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Identification and classification of geometrical parameters related to foot pathologies

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Identification and classification of geometrical parameters related to foot pathologies

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RÉSUMÉ

Malgré que la forme et la fonction du pied aient fait l'objet de plusieurs études, la classification exacte des pathologies demeure limitée. Cette difficulté repose en partie sur les méthodes d'évaluation des désordres aux pieds elles-mêmes, telles l'inspection visuelle, les mesures anthropométriques, la radiographie, et sur les quelques mesures qui caractérisent la morphologie du pied. La présente étude a été menée dans le but de fournir une technique fiable et non-invasive de l'évaluation du pied; elle vise également à identifier les paramètres géométriques qui caractérisent le mieux les différences entre le pied plat (PP), la pronation (PR), le pied creux (PC), la supination (SU) et le pied normal (PN), pour ensuite les classer dans les groupes appropriés.

Quinze sujets ont d'abord été évalués pour tester la fiabilité de l'instrument utilisé pour cette étude. Ensuite, 321 pieds ont été classés cliniquement dans l'une des quatre pathologies mentionnées plus haut et au sein du groupe des sujets normaux. Pour la description de la géométrie des pieds, 15 angles ont été mesurés à partir d'images encodées de couleur provenant de quatre prises de vue distinctes. L'analyse en composantes principales (ACP) et l'analyse discriminante pas à pas (AD) ont servi à déterminer les caractéristiques géométriques des différents groupes.

Trois modèles ont ensuite été élaborés, la ACP, la AD et la technique de Logique floue, pour classer les pieds étudiés dans leurs groupes respectifs. Les résultats ont démontré qu'une seule série d'images était suffisante pour mesurer les angles du pied avec un ICC de 0,99 pour la fiabilité intra-évaluateur et un ICC de 0,89 pour la fiabilité inter-évaluateur. Les ANCOVA ont ensuite fourni une description clinique quantitative des troubles du pied. Ainsi, la ACP a permis d'identifier neuf angles tandis que la AD a permis d'identifier 10 des 15 angles des différentes vues anatomiques en tant que paramètres géométriques les plus pertinents. Ensuite, en utilisant les trois modèles de l'ACP, AD et de Logique floue, les pieds ont été classés dans leurs groupes respectifs avec un taux moyen de classification de 76,7 %. Parmi les trois méthodes de classification, la Logique floue a produit la plus haute précision. La AD a fourni une classification acceptable tandis que la ACP a été de piètre performance. Quatre-vingt-quatorze nouveaux pieds ont été utilisés pour la prédiction. L'exactitude des prédictions a été de l'ordre de 39,1 %, 53,8 % et 76,6 % pour la méthode de la ACP, de la AD et de la Logique floue respectivement.

Cette étude a donc permis d'élaborer une nouvelle technique fiable pour l'évaluation de l'attitude du pied face à ses pathologies. Elle a également fourni des approches innovatrices pour l'identification et la classification des types de pied associés aux nombreux paramètres géométriques des différentes vues anatomiques.

Mots clés: Pied, Classification de types de pieds, Le pied plat, Pronation, Le pied creux, Supination, Membre inférieur, Analyse en composantes principales, Analyse discriminante, Logique floue

ABSTRACT

Foot shape and function has been the core of many studies, however successful classification of the deformed foot remains limited. The difficulty lies in part on the means of assessing methods of foot disorders such as visual inspection, anthropometric measures, radiography, etc. and on few measurements to characterize foot morphology. The present study was conducted to provide a reliable non-invasive technique for foot assessment, and to identify the geometric parameters that best characterize the differences between pes planus (PP), pronation (PR), pes cavus (PC), supination (SU) and able-bodied (AB) foot types and classify them into their appropriate groups.

First, fifteen subjects were evaluated to test the reliability of the instrument used in this study. Then 321 feet were clinically sorted into the above-mentioned four pathologies and into an able-bodied group. Fifteen angles were then measured on color-coded images taken from four views to describe the geometry of the feet. Principal component analysis (PCA) and stepwise discriminant analysis (SDA) were performed to determine the relevant geometric characteristics of the groups. Afterwards, three models were developed, namely the PCA, the SDA and the fuzzy logic technique to classify the feet into their respective groups. The results demonstrated that a single set of images was sufficient for foot angles measurement with an ICC of 0.99 for intratester and 0.89 for intertester reliability. ANCOVA then provided a quantitative clinical description of foot ailments. In doing so, PCA identified 9 angles while SDA characterized 10 out of 15 angles from different anatomical views as the most relevant foot geometric parameters. Then, using the three PCA, SDA and Fuzzy logic models feet were classified in their respective groups with a mean classification rate of 76.7%. Among the three classification methods, Fuzzy logic performed with the highest accuracy. The SDA provided an acceptable classification while PCA performed poorly. Ninety-four new feet were used for prediction. Correct prediction using PCA, SDA and Fuzzy logic were 39.1%, 53.8% and 76.6% respectively.

This study provided a novel and reliable technique to assess foot attitude related to foot pathologies. It also presented new approaches to identify and classify foot types associated with several geometrical parameters taken from different anatomical views.

Key Words: Foot, Foot type classification, Pes planus, Pronation, Pes cavus, Supination, Lower extremity, Principal Component Analysis, Discriminant Analysis, Fuzzy logic

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LIST OF ABBREVIATIONS

1st and 2nd MTP:	Axis of 1st and 2nd MTP bones in reference to the horizontal axis.
1st MTP/Med:	First metatarsal inclination in reference to the horizontal axis.
2nd and 5th MTP:	Axis of 2nd and 5th MTP bones in reference to the horizontal axis.
2nd and 5th MTP/flex:	Axis of 2nd and 5th MTP bones in reference to the horizontal axis in plantar flexion view.
AB:	Able-bodied.
AP:	Antero-posterior.
Bisect/heel:	Bisecting of calcaneus bone to the vertical axis.
Bisect/leg:	Bisecting distal third of the leg to the vertical axis.
Calca-inclination:	Clacaneus inclination in reference to the horizontal axis.
FL:	Fuzzy logic.
Heel/flex.:	Medial heel angle in reference to vertical in plantar flexion view.
Lateral base:	Lateral base of the foot in reference to the vertical axis.
Leg/heel:	Hindfoot angle.

Med:	Medial.
Medial base:	Medial base of the foot in reference to the vertical axis.
MTP:	Metatarsophalangeal.
PA:	Postero-anterior.
PCA:	Principal Component Analysis.
PC:	Pes cavus.
PF:	Plantar flexion.
PP:	Pes planus.
PR:	Pronation.
SDA:	Stepwise Discriminant Analysis.
SU:	Supination.

