1 FEET AND FOOTWEAR

From a time when foot coverings of hide, skins, wood, bark and reeds were rough approximations of the irregular shapes they covered, to modern day developments in technology and ergonomic footwear design, mankind continues to search for shoe comfort and fit to facilitate the foot in its function of weight bearing, locomotion and support (Hawes & Sovak, 1994:1213; Rossi, 2003:10).

1.1 Shoe fit: an interaction of form and function

The dictum *form follows function* (originally four words, *form ever follows function*) was coined by an American architect Louis Sullivan in 1896 to describe the design of man-made objects as an expression of the natural world (Sullivan, 1947:208). The dimensional relationship of the form of footwear that follows function of the foot is thus integral to good footwear fit.

To explore and define the concept of fit, a number of factors that relate to both the foot and the shoe must be considered. One definition of shoe fit is the "ability of the shoe to conform to the size, width, shape and proportions of the foot" (Rossi, 2000: 63). Another is that fit relates to a sizing that allows for proper alignment and foot function inside the shoe (Rossi, 2000:63). Wunderlich and Cavanagh (2001:605) corroborate the sentiment expressed by Miller and Redwood (1989:44) that an acceptable fit can be obtained by a match of the footwear to the foot shape and foot measurements. Hence the importance of accurate foot measurement.

Certainly, for foot function, this will mean that some areas of the foot need a close snug fit to the shoe while other areas of the foot require clearance away from the shoe. Thus, poor fit could be characterized by both excessive tightness as well as excessive clearance (Lord & Pratt, 1999:252).

1.2 Importance of anthropometric studies and footwear surveys

Whether designing a new shirt or cutting leather for a pair of shoes, accurate body measurement data is critical to produce a superior yet more cost effective product (Parham, Gordon & Bensel, 1992:2; Robinette & Daanen, 1999:380).

The single most important factor about the shape of the last is that it should match the shape of the foot that the shoe is intended for (Fuller, 1994:254). Several morphometric studies have indicated ethnic and/or racial differences in foot morphology and endorse unique shoe lasts for each population (Hawes, Sovak, Miyashita, Kang, Yoshihuku & Tanaka, 1994:196; Anil, Peker, Turgut & Ulukent, 1997:79; Baba, 1975:156; Benard & Stephens, 1979:287; Thompson & Zipfel, 2005:22).

As late as nineteen hundred in North America, foot studies had little impact on the actual process of last making (Cavanagh, 1980:192). Subsequently, however, in North America, Europe and Asia, foot measurement surveys are often undertaken, frequently in conjunction with their footwear industries, to promote close co-operation between last and footwear manufacturers to ensure good fit (Baba, 1975:156; Kouchi, 1995:1919; Kusumoto, Suzuki, Kumakura & Ashizawa, 1996:373; Hawes *et al.*, 1994:196, Miller & Redwood, 1989:45; Liu, Miller, Stephanyshyn & Nigg, 1999:347).

Studies are conducted regularly since over the course of time, the average size of a population may change (Smith & Norris, 2004:1195). In some populations, for example, the CAESAR project showed that leg length has grown faster in relation to the growth of the trunk (Vitronic, n.d; CAESAR, n.d).

1.3 Importance of footwear fit to health

Footwear fit is inextricably linked to foot health in both diabetic and non diabetic populations (Chantelau & Haage, 1994:114; Chantelau & Gede, 2002:408; Nancarrow, 1999:57; Macfarlane & Jeffcoate, 1997:867). Footwear used to support erect body weight for a working day must fit well, as well as provide shock absorption against ground reaction forces (GRF) from rigid surfaces (Klenerman, Nissen & Baker, 1976:136; Johnson, 1994:68).

Medically, the function of a shoe has been variably described as: to protect the foot from hard surfaces; to enable full function of the foot; to protect from extremes of temperature and moisture as well as from trauma such as knocks and scratches (Cheskin, 1987:1; Lord & Pratt, 1999:249). Prevention of deformity has been described as a further "function" of the shoe (Jackson, 1990:325).

However, it is well documented that foot pathology such as blisters, corns, callus and toenail deformities can be caused by ill-fitting footwear (Stewart, 1972:120; Mantaura & Bryant, 1989:347; Dawber, Bristow & Mooney, 1996:21). In general, however, society ascribes a cosmetic or decorative fashion value to footwear (Lord & Pratt, 1999:249; Seale, 1995:379; Arlen, 1984:247).

A recent study of a sample of South African women showed that 80 percent ascribe foot pathology to their footwear (Thompson & Zipfel, 2005:27). This finding became the initial stimulus that prompted further investigation into footwear fit for South African women and gave rise to the current study's research question – does the shoe fit the foot?

To investigate the physical aspect of footwear fit, it is necessary to explore the physical parameters of both shoe and foot.

1.4 To make a shoe: the last is first…

Footwear is manufactured using specialized foot forms or "lasts" (Figure 1.1). The origin of the word "last" is from an Anglo Saxon word "laest", meaning footprint or foot track (Rossi, 2000:98). The last is the working surface on which the components that make up a shoe (such as the upper, the sole and the heel) are shaped and affixed to each other (Figure 1.2). Thus, lasts determine the exact size, shape and fit of the footwear produced on them. It follows then, that there can be as many different lasts as there are sizes and shapes of shoes.

Until the nineteen sixties in Europe and the United States, last model makers shaped lasts by hand from wood. Plastic has largely replaced wood in commercial last making and shoe manufacture (Figures 1.1 and 1.2), since it has superior shape-retaining properties through temperature and humidity changes (Rossi & Tennant, 1984:67). Measurements on a plastic last will, thus, not change due to warping or swelling. However, when describing the addition of volume to a last shape, last makers may still refer to the "adding of wood" to describe this action.

Figure 1.1: Female last[a] circa 2003.

[a]Photograph illustrating the polyethylene material used in South Africa.

Figure 1.2: Sandal upper and sock affixed[a] to last.

[a]Photographed in Kwazulu Natal during shoe production, 2003.

1.4.1 Measurement sets for last making

Lasts are interpreted by a model maker from sets of measurements, either based on the existing British measurement set called the "UK standard" or on unique measurement sets as requested by a particular manufacturer (Vandenheede, 2003; Wilson, 2005). The most basic of these will include only three measurements taken from the foot (foot length, tread width and tread girth, also known as ball girth) while custom requirements could necessitate some 15 to 30 measurements of the foot to create a custom last (Rossi, 1980:533; Miller & Redwood, 1989:44).

The basic measurements to make a last are calculated from foot measurements, to which a number of additional allowances or certain differences are made (Figure 1.3) for the purposes of making the shoe. For example, the area on the last that equates to the toe end of the shoe (called the "toe recede" on the last) will extend beyond where the physical tips of the toes would end (Figure 1.3).

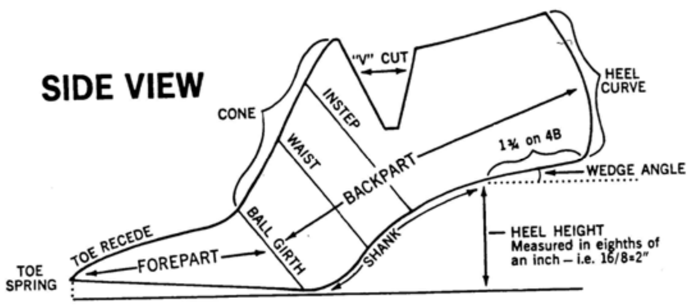

Figure 1.3. Regions[a] for measurement parameters on a last. (Adrian, 1991:7)

[a]Region of toe recede is tapered in this example.

1.4.2 Different lasts for different styles

Last makers begin a last for a new style by making a model last. A model last for a woman's shoe in South Africa is generally made to what is referred to as a "women's UK size 4" (this corresponds to a foot length of 234 mm) and a tread width of 78 mm (Vandenheede, 2003; Wilson, 2005).

Any styling that deviates from the natural form of the foot (for example, a pointed toe shape) must be embodied in the form of the last so that it will translate onto the shoe; thus different lasts are used for different styles (Miller & Redwood, 1989:70).

Particularly in women's footwear, the demand for variation in fashion means that there is a last for every single different construction style and heel height. Since there are so many shoe styles, with corresponding lasts, it would be bewildering to attempt to compare all women's lasts in South Africa with the population's feet. However, it will be seen that variation in shoe styles is based on a few basic style forms. Fashion, on the other hand, is constantly evolving, reflecting contemporary attitudes, trends or lifestyles and is, usually, a variation of a basic style.

