumulative distribution is F(x). Usually, values below 0,05 in this test will indicate a distribution that is not normal (Massey, 1951:68).

However, because of the size of the sample, the Kolmogorov-Smirnov test was used in conjunction with the Central Limit Theorem, which states that,

> "If repeated random samples of size *N* are drawn from any population, with mean μ and standard deviation σ, then, as *N* becomes large, the sampling distribution of sample means will approach normality, with mean μ and standard deviation $\sigma/\sqrt{N}$" (Healey, 1993:150).

The importance of the Central Limit Theorem is that it removes the constraint of normality in the population if *N* is 100 or more. This means that, whenever the sample size is greater than 100, one can assume that the sampling distribution is normal with a mean equal to the population mean and a standard deviation equal to $\sigma/\sqrt{N}$ regardless of the shape of the population (Healey, 1993:150).

3.3.3.3 Inferential statistics

Beyond determining whether any of the variables for foot measurements did not fit the respective variables in the last measurement, Pearson correlation analysis was carried out in respect of the whole sample, as well as by ethnic group. Correlations were carried out to establish links between variables. The correlations are a form of validation whereby common measurements that are theoretically linked can be proven practically since the objective is to gauge the proportion of people fitting or not fitting in shoes.

3.3.3.3.1 Pearson correlation analysis

Correlation is a measure of the relationship between two or more variables and is used to determine if any linear relationship exists between two continuous variables that can be considered statistically significant.

Correlation coefficients can range from -1.00 to +1.00. A value of +1 indicates a perfect linear dependence with positive slope. This means that, as the X variable's value increases, an associated proportionate increase is seen in the value of variable Y (Melville & Goddard, 1996:77). The formula for the Pearson's product moment correlation coefficient ("*r*") is represented as:

$$r = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sqrt{(\sum X^2 - \frac{(\sum X)^2}{N})(\sum Y^2 - \frac{(\sum Y)^2}{N})}}$$

Expressed another way, the value of -1.00 represents a perfect negative correlation (as one variable's values tend to increase, the other variable's values tend to decrease) while a value of +1.00 represents a perfect positive correlation (as one variable's values tend to increase, the other variable's values also tend to increase). A value of 0.00 represents a lack of correlation. A statistical test is attached to the correlation testing if there is a significant difference from 0.

Pearson correlations were used to examine the inter-correlation between variables. For example, each variable was tested in relation the variables for Body Mass Index (BMI) to see whether any patterns emerged, for example, foot width to BMI by ethnic group, foot girth to BMI by ethnic group, arch height to BMI by ethnic group.

Hypothesis testing for Pearson correlations comprise the following:
H_1 can indicate either (a) that there is a linear correlation (two-tailed), or (b) that there is a positive slope correlation (one-tailed upper tail), or (C) that there is a negative slope correlation (one-tailed lower tail). H_0 is the complement of H_1.

The existence of such patterns will not imply cause and effect. It merely finds that there is a high correlation or not, which will indicate direction for further investigation.

3.3.4 Summary of multi-ethnic 3-D metric methodology

Laser 3-D scanning, in combination with manual measurement for validation, by convenience sampling of the right foot of each of 500 active women aged 21 to 69, of differing ethnic origins, in two major urban regions, over a period of 12 months, yielded 13 foot measurements of each participant in addition to 3-D foot data. From all the feet sampled, those feet corresponding to an actual UK size 4 formed one sample group in order to be compared to the last. Comparable last measurements were recorded by means of laser 3-D scanning of a UK size 4 last.

Data was analysed by means of both descriptive and inferential statistical methods. Descriptive statistics consisted of the mean as the measure of central tendency; minimum, maximum value and standard deviation as the measures of dispersion; and the Kolmogorov-Smirnov test for normality of distribution. Frequency counts determined what percentage of participants would fit the footwear derived from the sampled last, and conversely, what percentage would be at risk of pathology from wearing footwear derived from such a last. Inferential statistics took the form of Pearson product-moment coefficients of linear correlation to examine the inter-correlation between variables and Body Mass Index.