I would like to dedicate this thesis, with love, to my family.

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Chapter 1

1. INTRODUCTION

Structural deformity of the foot and ankle may have adverse effects on health, such as pain, abnormal gait pattern, and significant reduction in functional performance (Dahle et al., 1991). Many foot problems are found in newborns or in young children, but the majority of these problems are observed among adults (Burns, 1996) and the elderly (Benvenuti et al., 1995). Since the majority of patients end up with a permanent disability (Sari-Kouzel et al., 2001), these problems demand serious clinical attention. Effective treatment of a foot deformity depends on the accuracy of the identification and classification of clinical observations (Sell et al., 1994; Wainwright et al., 2002).

Many studies have proposed anthropometric measurements of the medial longitudinal arch or the hindfoot angle as a main characteristic by which to identify and classify foot deformities (Kilmartin and Wallace, 1992). However, anthropometric methods are usually limited to a single parameter, such as arch height or hindfoot angle, and therefore this technique is neither accurate nor precise. Updated and more accurate models for classification and identification are needed to provide better quantitative information about different types of foot deformities.

In this chapter, the epidemiology and etiology of foot deformities will be addressed to emphasize the importance of this musculoskeletal disorder and illustrate its complex origins. This will be followed by a description of the most common foot problems, highlighting their similarities and differences. Next, the most common clinical examination methods used in the diagnosis of complex foot problems will be outlined. Finally, the general objectives of this thesis will be presented.

1.1 Epidemiology and etiology of foot problems

Structural abnormality of the foot and ankle, with its high incidence and significant impacts on the patient's performance, is considered a serious orthopedic problem (Gould et al., 1980). It is more common among females than males (Greenberg and Davis, 1993). Pes cavus is one of the most severe foot deformities. It is very common within the adult population, constituting 31% to 81% of cases of foot deformities (Hsu et al., 1991), equally distributed in both sexes (Turek, 1984). Harris and Beath (1952) reported an 11.8% incidence of pes cavus among young men in Canada. Pes planus, observed in 4.6 million individuals (Greenberg and Davis, 1993) in the United States, is more common in African-Americans than Caucasians. Another comprehensive study found a 22.5% incidence of all kinds of low arch, including severe with short Tendo-Achillis, spastic and mild pes planus (Harris and Beath, 1952). The most commonly observed deformity of the hindfoot is the calcaneus varus (Tiberio, 1988).

Generally, the etiology of foot problems can be divided into three categories: idiopathic, neurological deficit, and musculoskeletal disorder (Neale and Adams, 1985). Idiopathic foot deformity refers to a primary foot problem with an unknown etiology. Foot problems due to neurological disease can involve metabolic, radicular and locally compressive neuropathies that manifest themselves in the foot area and can cause considerable pain and dysfunction (Burns, 1996). In cases of foot deformity caused by musculoskeletal disorders, the foot structure is affected, resulting in an abnormal foot attitude and structural misalignments. The latter is the most common foot problem in adults (Neale and Adams, 1985). For these reasons, this thesis focuses mainly on foot problems with the etiology of musculoskeletal disorders.

1.2 Common foot deformities

Changes in soft tissues, bones and joints all contribute to acquired foot disorders and the outcome is a complex and challenging range of foot deformities. Because of this, some foot pathologies have common characteristics but different diagnoses. For example, a flattened arch can be associated with both pes planus and a supinated foot. In this section, four common foot problems within the musculoskeletal disorders category will be briefly described to highlight their particularities as well as their similarities. The definition, mechanism and clinical features of pes planus (PP), pronation (PR), pes cavus (PC), and supination (SU) are presented below.

1.2.1. Pes planus

Pes planus, illustrated in Figure 1.1, is a generic term used to describe any condition of the foot in which the longitudinal arch is abnormally low or absent (Tachdjian, 1990). Quantification of sagittal plane arch height has long been used as a means of categorizing foot type, largely in individuals with pes planus (Menz, 1998; Cavanagh and Rodgers, 1987). Clinical findings show that in a weight-bearing position the heel is tilted in a valgus direction. There is external rotation of the foot in relation to the leg causing forefoot abduction, combined with plantar flexion of the calcanus bone, resulting in the flattening of the sole which makes contact with the ground. Identification of the pes planus deformity can be difficult because of its association with other conditions where there is a dropping of the longitudinal arch. Its degree of severity may lead to associated deformities in the forefoot, such as an everted forefoot, and the hindfoot, such as an everted calcaneus.

Figure 1.1. Pes planus deformity in the left side in weight-bearing position.

1.2.2. Pronation

Pronation is characterized by an abnormal mobility of the calcaneus in relation to the subtalar joint. Pronation is a combination of motions including abduction, eversion and dorsiflexion of the foot and medial rotation of the ankle (Root, 1971). An abnormal pronation, presented in Figure 1.2, can be used to describe a condition where an increased amount of subtalar joint pronation is present (Aquino and Payne, 2001). This condition often exists with a laxity of subtalar joint ligaments, heel valgus, forefoot abduction, and decrease in arch height. Although pronation is a deformity mainly characterized by a valgus of heel, its degree of severity may lead to associated forefoot compensation.

Figure 1.2. Pronation of the left side of the foot in weight-bearing position (adapted from Root et al., 1977).

1.2.3. Pes cavus

Pes cavus, as shown in the Figure 1.3 A, is characterized by a raised longitudinal arch (Turek, 1984), claw toes and forefoot equinus in relation to the hindfoot (Ritchie and Keim, 1968). Figure 1.3 B shows a pes cavus with inverted forefoot (Root, 1971). An inverted heel may be also present in subjects with pes cavus (Root, 1971), as shown in Figure 1.3 C. Although pes cavus is a deformity mainly characterized by an elevated longitudinal arch, its degree of severity may lead to associated deformities in the forefoot and hindfoot.

A B C

Figure 1.3. Pes cavus, A) medial , B) antero-posterior, C) postero-anterior.

1.2.4. Supination

Supination is described as a subtalar joint deformity accompanied by pronation. Figure 1.4 illustrates this deformity in a right foot. Supination is characterized by calcaneus inversion, adduction and plantar flexion in relation to the talus with a forefoot varus or adduction. The compensation for a forefoot valgus results in an inversion of the calcaneus. Supination can be observed as hyper mobility of the calcaneus bone in a medial direction in a weight-bearing position. Since this deformity usually appears with pes cavus its etiology may be neuromuscular and idiopathic. As for other foot pathologies, supination may lead to associated deformities of the foot and ankle.