Differing classifications exist as to what constitute the basic styles. Riches (1980a:1.2) maintains that there are three shoe styles: open tab, closed tab or slip on (Figure 1.4). Both open and closed tab styles are those that have some form of fastening so that the foot can enter the shoe easily and by which the shoe holds firmly onto the foot. Slip on footwear has no special fastening to keep the shoe on the foot.

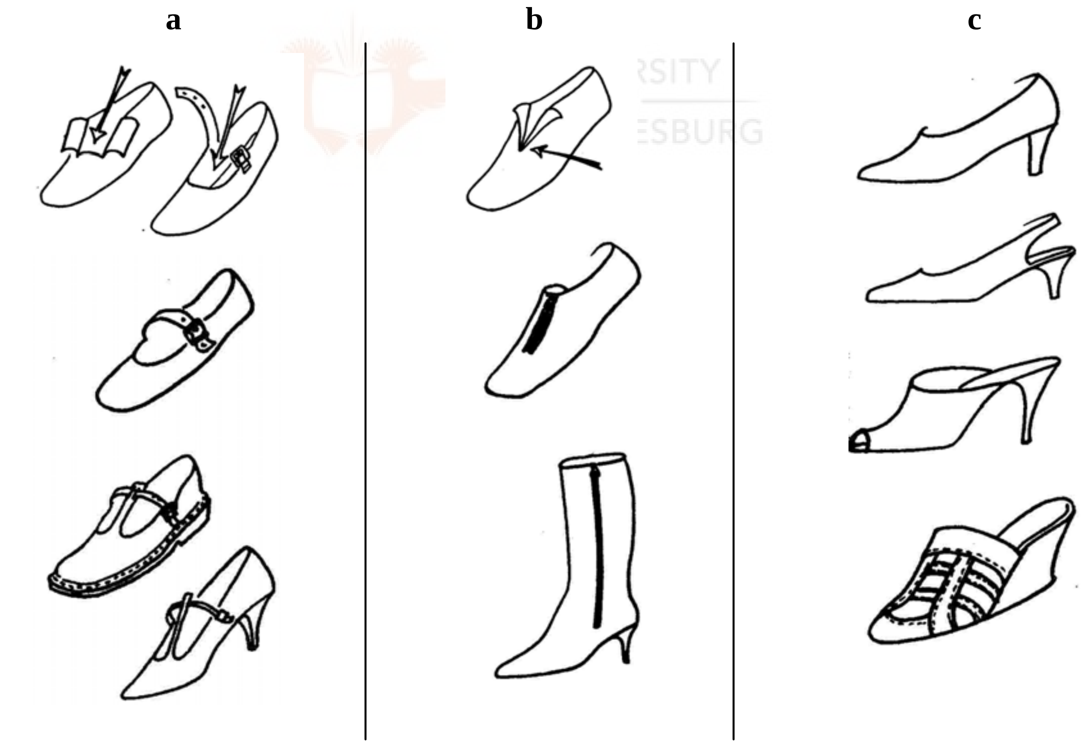

Figure 1.4: Examples of [a]Open Tab, [b]Closed Tab and [c]Slip On styles. (Riches, 1980a:7)

[a]Open tab footwear has ample opening to admit the foot in the instep area. [b]Closed tab footwear has a limited opening that is not as wide as open tab footwear. [c]Slip On footwear admits the foot easily and is held in place by "clip" and friction.

In contrast, Rossi (1985:169) maintains that there are only seven shoe styles; boot, clog, oxford, moccasin, mule, pump and sandal, (Figure 1.5), while Menz and Sherrington (2000:659) added a further eight general shoe styles but omitted the mule style to form a new grouping of 14 style options (Table 1.1).

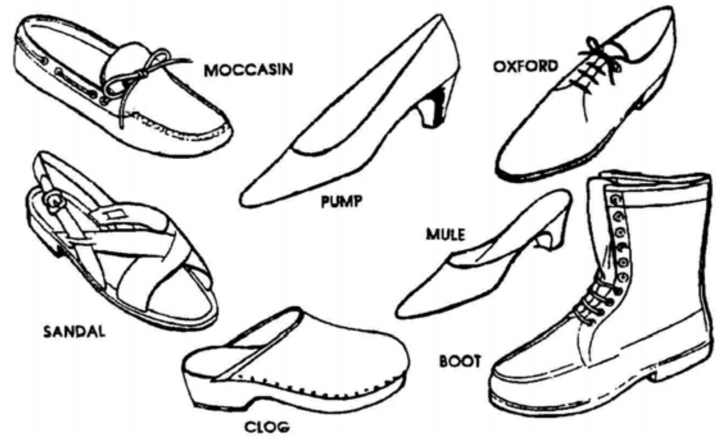

Figure 1.5: The seven basic shoe styles. (Rossi, 1985:170)

Table 1.1 by contrast, shows the overlapping of these three methods of classification, mainly on the basis of their function.

Table 1.1. Overlapping of shoe style classifications

Riches (1980a)	Rossi (1985)	Menz and Sherrington (2000)
Slip on	Mule or clog	Mule
Slip on	Mule or clog variant	Backless slipper
Slip on	Mule or clog variant	Thong
Slip on	Mule or clog variant	Slipper
Slip on	Pump	Court shoe
Slip on	Moccasin	Moccasin
Slip on/ open / closed tab	Pump variant	High heel
Slip on/ open/ closed tab	Sandal	Sandal
Closed tab	Oxford	Oxford
Open/ closed tab	Oxford variant	Walking shoe
Open/ closed tab	Oxford variant	Athletic shoe
Open tab	Oxford variant	Surgical/bespoke footwear
Open/ closed tab	Boot	Boot
Open/ closed tab/ slip on	Boot variant	Ugg boot

The classification by Riches (1980a) is related to footwear manufacture considerations while the classification by Rossi (1985) appeals to foot health specialists such as podiatrists who are concerned with foot function. The classification by Menz and Sherrington (2000) extrapolated the Rossi classification using commonly known names in order to facilitate a consumer survey process.

1.4.3 Last curvatures: art or science?

In the traditional last making process, the model maker or last maker uses artistic skill to form the curvatures of the last, for which generally only six measurements are taken, using a combination of a last stick and last tape (Riches, 1980b:3.29; Cavanagh, 1980:189). Depending on the sculptural skill and experience of the individual last maker, the outcome can be highly variable. Advances in computer technology make alternative, high speed and digitally accurate means of measurement available to reproduce these curves, based on actual 3-D recorded curves.

Dimensional accuracy is important when considering fit in any section of the shoe. For example, heel curves in a last should be matched to the heel curve shapes of the feet in the population for whom the shoe is intended (Lucock, 1972:C10/3).

It is theoretically possible to have two individuals whose foot shapes are different, yet share identical forefoot circumference. As can be seen from Figure 1.6, each shape might have the same girth circumference but have a different width. This results in a different forefoot shape.

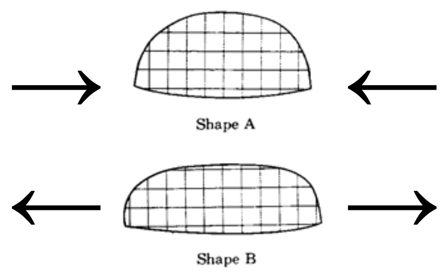

Figure 1.6: Identical ball girths on different shape[a] lasts.
(Rossi & Tennant, 1984:82)
[a]Different bottom or tread width will affect foot function.

In conventional shoe manufacture for women, crowding of internal foot structures such as metatarsal heads, blood vessels and nerves occurs when the forepart width of a shoe is narrowed in a cosmetic attempt to make the shod foot look more slender. Last shapes that are altered in this way will thus fit and feel differently on the foot.

In the same way, ball or joint volume shape differences exist between different foot types, as seen in Figures 1.7 and 1.8. These foot types could share certain common measurements but require a different last.

a b c

Figure 1.7: A pes planus[a], ”normal [b]” and a pes cavus[c] foot. (Author’s collection)

[a]Pes planus is characterized by loss of the medial longitudinal arch of the foot with altered postural changes: heel in valgus; subluxed subtalar and abducted midtarsal joints and supination of the forefoot relative to the rearfoot (Canale, 1998:1712).