3.4 Part three: Scaleable measurement comparison

In industry, all lasts are graded or scaled up (or down) from a model size 4 (Figure 3.51). The patterns for a size 3 (smaller) and sizes 5 to 10 (larger) are drawn by means of linear proportional grading or scaling. However, industry uses two grading scales on the same last; an increase of 8.463 recurring mm (one third of an inch) for length and 6.3475 mm (one quarter of an inch) for width. This means that, between sizes, the length difference will be 8.46mm but the width difference will only be 6.35mm.

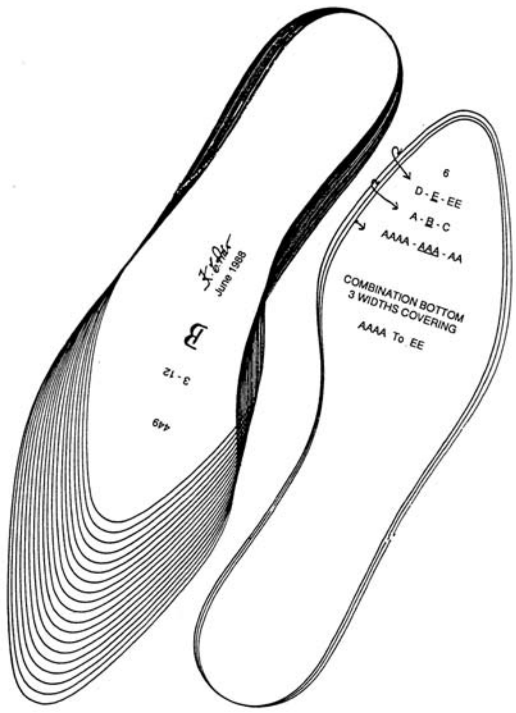


Figure 3.53: Linear grading of last bottom patterns. (Adrian, 1991:15)

3.4.1 Calculation and comparison of proportional scaled data

By using all the data for feet that were not "size 4" and applying a proportional scale to each foot's measurements so as to achieve a base foot length measurement of 234mm (UK 4 foot length as used by industry), a second group of data that were all foot length 234mm was formed. This enabled a comparison of means of both the data sets; one that corresponds to an actual "naturally" size 4 foot (N = 129), and the other to the new re-scaled size 4 data (N = 324).

A *t*-test for two independent sample means was conducted, to establish whether there was any significant difference between the means (Welkowitz *et al.,* 1982:159). The *t*-test is calculated as follows:

$$t = \frac{(\overline{X}_1 - \overline{X}_2) - (\mu_1 - \mu_2)}{s_{\overline{X}_1 - \overline{X}_2}}$$

A Student's t-test makes two assumptions about the data set: first, that the two samples are normally distributed, and second, that their variances (or standard deviations) are roughly the same.

Variances can only be pooled in the *t*-test calculation if the variances are approximately equivalent. In order to determine this (and thus the suitability of using a student's *t*-test), the variances will be tested for similarity by means of Levene's test for equality of variances. If the Levene's test is significant (value for significance is < 0.05), the two variances will be significantly different. If the significance value result in the Levene's test is > 0.05, the two variances are not significantly different, that is to say, the variances are approximately equal (Welkowitz *et al.,* 1982:159).

If the proportions for any dimension in reality were less than that applied to foot length as the foot increased in size, then the *t*-test would show that the mean measurements for such dimensions were significantly different ($p < 0.05$) for the scaled down group (the group that was scaled by one proportion across all dimensions), when compared to the mean measurements of the actual size 4 group.

If the *t*-test shows, statistically, no significant difference between the means, then this indicates that grading intervals or proportions utilized in the footwear industry should be the same for different dimensions such as foot length and tread width.