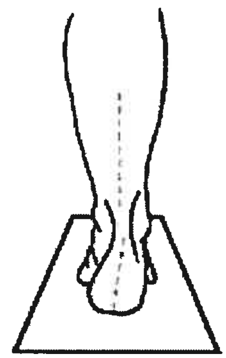

Figure 1.4. Right-side supination of the foot (adapted from Root et al., 1977).

Detection of the four afore-mentioned foot deformities is difficult because of their complex interrelation and their similarities, especially those between pes planus and pronation or pes cavus and supination. Therefore, it can be useful to diagnose foot deformities based on several parameters taken from different perspectives to better describe foot morphology in a clinical environment.

1.3 Clinical examination methods

In a clinical setting, a visual inspection is often used as a simple and quick method to identify foot deformities (Razeghi and Batt, 2002). However, this technique is rather qualitative; providing no quantitative information, and the diagnosis strongly depends on the skills of the observer. Because of the multiplicity of possible diagnoses and the similarities among the various foot deformities, the visual observation of the physician might be erroneous, leading to an improper treatment or rehabilitation program.

Goniometry, a popular tool for foot assessment, is an important component of a comprehensive evaluation of the joints used by most clinicians. This technique has been widely used to assess mobility of the ankle in both normal (Clapper and Wolf, 1988) and pathological conditions (Elveru et al., 1988a). However, this technique is only useful for measuring the range of motion of the joint.

Planar radiography (Saltzman et al., 1994) and magnetic resonance imaging techniques (MRI) (Yu and Tanner, 2002) have also been used in many clinics to observe the structure of the foot and the underlying pathologies in different foot deformities. These techniques provide clinicians with the most accurate information about the shape and arrangement of the foot bones, leading to accurate diagnoses of foot deformities (Stindel et al., 1999). However, radiographic techniques are invasive due to radiation exposure. Moreover, these are very expensive and rely on the use of high-technology equipment and well-trained operators; resources that are not available in every foot clinic. Therefore, there is a need to develop a new, non-invasive, quantitative, accurate, quick and easy technique for clinicians to use in their assessment of foot problems.

A novel, non-invasive, computer-aided, color-coded video system for foot and posture assessment was developed for the clinical assessment of foot disorders and body posture compensations (Biovision, Cryos Technologies Inc.). In this technique, a digital camera is used to obtain weight-bearing foot images from various views. The advantages of this system are its simplicity, its minimal skill requirements, and the ease with which it can be learned and used. This system is used for foot assessment in clinical environments, serving as a good alternative to visual examination and radiography, especially for able-bodied subjects. Nonetheless its reliability has not been established and to date few if any methods rely on more than a few geometric parameters to classify the most common foot pathologies.

1.4 General objectives of the thesis

The general objective of this thesis was to determine the reliability of a color-coded video-based system for assessing quantitative parameters that are used to describe foot pathologies. Furthermore, this thesis was aimed to identify the geometric parameters that best characterize the differences between five foot types which include four pathologies and an able-bodied group. Though a specific color-coded system has been used in this thesis, the methods developed here can be applied to other similar equipment. The specific objectives of this thesis are detailed at the end of the review of literature chapter.

Chapter 2

2. REVIEW OF LITERATURE

This chapter reviews the literature related to the most commonly used techniques for the evaluation of the foot and its related pathologies. This is followed by the reliability and accuracy of these systems in assessing foot deformities. Next, joint parameter measurements used for identifying foot problems are reviewed followed by classification studies on foot deformities. In the final section, the specific objectives of this thesis are detailed.

2.1 Review of the foot and ankle measurement techniques

The majority of techniques in the evaluation of foot problems in a clinical setting are qualitative. They may be performed with the foot in the unloaded (sitting or lying down) or loaded (upright standing) positions. In this section we have focused mainly on the more common static methods that are clinically applied for assessing foot problems. The advantages and disadvantages of these techniques are also discussed. Though dynamic assessments of foot ailments are often performed in university-based research laboratories, these are very costly and are seldom used in clinics. Therefore, dynamic measurement techniques are not presented here.

2.1.1 Visual techniques

Visual assessment is a simple method (Razeghi and Batt, 2002) and is part of a complete clinical examination of the foot. Inspection of the foot from different views is required to accurately characterize foot disorders. Visual techniques vary from direct eye observation to the use of visual devices such as the podoscope and the footprint mat.

A podoscope is a general term describing any device for assessing the plantar portion of the foot. In its simplest form, it consists of a plexiglass surface on which the subject stands and an inclined mirror to observe the plantar pressure distribution as shown in Figure 2.1. Cowan et al. (1994) used a specially built podoscope using three mirrors to record anterior, posterior, medial and plantar views of the foot simultaneously. This technique is quick, cost-effective and simple to use. It is often found in podiatric clinics in North America and Europe.

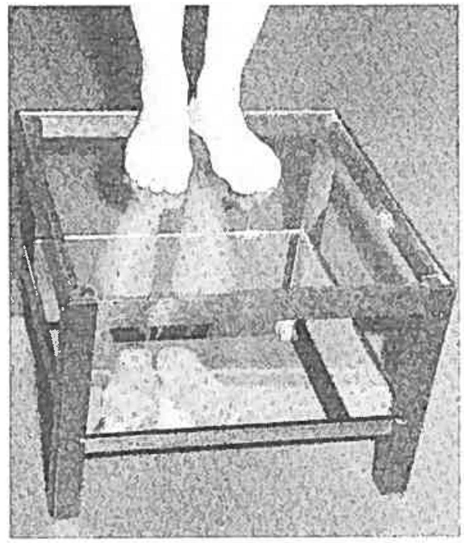

Figure 2.1. Podoscope with a subject in weight-bearing position (from Neale and Adams, 1981).

There are some disadvantages to using visual techniques. Clinical interpretation is often more complex and depends on the observer's skill. Cowan et al. (1994) reported a poor intertester reliability (r =0.35) for visual technique on foot assessment since it only provides a general idea about the foot pressure distribution. The podoscope method is limited to the assessment of the plantar aspect of the foot and does not give any indication of the orientation or attitude of the foot. Additionally, information about the shape, orientation and position of the foot are not accessible.