Whilst definitions of “normalcy” continue to be debated, a [b]”Normal” foot displays a neutral subtalar position so that forefoot and rearfoot are neither supinated nor pronated (Phillips, 2000:342).

[c]Pes Cavus displays a high medial longitudinal arch of the foot with altered postural changes: heel in varus; forefoot is plantarflexed excessively on the rearfoot or the rearfoot is dorsiflexed excessively on the forefoot (Smith, Pitts & Green, 1992:731).

Because of the differences in elevation and posture of the forefoot in the above three foot types, it can be understood that the height and shape dimensions in the region of the metatarsophalangeal joints (ball of the foot) forefoot region, will also differ (Figure 1.8).

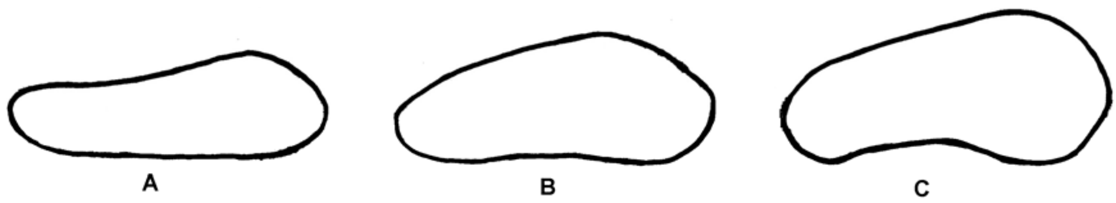

Figure 1.8: Coronal plane forefoot shapes of three different foot types in the study. A. Flat Arch, B. Average Arch, C. High Arch

1.4.4 Last sizing and grading

The English system is believed to have originated in 1324 when King Edward II legalised a standard that three average sized barley corns, placed end to end, would equal one inch (Cavanagh, 1980:195). For example, if a human foot was thirteen inches long (thirty-nine barley corns) and each size smaller than “size thirteen” was one barley corn less, then “size twelve” would be thirty eight barley corns, or twelve and two thirds inches long. This is reflected in the present sizing system in which the length unit between English sizes is one-third of an inch (Figure 1.9). Lasts are thus “graded” in length increments of one-third of an inch (Rossi & Tennant, 1984:80; Turner, 2006:4).

These concepts, however, are not so simple. Size zero (British) starts at exactly four inches for a child’s entry level shoe. Children’s shoe sizes progress through thirteen sizes until they end at eight and one-third inches, at which point both men’s and ladies’ sizes commence. Size two for adults is, thus, nine inches long as seen in Figure 1.9 (Rossi & Tennant, 1984:82).

In the North American sizing system, the length difference between sizes is the same (one third of an inch) but size zero starts at one twelfth of an inch before size zero British, i.e., at three and eleven twelfths inches instead of four inches. British shoes on the American population therefore, fit slightly looser (Rossi & Tennant, 1984:88; Turner, 2006:4).

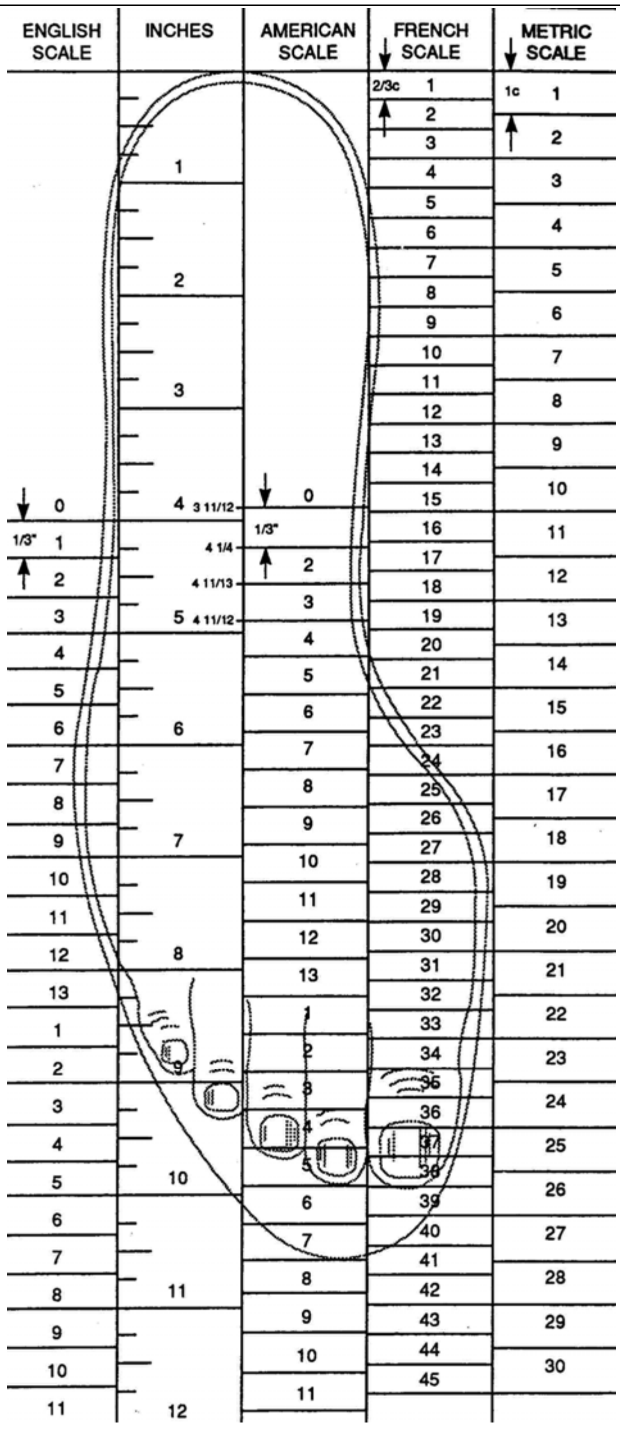

Figure 1.9: International Scale Comparisons[a].
(Adrian, 1991:72)

[a]Note that due to base model differences, the shoe sizes cannot be read off this scale. For example, American size 6B women's = base length 9 2/3 inches whilst English size 6B women's = base length 10 1/6 inches.

Moreover, whereas men and women's sizes in the British system are the same length, the American system for women's sizes does not match that of men (Figure 1.10).

Schuhgrößen-Vergleichstabelle
Footwear Size Scale conversion
Table de Conversion des Pointures de Chaussures

Damen und Mädchen → Women and Girls Dames et Jeunes Filles			Herren und Knaben → Men and Boys Hommes et Garcons		
Europa Europe Europe	GroBbritannien Great Britain Grande Bretagne	USA United States Etats Unis	Europa Europe Europe	GroBbritannien Great Britain Grande Bretagne	USA United States Etats Unis
31	12 1/2	1	32 1/2	13 1/2	1
32	13	1 1/2	33	1	1 1/2
32 1/2	13 1/2	2	34	1 1/2	2
33	1	2 1/2	34 1/2	2	2 1/2
34	1 1/2	3	35	2 1/2	3
34 1/2	2	3 1/2	36	3	3 1/2
35	2 1/2	4	36 1/2	3 1/2	4
36	3	4 1/2	37	4	4 1/2
36 1/2	3 1/2	5	38	4 1/2	5
37	4	5 1/2	38 1/2	5	5 1/2
37 1/2	4 1/2	6	39	5 1/2	6
38	5	6 1/2	39 1/2	6	6 1/2
39	5 1/2	7	40	6 1/2	7
39 1/2	6	7 1/2	41	7	7 1/2
40	6 1/2	8	41 1/2	7 1/2	8
40 1/2	7	8 1/2	42	8	8 1/2
41	7 1/2	9	43	8 1/2	9
42	8	9 1/2	43 1/2	9	9 1/2
42 1/2	8 1/2	10	44	91/2	10
43	9	10 1/2	44 1/2	10	10 1/2
44	9 1/2	11	54	10 1/2	11
44 1/2	10	11 1/2	46	11	11 1/2
45	10 1/2	12	46 1/2	11 1/2	12
45 1/2	11	12 1/2	47	12	12 1/2
46	11 1/2	13	48	12 1/2	13
			49	13	14
			50	14	15

Figure 1.10: Footwear Size Scale Conversion[a].
(Adrian, 1991:73)

[a] Continental, British and North American sizes.

A third system called Continental sizes (sometimes referred to as Paris Points) consists of one continuous range based on the metric system. Size zero Continental starts at zero centimeters and the difference between sizes is two thirds of a centimeter (Cavanagh, 1980:196).