Footprint is another commonly used method for assessing foot disorders, more specifically in the medial arch (Forriol and Pascual, 1990; Kanatli et al., 2001; Urry and Wearing, 2001). Footprint measurements were proposed to analyze pre and post surgical treatment of the foot (Gould, 1988) and to identify and classify foot arch types (Igbigbi and Msamati, 2002; Lindsey et al., 1998; Hawes et al., 1992; Kanatli et al., 2001).

Footprints are made by coating the sole of the feet with ink and having the subject stand on a white paper placed on a screen. The footprint is divided into sections (Kilmartin and Wallace, 1992) and lines are drawn to calculate different indices. Arch index, arch length index and footprint index are defined based on the area of the contact on the imprint. For example, as shown in Figure 2.2, the footprint index is defined as a ratio of the non-contact area (A) to the contact area of the toeless footprint (B). The non-contact area is located between the medial border of the footprint and the medial footprint outline, whereas the contact area consists of the footprint area without the toes. The footprint index provides an estimation of the pes cavus or pes planus involvement (Razeghi and Batt, 2002; Irwin, 1937).

The footprint method is used widely in clinical assessments and is an inexpensive method. However, some footprints have limited contact or non-contact areas to detect severe low or high arches. For example, the non-contact area is absent in a severe pes planus deformity (Razeghi and Batt, 2002). Similar footprints are sometimes found for different foot problems which can not be differentiated by this technique.

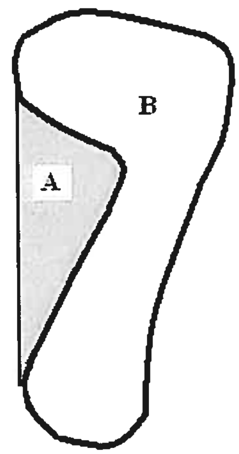

Figure 2.2. Footprint of right foot: A) non-contact area, B) contact area.

2.1.2 Anthropometric measurement techniques

The use of anthropometric measurements is another direct method for measuring surface landmarks. This technique represents the position of the different structures of the foot; particularly arch height (Razeghi and Batt, 2002); longitudinal arch angle, navicular drop and hindfoot angle (Vinicombe et al., 2001). The longitudinal arch angle is formed by drawing a line from the center of the navicular and the trochlea tail to the lowest point of first metatarsal head (Shereff, 1991). Navicular drop measure is the displacement of the navicular tuberosity measured on non-weight-bearing and 50% weight-bearing position. The hindfoot angle represents the angle between bisecting of the lower leg and the calcaneus bone. These measurements provide clinicians with information about foot orientation in the sagittal or the coronal planes to identify and classify the foot type.

Anthropometric methods are reliable when the able-bodied foot is assessed; however, these techniques are limited to the measurement of only one parameter such as the arc height or the hindfoot angle. Besides, the data collection and processing by these techniques are time consuming (Saltzman et al., 1995).

2.1.3 Radiographic techniques

Radiographic techniques include radiography, arthrography, computed tomography (CT) scan, magnetic resonance imaging (MRI), etc. The most common methods used for assessing foot problems are described below.

Standard radiographic measurements have been long considered as a gold standard for foot measurements in the clinical environment (Robinson et al., 2001). Radiographs are taken in both the non-weight-bearing and weight-bearing positions (Shereff, 1991). It has been shown that standardized weight-bearing foot radiographs are an objective and reliable way to assess both bony structure and soft tissue dimensions (Morag and Cavanagh, 1999).

MRI uses radio waves and a strong magnetic field rather than X-rays to provide detailed pictures of the internal organs and tissues of the body segments. It is used for diagnosing musculoskeletal system problems related to joint disorders especially in the foot and ankle (Woodburn et al., 2002). MRI, with its multiplanar capabilities, ability to image bone marrow, non-invasiveness and lack of ionizing radiation has become a valuable tool in evaluating patients with foot and ankle problems (Lucas et al., 1997; Eustace et al., 1996). Using this technique, the hindfoot bones' parameters in normal and abnormal conditions including pes cavus and pes planus subjects were characterized by Stindel et al. (1999; 2001).

There are however some disadvantages with radiographic techniques. Radiography has radiation side effects and ethically is not an appropriate method for studying able-bodied subjects. This technique is basically used for diagnostic purposes and seldom used in posture assessment. Radiographic equipment is expensive to purchase. Magnetic resonance imaging examination is costly and takes more than 20 minutes to prepare the image (Stindel et al. 1999). Very slight movement in the area being scanned can result in distorted images that will have to be repeated. Furthermore, this technique is not applicable for postural evaluation of the foot in the weight-bearing position.

2.1.4 Goniometry

Measuring angles with a goniometer is an important part of a comprehensive evaluation of the joints used by rehabilitation specialists and clinicians. This method is rapid and provides clinicians with quantitative information as part of a static lower-extremity examination but has a poor intra and intertester reliability for assessment of subtalar joint position in both non-weight-bearing and weight-bearing positions (Picciano et al., 1993). The assessment of the foot alignments with goniometry is a time consuming method and patients may get tired during the measurements. Furthermore, it does not provide information on body posture unless additional measurements are taken.

2.1.5 Video-based systems

Imaging measurement techniques are the most widely used methods to capture complex human movements (Winter, 1990). There are many different types of imaging systems available to analyze human movement such as television, movie camera and optoelectric devices. Since the first video camera-based systems for movement analysis were introduced in the 1970s, many systems in this field have been developed and are currently on the market. Many studies have focused on the analysis of foot and ankle kinematics during gait (Mueller and Norton, 1992; Nawoczenski et al., 1998; Nester et al., 2002). Force plate and electromyographic information were often taken simultaneously with videographic data (O'Connell et al., 1998; Kenutzen and Price, 1994; Nawoczenski et al., 1998). These systems made it possible to combine the kinematics and kinetic analysis in dynamic conditions simultaneously. It is also possible to measure the joint movements three-dimensionally.

However, video-based kinematic systems are expensive and usually confined to research laboratories or to hospital rehabilitation clinics. These systems are not relevant to analyze foot problems in the static position since they require a large number of markers and are time consuming. Furthermore, marker placement is considered to be a cause of errors (O'Connor et al., 1993).

Photography with a digital camera has been employed as a reliable and practical method in many urologic studies (Kuo et al., 1999). Because of the low cost and the ease of use, digital cameras have been widely used in various clinical and surgical settings including otoscopy and sinonasal endoscopy (Melder and Mair, 2003). In orthopedic surgery, digital cameras are used repeatedly to take quality pictures of radiographic findings (Elbeshbeshy and Trepman, 2001). This technique has also been used to characterize foot problems (Cowan et al., 1994; Garrow et al., 2001). Foot measurements can be taken directly from the non-invasive pictures. The difficulty lies in identifying the appropriate bony or soft tissue landmarks on the picture. Additionally, warts, skin irritation, calluses, etc. can make it more difficult to take reliable measurements of the various foot parameters. One way to overcome these drawbacks is to filter out the noise and accentuate the clinical information.