It is important to note that the British, American and Continental systems derive size from a "stick length" measurement of the last, not of the actual foot, as in the Japanese system.

Japan has its own sizing system, sometimes referred to as the metric system (Kouchi & Mochimaru, 2004). In the Japanese shoe size system, shoe size is determined by length and ball girth, and the shoe size indicates the size of the foot that fits to the shoe, not the size of the shoe itself. Human foot length and foot circumference correspond respectively to the length and ball girth of the shoe. Length is indicated in centimeters. Since foot circumference could be widely different even when the foot length is the same, there are shoes of the same length but with different ball girths. A woman's shoe with average circumference (for the Japanese population) is called "E", and becomes EE, EEE, EEEE, with increasing ball girth, while "E" becomes D, C, B, or A with decreasing ball girth. To cope with the variation in foot size, Japanese shoe length sizes change by 5 millimeters, with ball girths changing by 3 millimeters. In the Japan Industrial Standard (JIS) of shoes, sizes range from 20A to 30G for adult males, from 19.5A to 27EEEE for adult females, and from 10.5B to 26G for children's shoes.

There have been two unsuccessful attempts to address the incompatibilities of the various systems by creating a single metric world system, called Mondopoint 5mm and Mondopoint 7,5 mm, in which (respectively) foot length size increments would be 5 millimeters or 7,5 millimeters (Riches, 1980b:36).

Since all measurements for last sizing and grading systems start with dimensions of the foot, the next section will examine the general anatomy and morphology of the foot, as well as anomalous and typical variations in morphology.

1.5 The foot: general anatomy for anthropometry

The skeleton of the human foot is a complex asymmetrical arrangement of twenty six bones that can be divided into three groups, namely the tarsus, metatarsus and the phalanges (Figure 1.11). Differences in size and shape of the underlying bones, overlaid by the myriad of muscles, ligaments, tendons, cartilage, nerves, blood vessels and skin, result in individual variations in morphology.

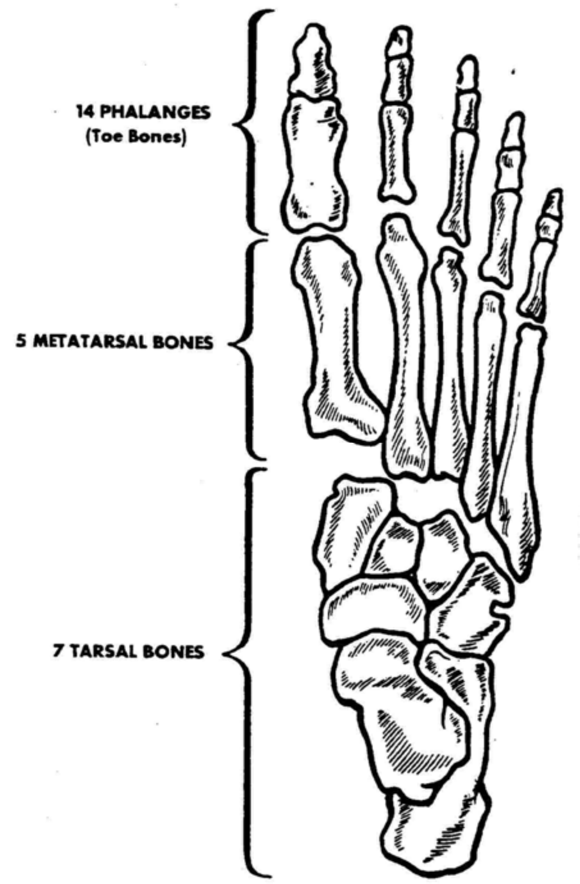

Figure 1.11: Bones of the foot[a].
(Rossi & Tennant, 1984:1)
[a]Brackets indicate tarsal, metatarsal and phalangeal regions of the foot.

Certain anatomical structures beneath the skin determine the external shape and size of the foot and ankle. One approach in clinical examination of the foot is to define palpable bony external landmarks, as these indicate the position and extent of underlying bone structures (two of these are shown in Figure 1.12 for the purposes of illustration).

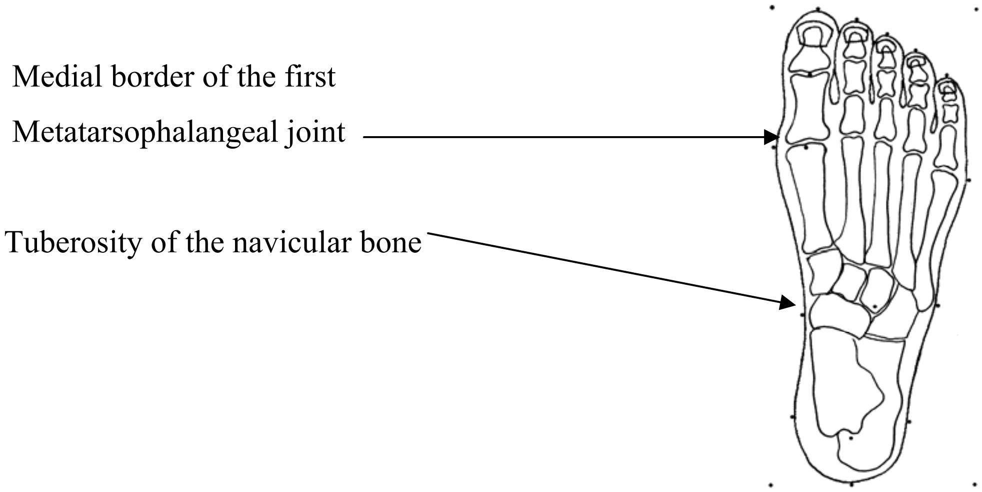

Figure 1.12: Dorsal view of two palpable bony landmarks of

Palpation will also reveal the shape and position of muscles, joint, tendons and ligaments (Lumley, 1990) as found attached to underlying bone (Figure 1.13).

Figure 1.13: Position of retinacula and synovial sheaths of the foot.
(Backhouse & Hutchings, 1989:291)

In turn, all of the palpable and underlying anatomy is covered in skin, which defines the anthropometric shape and dimensions of the foot and ankle (Figure 1.14).

Figure 1.14. Foot surface anatomy. (Backhouse & Hutchings, 1989:278.)

Key:
1. Fibula to lateral malleolus
2. Peroneal tubercle;
3. Talus (distal projection)
4. Extensor digitorum brevis muscle
5. Calcaneal tubercle
6. Base of the fifth metatarsal
7. Peroneal tendons
8. Achilles tendon
9. Calcaneus (proximal projection)
10. Tibia to medial malleolus
11. Sustentaculum tali
12. Navicular tubercle
13. Base of first metatarsal
14. Head of first metatarsal

Adequate references exist to assist in location of bony landmarks, as undertaken in a measurement study. For example, the lower part of the fibula is palpable about 15 centimeters above the lateral malleolus, and extends downwards, ending up lower than the level of the medial malleolus. To detect the groove for the peroneal tendons, one would press firmly with a fingertip upwards and forwards from behind the most distal part of the lateral malleolus (McKears & Owen 1979:38).

1.5.1 Anomalous variations in morphology

Foot anomalies, pathologies and trauma can change the conventional morphology of the foot (Hughes, 1995:228), thus impacting on selection criteria of footwear. Examples of such conditions are hallux valgus (commonly known as ‘bunions’) and deformities of the digits such as hammer toes. The incidence of such anomalies in the South African population is not known.

1.5.1.1 Loss of muscle function

Certain neurological conditions such as polyneuritis and cerebral palsy, for example, will affect muscular function in the lower limb and the foot. Impaired neural function leads to muscle atrophy with resultant changes in muscle bulk, thereby impacting on the typical muscular morphology of the foot (Rendall, Thomson & Boyd, 1997:79).

1.5.1.2 Oedema

Similarly, pathologies such as systemic illness, infections, vascular impairment, trauma, arthritides, toxins, medication interactions, or metabolic illnesses such as diabetes mellitus or hypothyroidism can lead to oedema or swelling of the foot, and thereby alter the foot’s typical morphology (Beers & Berkow, 1999:169, 426, 484, 1056, 1266, 2644). See also 1.5.2.3 for non pathological causes of swollen feet.

1.5.2 Typical variations in morphology

Many different classifications of feet on the basis of size and shape have been attempted. Some classifications are based on typical variations in structural type due to variation in medial longitudinal arch height such as pes cavus or pes planus; others on foot function related to planar movements such as supination and pronation (Rendall *et al.,* 1997:68). Still others have classified the feet according to forefoot shape such as “Square Foot”, “Greek Foot” or “Egyptian Foot”, determined by differing metatarsal and phalangeal (toe) lengths (Viladot, 1973:165).

In the shoe industry, feet may be termed long-narrow, short-wide, in flared, out flared, fleshy or bony (Riches, 1980b:3.15). These terms are echoed in descriptions used in traditional last manufacture.

Anthropometric classification of body types and structures involves three main somatotypes: ectomorph, mesomorph and endomorph, as classified by the psychologist Sheldon (1940:35). A typical ectomorph would be tall, slender, long boned and slim muscled. Mesomorphs appear muscular, stocky and heavy boned while endomorphs are small-boned, fleshy and plump. No body type is entirely any one of these but rather a combination of two or three types, usually with one type dominant. According to Rossi (1988:394), foot forms will follow somatic or body forms, each with their own footwear requirements. Although recent studies have not adequately investigated this in terms of anthropometry, skeletal variation has been shown in modern humans (Zipfel, Kidd & Berger, 2003:231; Zipfel, 2004:1; Kidd & Oxnard, 1997:57-69).

While most studies have investigated the variation in volume or foot length, only recently have studies investigated changes in foot shape and their interaction with footwear due to such changes (Kouchi, 1996:861, Houston, 2002:10; Luximon, Goonetilleke & Tsui, 2003:380; Kurz & Stergiou, 2004:53; Krauss, Grau, Janssen, Maiwald, Mauch & Horstmann, 2005:2). Beyond structural variations, there are variations in the foot due to age, gender and other factors.

1.5.2.1 Age

Although Anderson, Blais and Green (1956:287) state that feet stop growing in length in 75% of girls by age 14 even though they may increase in stature, it has also been stated that completion or cessation of growth in the foot occurs between age 20 to 21 in females (Tachjian, 1990:62). In a study conducted by Lewis, Lavy and Harrison (2002:732), they highlight the fact that the Greulich and Pyle Atlas, conventionally used to assess skeletal maturity in studies in the developed world, is not necessarily relevant to sub-Saharan populations. This is due to the possibility of maturation delaying factors such as poor nutrition and chronic diseases such as malaria.

The prior statement by Anderson *et al.,* (1956:287) also does not address probable change in foot shape, volume or proportion after age 14 in females. In fact, Rai, Bansal and Prakash (1978:129) confirmed earlier observations made by Hill (1958:349) that foot girths continue to increase even after foot length growth has ceased.

As a consequence of general loss of tone, decreasing collagen levels and other effects of ageing, female foot size can alter with age (Frey, Thompson, Smith, Sanders & Horstman, 1993:79; McGlamry, 1978:233; Schuster, 1978:236). Foot spread can contribute to increased foot width with ageing, while loss of plantar fibro-fatty pad thickness and elasticity can increase with age and contribute to the altered shape and function of the foot (Özdemir, Söyüncü, Özgörgen & Dabak, 2004:47).

In addition to the influence of age, there are also foot size and shape variations due to the local environment of the foot.

1.5.2.2 Growth environment

While the extreme deforming and growth-inhibiting effects of ancient practices such as Chinese foot binding have been documented (Jackson, 1990:323), other environmental factors can affect the size and shape of the foot, sometimes within the same day. These include heat and moisture.

1.5.2.3 Temperature and fluid balance

Foot shape can be affected by heat, humidity or moisture and friction within the shoe. Foot volume can differ by 5 percent at the end of a day compared to early morning, due to thermal conditions (Rossi & Tennant, 1984:92). Increased ambient temperature and fluid imbalances in the body can result in accumulation of fluid in the tissues (Hargens, 1981:1) often visible as swollen feet.

1.5.2.4 Load

The weight bearing foot is different from the static or "at rest" foot in shape, size and proportions (Rossi & Tennant, 1984:91). "Weight bearing" refers to the foot on standing erect, not walking or running. Foot dimensions change as a result of loading in weight bearing as opposed to non weight bearing. These altered dimensions, such as increased tread width and lowered arch height, differ between individuals according to the flexibility and structural mechanics of the foot (Lord & Pratt, 1999:253).

Tests have shown that the foot on weight bearing elongates, not only distally but proximally as well, where there is a certain amount of rearward thrust of the heel (Rys & Konz, 1994:686). This may be due to the lowering of the medial longitudinal arch and increase in the talocalcaneal angle as the arch lowers, thus thrusting the calcaneus distally. On weight bearing, the foot widens across both the ball and the heel, and there is more spread of volume at the waist and instep. After four hours of standing, forefoot maximum width can increase by three percent (Rys & Konz, 1994:686).

1.5.2.5 Activity

Understandably, there are morphological variations of the foot during movements such as walking, running, dancing and jumping. During such activity, the foot moves through multiple planes (Seibel, 1988) and assumes different combinations of size, shape and proportions, due to the differing bulk of underlying anatomical structures, as different muscles contract and relax (see 1.5).

1.5.2.6 Asymmetry

In 1982, the National Prescription Footwear Association in the United States of America, in collaboration with podiatrists and retailers, performed measurement of 6 800 pairs of adult men and women's feet in 23 cities. Measurements taken were overall foot length, ball width, heel to ball length and heel width of both the left and the right foot. Measurements were recorded both with the participants seated and then again on weight bearing. Not a single perfectly matched pair of feet was found (Rossi, 1983:105).

1.5.2.7 Gender

Apart from variations due to body type, variations in foot shape and size have been ascribed to gender, age and race (Cheskin, 1987:235; Kouchi, 1989:142). According to some American studies, the mean female foot length is approximately 91 percent of the mean male foot length (Rys & Konz, 1994:679; Konz & Subramanian, 1989:204).

Gender differences (sexual dimorphism) in adult lower limb structure and foot shape indicate that the female foot is not a scaled-down version of a male foot. Different shape characteristics are found, for example, at the medial arch, the lateral side of the foot, the first toe and the ball of the foot (Wunderlich & Cavanagh, 2001:610). Sexual dimorphism in the skeletal foot is well documented (Kidd & Oxnard, 1997: 57-69; Kidd, 1995:187-199; Zipfel, Kidd & Berger, 2003:231; Ferrari, Hopkinson & Linney, 2004: 434; Zipfel, 2004:206-359; Tobias, 2005:205). These “dimorphisms” are subtle, yet verifiable and manifest in “external” morphology (Zipfel, 2004: 206-359; Krauss *et al.,* 2005).

Radiological evidence of gender differences in an African population was found in a Ugandan study in which the calcaneal angle in females was found to have a significantly higher mean value ($p < 0.01$) than that of males (Igbigbi & Mutesasira, 2003:328).

1.5.2.8 Pregnancy

Increased production of oestrogen and the increased level of aldosterone secretion are responsible for the sodium-retaining effect that results in generalized and lower limb oedema in pregnancy (Bell, Davidson & Scarborough, 1968:1161). Also to be taken into consideration are the physical factors such as increased pressure of the growing uterus against blood vessels and lymphatics in the lower abdomen (supplying the lower limbs) that can lead to hypertension (Beers & Berkow, 1999:2022).

1.5.2.9 Ethnic, tribal or population sub-group

Not only have studies shown sexual dimorphism but metric and morphological variation is present between human sub-group phenotypes and populations (Patriquin, Loth & Steyn, 2003:255). Evidence of tribal variations in foot morphology exists in a variety of sources. Archeological findings in the British Isles have shown differences between Saxon and pre-Saxon foot bones that translated into general foot morphology differences between modern Scots-Irish females and modern English females at that time (Jackson, 1996:67).

Several studies indicate ethnic and/or sub-group differences in foot morphology, and endorse unique shoe lasts for each population group (Hawes *et al.,* 1994:191; Benard & Stephens, 1979:295; Anil *et al.,* 1997:87; Baba 1975:156; Parham *et al.,* 1992:9).

Early research into the morphology of "Bantu" and "European" feet in South Africa found marked differences in contact area of the sole, in which the "Europeans" examined were found to have an elevated arch that did not contact the ground. By contrast, the "Bantu" examined had hypertrophy of the skin's stratum corneum layer along the entire extent of the sole, attributed to total sole contact with the ground, including the area of the medial longitudinal arch (Wells, 1931:192).