A computer-aided color-coded video-based system (Biovizion, Cryos Technologies Inc.) was developed for the clinical assessment of foot disorders and body posture compensations. This technique is novel for assessing foot deformities. As shown in Figure 2.3, a digital camera is used to capture black and white weight-bearing foot images from varying views. The grey scale is based on 8 bits, hence 256 (0 to 255) grey levels. The resolution of the original images acquired with the camera is 384×512 pixels. A numerical filter then processes the pictures so that the grey levels are transformed into a color-coded image highlighting muscle and bone prominences. This process facilitates the measurement of the foot parameters to identify foot deformities. When angles are measured, the filter divides each pixel in thousand screen units. This allows an estimation of the angle at a 1/1000 of degrees, but in this study we used only the first digit after comma. This technique rapidly provides quantitative information for assessing the foot problems in clinical environment. The taken images can be viewed, immediately reviewed if necessary, downloaded to the computer and/or stored in a databank. The pathological images can be used for comparison with a normal image or used for following up the progress of the deformities particularly in pre-surgery planning and post-surgery monitoring. Though it has been used in clinics for over 5 years, the reliability of this color-coded video-base system is not yet known.

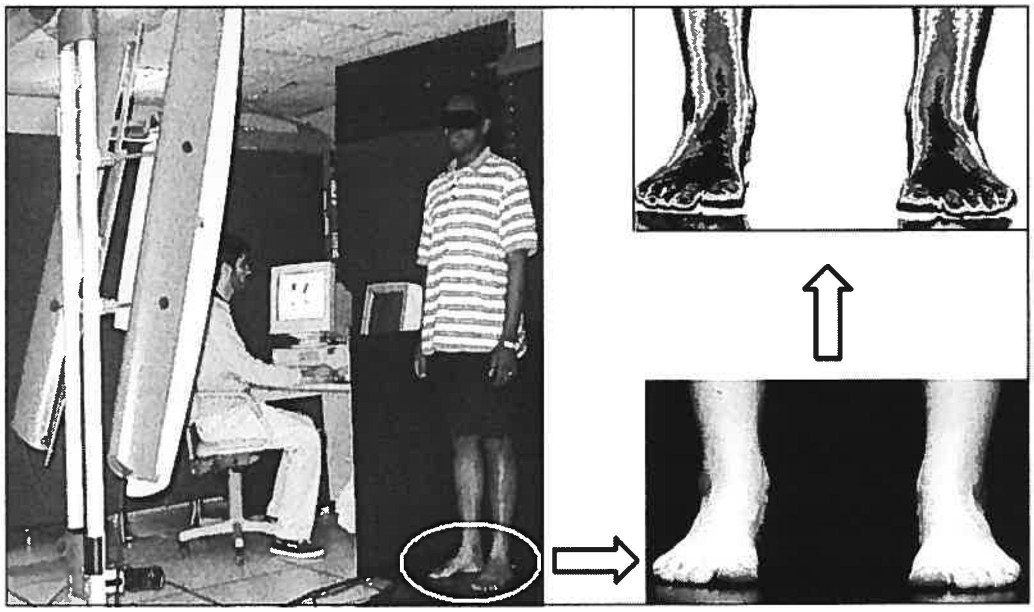

Figure 2.3. Image from of antero-posterior view of feet taken with a color-coded video-based system.

In summary, clinical evaluations of foot problems are still based on qualitative assessments (Morag et al., 1999). The visual technique is simple and often used as a part of the clinical examination to identify musculoskeletal disorders of the foot. This method, however, is not quantitative and the decision process is highly dependant on the operator's judgment. To improve the quality of the visual approach, a wide variety of devices are available that provide the clinicians with quantitative information (Cappozzo et al., 1997; Della and Cappozzo, 2000). These devices usually require highly skilled operators or are expensive and have a lengthy data collection time. A color-coded video-based system, however, can provide us with the quantitative information required for identification and classification of foot deformities in a short time. It is an with some other quantitative methods (r=0.7). Cowan et al. (1994) reported a low reliability (r=0.35) when a visual technique using a 35-mm camera was used to classify the foot based on the medial longitudinal arch. Due to the fact that there are controversial reports on the reliability of the visual observation technique, plus the lack of quantitative information on this technique, it is difficult to rely on it for clinical or research based foot evaluations.

Foot imprints were considered for many years as a reliable evaluation method (Irwin, 1937). He observed a high reliability (0.98) for the footprint index defined as the ratio of the non-contact to the contact areas of toeless footprint (Figure 2.2). This was also reported by Igbigbi and Masamati (2002) and Cavanagh and Rodgers (1986). The relationship between this method and radiographic measurements was studied by Kanatli et al. (2001). They found a correlation of r=0.45; p=0.004 between footprint analysis and radiographic measurement of talo-first metatarsal angle and talo-horizontal angle (r=0.40; p=0.014) of the medial arch. These findings indicate that footprint technique can be used effectively for screening studies as a simple and readily available technique for foot deformities assessment. Hawes et al. (1992) also tested the validity of the footprint parameters as a measure of arch height. They reported a high reliability with coefficient of over 0.90 for the footprint parameters. But they did not find acceptable correlation between footprint parameters and the height of the medial longitudinal arch. They concluded that some footprint measurements such as footprint index and arch index are invalid as a basis to predict or categorize the arch height.

Williams and McClay (2000) compared the reliability and the validity of several anthropometric measurements including medial longitudinal arch in 10% and 90% weight-bearing positions. They compared these measurements with measurements obtained from the radiography technique. The most reliable measurements were those obtained for the dorsum height divided by the truncated foot length with an intra-class correlation (ICC) of 0.92 for the 10% weight-bearing condition. The agreement between clinical and radiographic measurements of navicular height had ICCs of 0.87 and 0.91 for 10% and 90% weight-bearing position respectively. In another study, Saltzman et al. (1995) studied reliability of anthropometric measurements across subjects with foot deformities. They reported a higher intratester reliability coefficient (0.87 to 0.91) than intertester coefficient (0.74 to 0.79) for anthropometric measurements. In general, good reliability was documented for the anthropometric method.