In the study of genetics, combinations of deoxyribonucleic acid (DNA) polymorphisms are known as haplotypes (Hitzeroth, 1986:390). Haplotypes and polymorphisms have been found to distinguish, for example, the Khoisan people from other African peoples (Steinberg, Jenkins, Nurse & Harpending, 1975:528). A radiographic study of the calcaneal angle found significant ($p<0.001$) differences between Ugandan and Nigerian women (Igbigbi & Mutesasira, 2003:328).

In an early (unsubstantiated) observation, Cheskin (1987:235) grouped feet into three groups, namely Negroid, Mongoloid (Oriental) and Caucasoid. The classic male Negroid foot described by Cheskin is broad at the forefoot and narrow in the heel, although female feet could be slightly narrower and straighter. The Mongoloid female foot shape is described as short and broad in the forefoot and heel. The Caucasoid male foot is described as broad with straight toes, while the females are considered to generally have narrower feet, with an equal mixture of high, normal and low arches (Cheskin, 1987:235).

Tabulation of these statements in Table 1.2 shows an overall trend to a broad forefoot, with more difference present in the heel.

Table 1.2: Ethnic morphological differences in feet. (Cheskin, 1987:235)		
	Forefoot	Heel
Negroid male	broad	narrow, thick heel pad
Negroid female	slightly narrower than male Negroid	narrow, thick heel pad
Mongoloid male	short and broad	short and broad
Mongoloid female	short and broad	short and broad
Caucasoid male	broad	broad in warm climates
Caucasoid female	narrower than male Caucasoid	narrower than male Caucasoid

1.5.3 Relevance of anatomical variation to the current study

The great extent of known and expected variations in foot morphology would seem to negate the possibility of the footwear industry ever making a shoe that would fit even one group of individuals. Yet modern ergonomic and anthropometric studies have been successful in forming groups of statistically verifiable anatomical characteristics so that "clustered" body and foot types are defined.

The current study is important in that it started the process of gathering 3-D data from a representative cross section of the population so that as many anatomical variations as possible will be represented and be recorded in the data for future "cluster type" studies. Since 3-D foot data of female African feet were collected for the first time in this study, future analysis of this data may reveal a foot type previously not accommodated by the shoe industry.

1.6 Non physical factors affecting fit

Physical dimensions and variations are not the only considerations when it comes to footwear fit. More than three decades ago, the Battelle study as described by Rossi (1988:400) described thirty seven factors affecting footwear fit (Figure 1.15). Amongst these were mechanical factors such as anatomical or physical measurements and sensory factors such as materials and fabrics used. There are also many psychological and sociological factors such as price, peer pressure and fashion trends that exert enormous influence on the selection of footwear. Fashion has been responsible for such features as pointed toes, platform soles, fragile "spaghetti strip" uppers and backless shoes. According to Rossi (1988:401) these features are not compatible with proper fit, nor do they facilitate natural foot function.

It can be seen from Figure 1.15 that physical factors constitute the majority of reasons for determining fit. This fact supported the selection of physical dimensions as the starting point for this study.

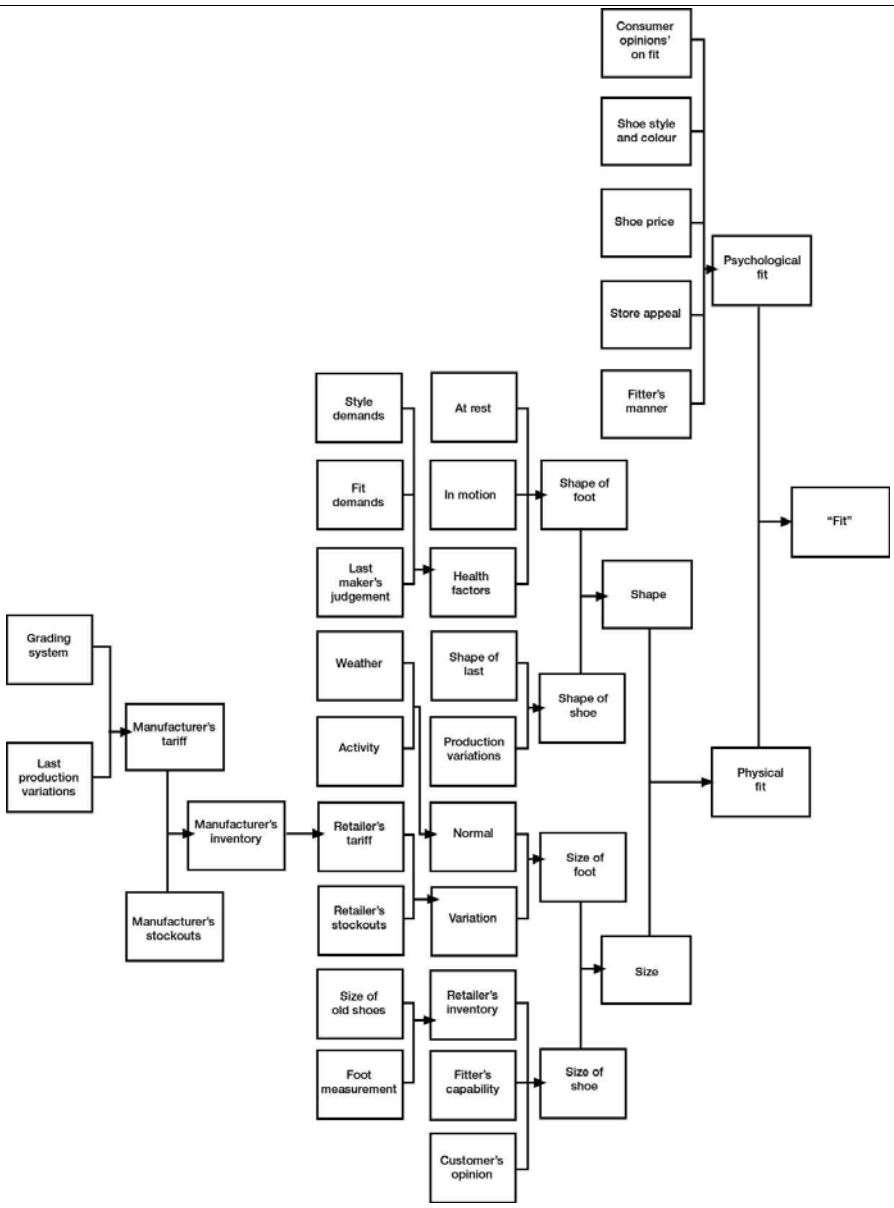

Figure 1.15: Factors affecting fit according to the Battelle Study. (Rossi, 1988:400).

Before conducting such an investigation into the accuracy of fit based on measurements, it was also necessary to explore the differences between the last and the foot in order to select physical parameters that could be measured and compared within the limits of the present study.

Interaction of the foot with the footwear is discussed in 1.7. This is carried out, firstly, to position the focus of the current study in the broader context of the subject, and secondly, to identify areas that will require future investigation.

1.7 Interaction between the foot and footwear

According to Rossi (1988:393), a shoe fits "when the dimensional profile and sections of the shoe correspond to the dimensional profile and sections of the foot". As discussed in 1.3, foot pathology due to pressure and friction can result from a mismatch between the foot dimensions and those of the shoe. Variations in feet will affect the match with footwear. The following area to be examined is that of the difference between the last and the foot.

1.7.1 Why the last cannot be identical to the foot

The last needs certain differences to enable it to be a tool for the shoemaking process (Miller & Redwood, 1989:69; Lucock, 1972:C10/2). For instance, the last does not replicate individual toe contours nor toe web spaces, since footwear is shaped to the toe area of the last as a working surface. In addition to filling in the contoured surface shape corresponding to the toes, lasts have a feather edge or line: this is a well-defined edge between the top of the last and the bottom of the last, so that the sole of the shoe can be attached to the upper.

Other differences include a length allowance, fashion allowance, extra depth over toes, extra or less girth allowance over the joint girth, toe spring and last pitch. Last pitch is also known as heel pitch or heel height (Riches, 1980b:20; Miller & Redwood, 1989:69). According to Lucock (1972:C10/2), these are adjustments intended to allow for all the movements of the foot within the footwear for which it is designed.

Certain styles of shoes will need further allowances in order to facilitate the manufacture of the shoe or some property of the shoe in wearing. Examples of these include wider heel seats for open-backed styles; shorter overall length for sandals and moccasins; and wider front cones for some styles such as boots.