Resch et al. (1995) and Chi et al. (2002) have studied the intra and the intertester X-ray measurements used in the clinical observation of the foot disorders. Chi et al. (2002) reported that the intratester reliability of the radiographic measurements of the distal metatarsal articular angle in hallux based systems are suitable for kinematic analysis of the foot and ankle, little is known about their reliability for foot shape measurements.

The reliability of the photography technique for assessing foot problems was determined by Garrow et al. (2001). They described the validation of a series of photographs for grading hallux valgus severity levels. They reported an excellent intertester repeatability (Kappa=0.86) for using the photography technique in a clinical setting.

In summary, the literature shows that investigators have applied or developed means of quantifying and assessing foot problems. These efforts have provided information on foot evaluation, each with their own advantages and disadvantages. Due in part to the limitations of the above-mentioned methods, the assessment and the diagnosis of foot disorders is still based on a qualitative evaluation.

2.3 Joint angle parameters

There are a number of joint angles measured in various views to quantify structural deformities of the foot. In this section the standard parameters for assessing foot problems are described.

The hindfoot angle or rearfoot to leg orientation (Gross, 1995) is defined as an indicator of subtalar joint position. This angle (shown in Figure 2.4) is formed between lines bisecting the distal third of the leg (A) and bisecting the calcaneus (B). This angle has been measured by many investigators (Weiner et al., 1997; Gross, 1995; Masharawi et al., 2002) during dynamic (McPoil and Cornwall, 1996) and static (Picciano et al., 1993) positions. The average value of the hindfoot angle in 150 able-bodied population (age ranged 6-16 years) has been reported as 4^{o} (ranged from 0 to 9 degrees) valgus of the heel by Sobel et al. (1999) in weight-bearing position. They also reported that the angle did not vary significantly with age, gender, height or weight in this sample of subjects. Novick and Kelley (1990) were measured hindfoot angle in twenty able-bodied subjects (age ranged from 20 to 58 years) in weight-bearing position. They reported 1^{o} of supination to 7^{o} of pronation of hindfoot angle. In their study, for left foot, a positive clock-wise angle value is indicative of pronation while a negative counter-wise angle is indicative of supination. The hindfoot angle is an essential parameter for the subtalar joint measurement to characterize hindfoot deformities as pronation and supination.

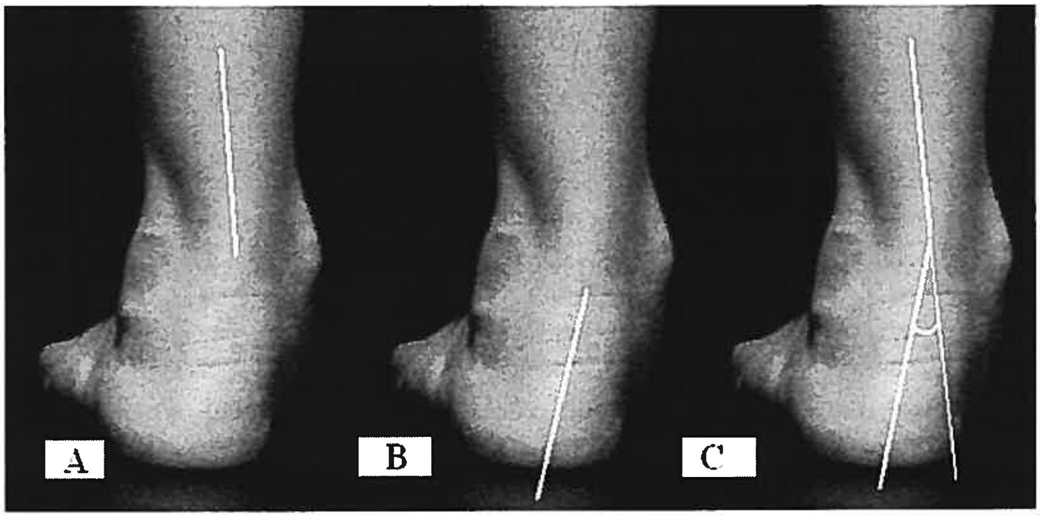

Figure 2.4. Subtalar joint measurement: A) line bisecting distal third of the leg, B) line bisecting the calcaneus and C) hindfoot angle.

The Meschan or metatarsal break angle is measured in a weight-bearing position from an antero-posterior view (Shereff, 1991). This angle, illustrated in Figure 2.5, is formed by the line of the first and the second metatarsal bones (A) in reference to the horizontal and same line of second and fifth metatarsals (B). According to Shereff (1991), this angle is about 140 degrees in able-bodied subjects.

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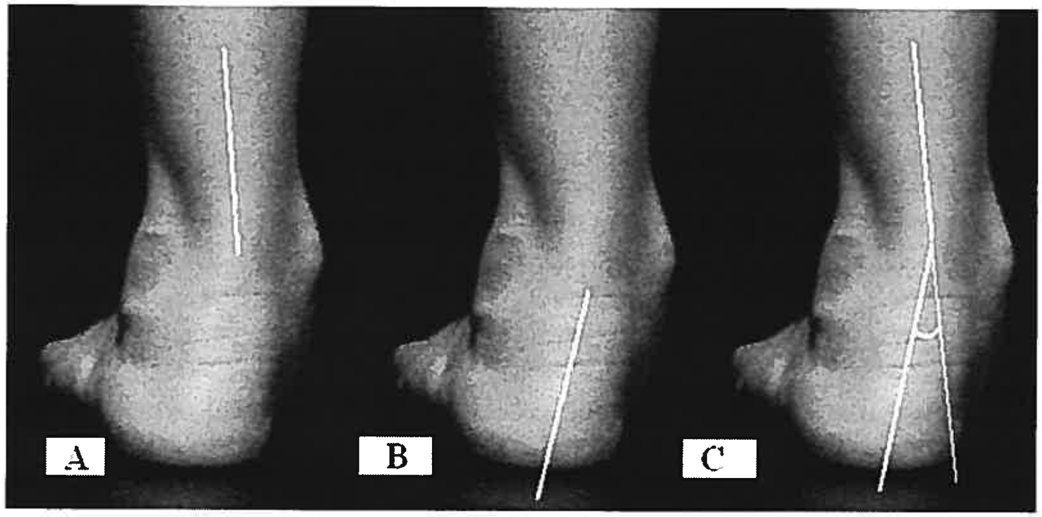