Since the last is most responsible for the fit, shape, style and size of the footwear produced on it (Miller & Redwood, 1989:56), it can be understood that the measurements for a last and its design are linked to foot health in a shoe wearing population.

1.7.2 Importance of toe function

In the gait cycle, all five toes may be in contact with the ground for longer than the heel and the base of the fifth metatarsal. Toe contact, in fact, occupies nearly three-quarters of the gait cycle (Hughes, Clark & Klenerman, 1990:248).

The metatarsal area thus not only carries body weight, but the toes also contribute a weight-bearing area (Mann & Hagy, 1979:24). Peak pressures under the toes, when the intrinsic forefoot muscles are able to contract together with the long flexors, are similar to peak pressures found under the metatarsal heads (Hughes *et al.,* 1990:245; Bojsen-Møller & Lamoreux, 1979: 479).

According to Stamm (1964:62) the primary function of toes is to press firmly against the ground with their pads to take weight from the metatarsal heads. As a result, the toes improve grip and prevent backwards skid. The outer and inner toes work to exert the precise and constantly changing amounts of pressure required to maintain balance when the heel is raised.

It is the combined contraction of three groups of muscles, namely the long flexors, interossei and lumbricals that brings about this pressor toe action. If contraction takes place in the long flexors alone, this would only flex the interphalangeal joints. This would result in just the tips of the nails touching the ground, as the interphalangeal joints are flexed (Figure 1.16, ii). It is the action of the interossei and lumbrical muscles that maintains the interphalangeal joints in extension, and this action then transfers the flexor action of the long flexors to the metatarsophalangeal joints (Figure 1.16 iii).

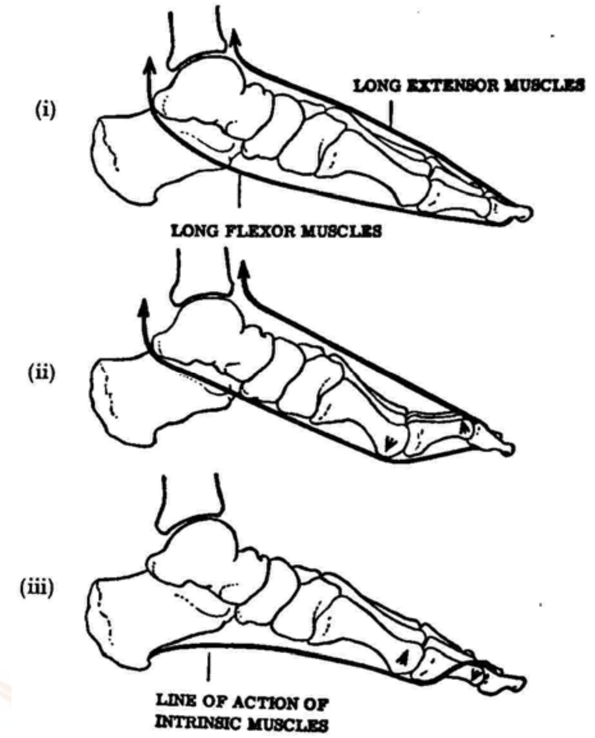

Figure 1.16: Action of muscles on toes. (Stamm, 1964:63)

i. Flexors and extensors in equilibrium; ii. Contraction of long flexors alone flexes interphalangeal joints and only brings nail tips to the ground; iii. Combined action with intrinsic muscles produces full function.

At the same time, it is the action of the interossei and lumbrical muscles, combined with that of adductor hallucis, that braces the transverse arch of the foot (Figure 1.16 iii.). It is entirely understandable that poor interossei and lumbrical action also then contribute, via medial column collapse, to the formation of digital and hallux valgus (bunion) deformity (Dawber *et al.,* 1996:21; De Berker, Bristow, Baran & Dawber, 2002:27).

Figure 1.16 also shows that when the interossei and lumbrical muscles are weak or paralysed, unopposed action of the long flexors will cause the progressive deformity of clawed toes. The fact that sufficient room for effective toe action is considered essential for maintaining integrity and painless function of the forefoot is endorsed by Arlen (1984:248).

At least one study of ethnic differences in forefoot shape has stated that greater length in front of the fifth digit is not provided in a typical shoe made for a Caucasoid population (Hawes *et al.*, 1994:196).

1.7.3 Aspects of shoe design and construction

The recede is the part of the last which projects beyond the tip of the toes; it forms the rounded contour of the shoe front. Poorly designed recedes can encroach on toes, thereby impeding natural dorsiflexion of the toes (Figure 1.17) as well as preventing length elongation during gait (Rossi & Tennant, 1984:95).

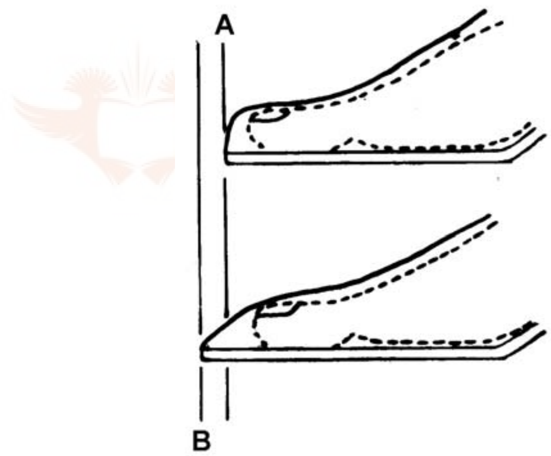

Figure 1.17: Impact of toe design on foot function.

Walled toe design (A) is shorter but a better fit than longer recede (slanted) toe design (B).

Since free toe dorsiflexion of all five toes is important (Stamm, 1964:62; Hughes *et al.*, 1990:248), there is a need to profile the varying "lengths" of the foot to the tips of all five toes. This will have relevance to the length allowances made on lasts.

1.7.4 Perception of fit

Many years of habitual foot deformation can contribute to a preference for tightness (Lord & Pratt, 1999:252). Similarly, the experience that a smaller shoe can stretch may mislead some consumers to the conclusion that, "since it's going to stretch", one should buy it tight to start off with (Rossi, 1988:401). Other reasons for accepting a shoe that is too tight may be due to a desire to make the feet appear smaller. Individual preferences for "tightness" can, therefore, influence a wearer's subjective perception of fit.

The implication of this aspect is that it may be necessary to educate patients and consumers to accept what they would initially perceive as a slightly looser fit than what they are accustomed to (Lord and Pratt, 1999:252).

1.7.5 Proportional Fit

According to Rossi and Tennant (1984:96), attention should be paid to the medial heel to ball measurement so that the correct proportional fit is achieved (Figure 1.18). Different heel-to-ball ratios can be a natural consequence of different arch heights in foot types such as pes planus and pes cavus. In pes planus, the arch is lower and therefore the heel-to-ball length is proportionately longer than the heel-to-ball length in a pes cavus foot (Figure 1.18).

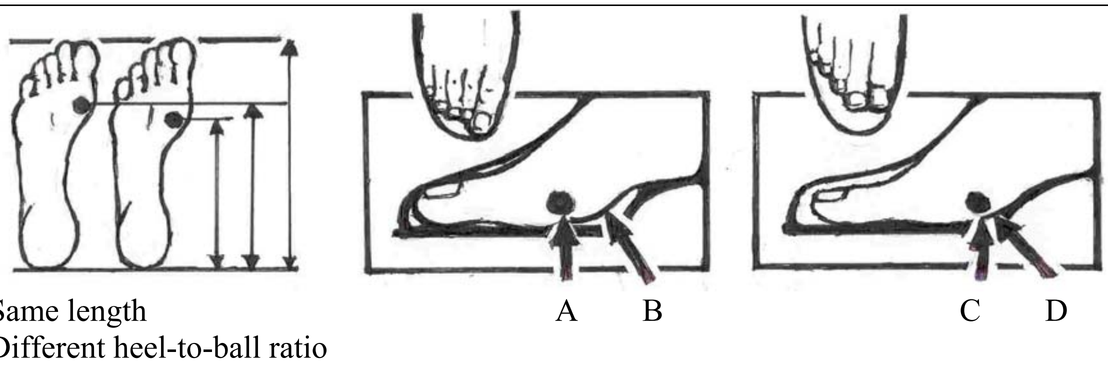

Figure 1.18: Proportional fit for heel to ball ratio. (After Rossi & Tennant 1984:96)

As shown in Figure 1.18, a mismatch in proportional fit in a heeled shoe will give rise to muscle tension in the unsupported portion of the mid foot (B). Continuous, unrelieved muscle tension will cause muscles to spasm, resulting in pain (Guyton & Hall, 1997:448).

1.7.6 Cost of pain and discomfort

Studies show that pain and discomfort factors can seriously affect concentration, thereby adversely affecting composure, interaction and job performance (Katz, 2002:S2).

Painful conditions contribute to reduced performance in the workplace. Cost studies have shown that 76% of lost productive time is attributable to reduced performance while at work, not by work absence (Stewart, Ricci, Chee, Morganstein & Lipton, 2003:2443). Chronic pain can give rise to depressed psychological states that, in turn, adversely impacts mood and motivation (Gaskin, Greene, Robinson & Geisser, 1992:707; Mongini, Ciccone, Deregibus, Ferrero & Mongini, 2004:59).

Whilst not specifically sampled in any foot related study, it is entirely feasible from the foregoing that low grade, constant foot pain can negatively influence mood and work performance. In terms of preventative medicine, the development of good footwear fit could, thus, positively impact on both psychological and physical factors affecting productivity and quality of life.

1.8 Summary

Footwear fit, while important to foot health, is an interaction of form and function, both of the foot and the shoe. Variations in foot morphology should be monitored in differing population groups in order to provide information for shoe manufacture. While many factors affect footwear fit, for the purposes of this study, only the physical aspect of the concept of fit is explored, insofar as a comparison is undertaken between the measurements used to make a selected last and the corresponding measurements of the feet of the sampled population.

2 FOCUS ON MEASUREMENT FOR INDUSTRY

2.1 Background

Although the previous chapter has shown that there are many factors affecting fit, the scope of this study concerns the physical dimensions or measurements relating to footwear fit for a sampled population.

In South Africa, measurements for last manufacture are derived from a variety of sources, none of which include recent statistically representative 3-D foot measurements of the South African female urban population. Many female last measurement sets still in use are the same as those dating from the early twentieth century when South Africa was a British colony (Thompson & Zipfel, 2005:22). British last measurements from that period were largely intended for what has now become a small ethnic section of the total population.

The South African last-making industry has freely admitted that most last modifications requested for the manufacture of lasts are based on the instinct or experienced opinion of the individual footwear manufacturer or alternatively, on replication of overseas sample shoes (Pratt, 2001; Vandenheede, 2003; Wilson, 2005).

No foot measurement study has been conducted for South African women since 1968, although male feet have been studied for the SA National Defence Force and for the Mining Industry (Ergotech: n.d.). The percentage increase of working age women of all ethnic origins taking up employment in commerce and industry in South Africa post-1995 suggests that the market for female footwear has changed nature in size and needs, as well as demographics (Figure 2.1).

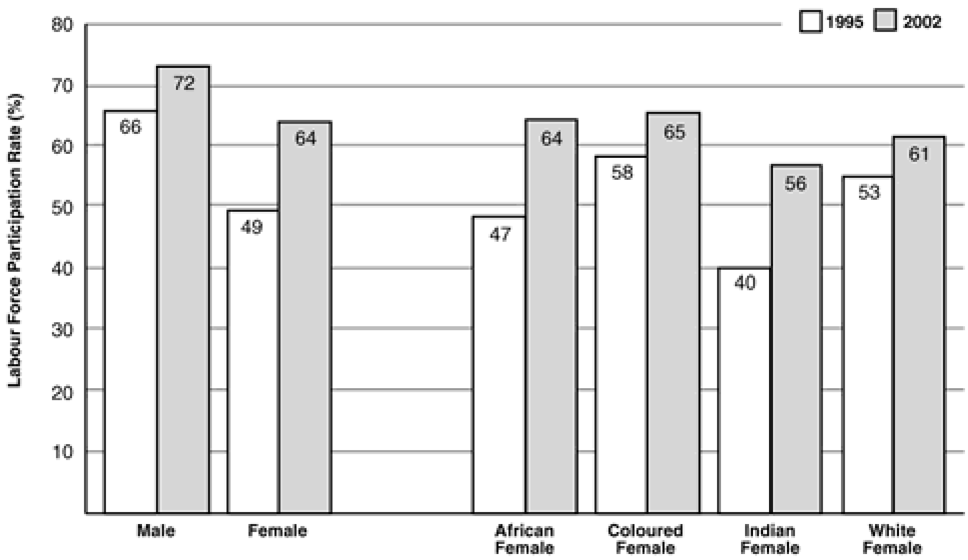

Figure 2.1: Female Labour Force Participation Rate[a].
(African National Congress, Umrabulo document, Number 22, February 2005)
[a]Between 1995 and 2002, previously disadvantaged groups showed greater increase in labour force participation than white females.

It became apparent that an updated measurement study of a representative sample of South African women was required. This data would form the core of a database from which different investigations could thereafter be conducted.

2.2 Scaleable Measurement Comparison

In a methodology development study conducted by Sokolowski (1999:172), 2-D sloper segments were derived from 3-D castings taken from the feet of five female subjects who represented five different sizes. Sloper segments constituted mapped areas of the foot that were defined according to anatomical landmarks, in a similar way to garment pattern making practice (Figure 2.2).

Figure 2.2: Sectioned casts for sloper segments. (Sokolowski, 1999:103).

Note: Two lateral sides are illustrated instead of the intended medial (inner) side plus a lateral (outer) side of the foot.

Analysis of results showed that not a single linear relationship between sizes existed for any of the sloper segments. In particular, the most non-linear relationships between sizes existed in the segments containing the plantar medial arch and lateral segments (T, U, V and X in Figure 2.2). Non-linear relationships could mean either that the sloper segment between sizes stays identical or that it changes so radically (up or down) that specific sloper shapes would need to be drafted for each size (Sokolowski, 1999:172). The implication of this limited study was to question the practice in the footwear industry of applying fixed (linear) interval grading between sizes.

The model size for women in the South African footwear industry is a “UK size 4”. The patterns for a size 3 (smaller) and sizes 5 to 10 (larger) are arrived at 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.

By arithmetically scaling every participant’s foot length (irrespective of foot length measured) to a fixed foot length of 234mm, and applying the same derived ratio to their other foot measurements, it was hoped to show (by a comparison of means of the measurements) whether there is a non-linear difference (for the purposes of last measurements) in either smaller or larger feet.

2.3 Formulation of the research question – does the shoe fit the foot?

In consultation with members of the footwear industry, a number of issues were presented. Firstly, as the preceding review of the literature has shown, the accurate computation of shoe fit is very complex. However, this should not prevent the scientific community and the footwear industry from pursuing knowledge of the dimensional differences present in both the population and the current products, as this knowledge could provide important information to predict fit.

It was felt that a study that could answer the simple research question in respect of one shoe style would be useful to extrapolate into a method to test other lasts and their suitability to produce footwear for the sampled population.

2.4 Aims of the study

On involvement of industry, it became clear that the aims of the study were fourfold.

The first aim was to find or create a method of 3-D foot image input, such that linear as well as 3-D measurements could be obtained, as well as the topography of the weight bearing foot.

The second aim was to compare eight mean foot measurement parameters of a sampled population with the comparable eight measurements from a standard mass production last to determine what percentage of the sampled population would fit the footwear derived from such a last. This would answer the research question, “Does the shoe fit the foot?”

Expressed in terms of working hypotheses, these became

H_0 : The shoe does fit the foot

H_1 : The shoe does not fit the foot

A third aim was to undertake a comparison of means in such a way as to endorse or question the practice of grading from a size 4 as the model for all other sizes.

Intrinsic to the completion of the first two aims was the fourth aim, namely the compilation of a 3-D database of female foot measurements in South Africa, for the purpose of this study, as well as for future industry research and development.

2.5 Anticipated outcomes

Beyond the achievement of the four primary aims, the results are expected to:

a. Determine the percentage of the sampled population whose feet could be at risk of pathology by wearing the selected shoe style.
b. Indicate and quantify which modifications, if any, are required to produce a product(s) to more accurately fit the South African female market.
c. Produce a "mother" last prototype model for the mean size curve applicable to the data.
d. Produce hardcopy prints suitable for development teams in non computerized SMEE industries showing foot morphology from side and top views, to increase visual awareness of different types of feet.