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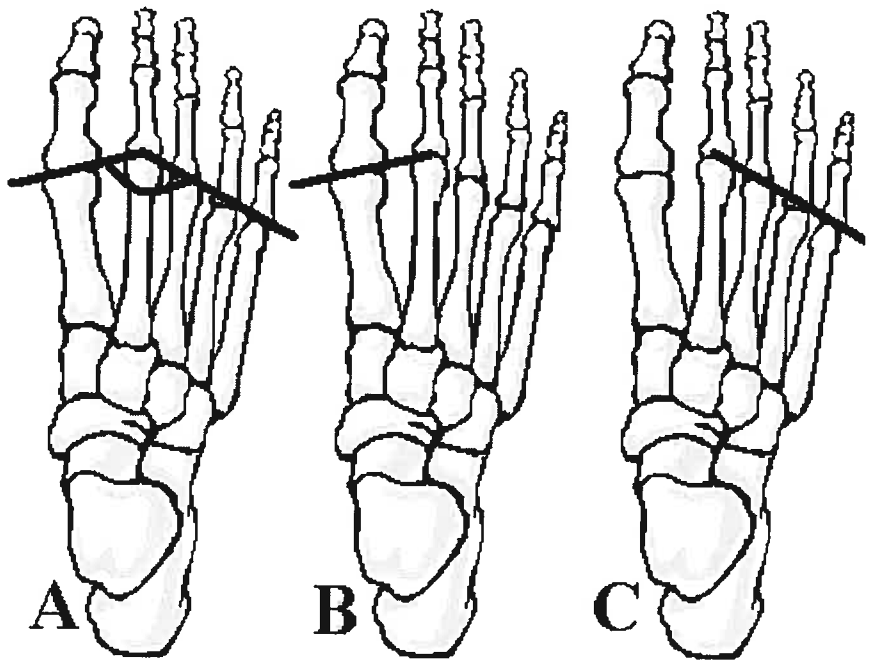


Figure 2.5. A) Meschan angle of right foot formed by: B) line of first and second metatarsals bones and C) line of second and fifth metatarsals.

The next standard angle describes the height of the medial arch and is measured by authors (Razeghi and Batt, 2002; Saltzman et al., 1995). Djian and Annonier (1968) first described the medial longitudinal arch using the Dijian-Annonier angle. As shown in Figure 2.6 the angle is formed by the calcaneal inclination and first metatarsal with 120 to 128 degrees of value for able-bodied subjects. However, the Djian-Annonier angle is used to describe midfoot deformities such as pes planus and pes cavus.

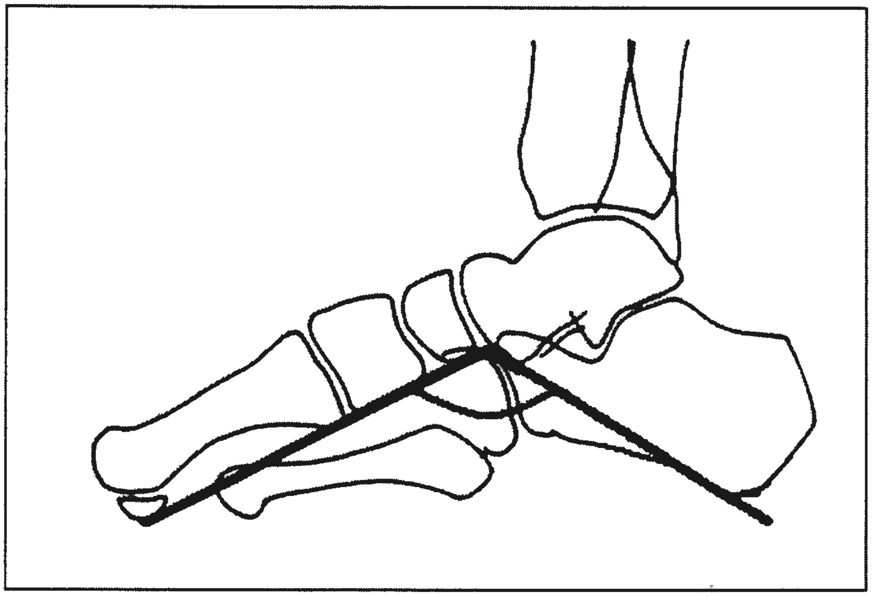


Figure 2.6. Djian-Annonier angle (adapted from Djian and Annonier, 1968).

The Meary-Tomeno is a line between the tarsal and first metatarsal bones (Shereff, 1991). As Figure 2.7 shows, the axis of the talar neck can be drawn as the line bisecting the angle formed by the lines tangential to the superior and inferior cortical margins of the talus. The midshaft axis of the first metatarsal is drawn as the line parallel to its superior cortical margin and extended through the center of the first metatarsal head.

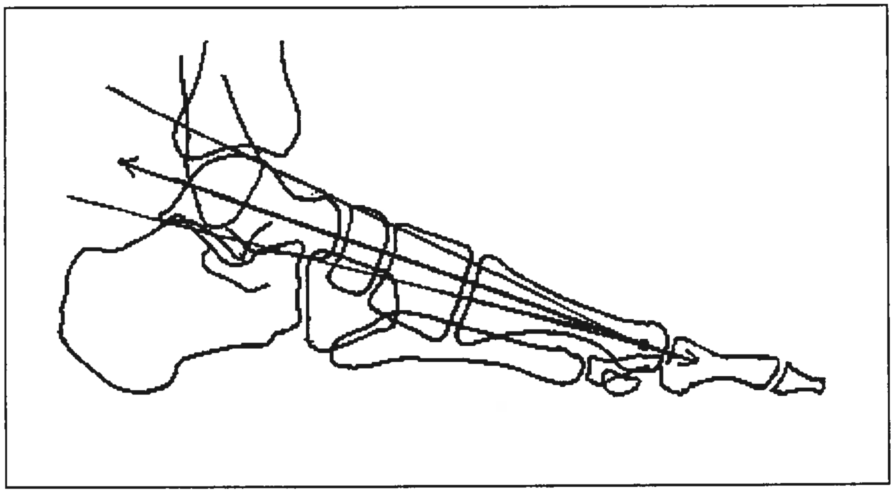


Figure 2.7. The Meary-Tomeno line (adapted from Shereff, 1991).

These angles describe the morphological features of the foot. Usually one or two angles are measured to describe a foot pathology and most often on a single view of the foot. In this study, we have employed several foot parameters taken from several views of the foot in a weight-bearing position.

2.4 Foot type classification methods

Foot type classification is based on visual, clinical, footprint and radiographic parameters (Razeghi and Batt, 2002). Most of these methods classify foot deformities in terms of one or a few parameters such as arch height. (Bertani et al., 1999; Song et al., 1996). Univariate statistical analysis is usually performed to compare different types of feet (Cowan et al., 1994; Kanatli et al., 2001).

Multivariate statistical techniques are employed for data reduction in different fields like gait analysis (Chau, 2001; Sadeghi et al., 2002) and electromyography studies (Pereza and Nussbaum, 2003). Several statistical techniques were applied such as factor analysis and principal component analysis (PCA) to determine which variables contain the most useful information within a particular clinical context. These approaches are employed for reduction of variables and for classification, but have not been used to classify foot deformities.

In this study principal component analysis, stepwise discriminant analysis and Fuzzy logic techniques have been employed to classify foot deformities. A description of each of these techniques will be presented briefly followed by advantages and disadvantages of each method.

Principal component analysis represents the original multivariate data in a new reference named principal components (PCs) (Marengo et al., 2003). Many studies have used this approach to reduce the number of variables (Du and Sun, 2005) and classifications (Kapur et al., 2004; Devillers et al., 2004; Lammertyn et al., 2004). For example, Devillers et al. (2004) used PCA to reduce the number of variables and classification of honey samples. They reported a fairly good separation of honey samples. This technique was also used in human locomotion studies to describe the variation of gait pattern in able-bodied subjects (Deluzio et al., 1997). In another study by Sadeghi et al. (2002) principal component analysis was employed as a classification and curve structure detection technique for knee muscle moments during walking. They reported that principal component analysis was able to identify three main contributions of knee muscles moment. The PCA technique does not provide a concrete reason for a particular classification decision and requires the skill of the investigator for any classification decision (Perez and Nussbaum, 2003).

Stepwise discriminant analysis is a method that allows the generation of one or more linear combinations of variables. This method can be employed for identification (Leone et al., 2002) and classification (Beharav and Nevo, 2003). This method is also used to determine linear relationships between variables. If there are two independent variables, using this method reduces the risk of type I error, but it cannot calculate any possible between-factors' interaction. However, this technique is used in this study because it gives a percentage of correct classification. As our feet types are known (sorted in groups by a podiatrist), the class membership is pre-determined. To our knowledge, this method has not previously been used for the classification of several foot deformities. Only one study by Song et al. (1996) has used this method to predict two foot groups, namely pes planus and able-bodied feet.

Fuzzy logic as an artificial intelligence technique is a modeling method well suited for the control of complex systems. The Fuzzy logic technique was first presented by Lotfi Zadeh in 1965 (Perez and Nussbaum, 2003). This method has been used for intelligent systems in medicine (Phuong and Kreinovich, 2001) and is a relevant method for diagnosing diseases (Bellamy, 1997). The mechanics of Fuzzy mathematics involve the manipulation of variables through a set of linguistic equations that can take the form of IF-THEN rules. Therefore, Fuzzy logic is a powerful technique to make a prediction model (Bell and Crumpton, 1997).

Fuzzy logic was preferred over Artificial Neural Networks (ANN) as the latter is trained on specific applications and does not necessarily provide a cause-effect relationship between input and output according to Taguchi and Jugulum (2002). For example, if ANN was used for pes cavus and supination feet, it will not work well if pes planus, or any other type of feet, are introduced.

In summary, classification methods are often based on one or a few joint angles. Because of the complexity of foot deformities such as in pes planus and pronation, there is a need to employ several parameters from different perspectives to better describe foot morphology in a clinical environment. To our knowledge, multivariate statistical analysis and Fuzzy logic modeling technique using several foot parameters have not previously been applied to the classification of foot types.

2.5 Specific objectives of this thesis

A novel technique for identifying and classifying foot deformities is the central interest of this thesis. It is hypothesized that the color-coded video-based system provides consistent measurements of foot parameters. Furthermore, measurements taken using the color-coded video-based system should have a high consistency when the same subject is evaluated by several evaluators. If so, then the system can provide accurate assessment of foot problems.

The first objective of this study aims to: a) determine intratester reliability in order to establish the minimum number of repetitions or trials required for clinical assessment of the foot parameters, b) document intertester reliability by assessing the variability among five evaluators and c) determine short- (in the morning and afternoon of the same day) and long-term (1 week after) reliability of the evaluation.

A thorough description of foot deformity characteristics may provide insights to their geometry and orientation in order to facilitate identification and classification of foot deformities. It is also hypothesized that each foot deformity will have its own specific geometry different from able-bodied feet. The second objective of this study is to: a) compare four foot disorders, namely pes planus, pronation, pes cavus and supination with an able-bodied group using 15 foot angles taken from four views, namely antero-posterior, postero-anterior, medial and posterior views of feet in plantar flexion and b) describe the differences among the groups.

Most studies have identified and classified foot types based on one or two parameters usually selected from a single view of the foot. Because of the complexity of the foot, it is necessary to evaluate the foot using 15 parameters in different views. Therefore, the third hypothesis of this study is that using several parameters from four different views will better classify the feet into their respective groups. The final objective of this study is to: a) identify which foot angles best distinguish an able-bodied group from pes planus, pronation, pes cavus and supination groups; b) classify these foot types into their appropriate groups employing two multivariate statistical models; namely principal component analysis and stepwise discriminant analysis and Fuzzy logic and c) test the ability of each classification model to predict foot types using these three methods.

Chapter 3

3. METHODS

This chapter deals with the application of a color-coded video-based system for foot assessment to classify foot deformities. Using this system, fifteen foot angles were measured. Some of these angles have been used in classical radiographic or goniometric measurements while others were developed to take advantage of the features of the color-coded video-based system for a better identification and classification of foot pathologies. The reliability of the color-coded system is first determined, then, using the angles, the geometric characteristics of four foot pathologies, namely pes planus, pronation, pes cavus and supination and that of the normal foot, are described. This is followed by a description of the principal component analysis, stepwise discriminant analysis and Fuzzy logic tools for classification of foot types. Finally, the tools to determine the ability of models to identify foot types of new subjects are detailed.

3.1 Color-coded video-based system

This study is based on a new instrument to assess foot and posture in a clinical setting. A digital camera as shown in Figure 3.1 is positioned on a vertical rail so that the camera can be adjusted from foot to shoulder level. Two fluorescent lights are placed parallel to the rail and on each side of the camera to ensure a uniformly lit body surface (84 lux) and appropriate contrast of the exposed flesh. To better identify the body surfaces, the background setting is covered with a black curtain. A laser pointer is fixed to the camera to facilitate the alignment of the camera's optical axis. To control the experimental procedure in capturing the pictures, the camera-subject distance was approximately 1.7 meters.

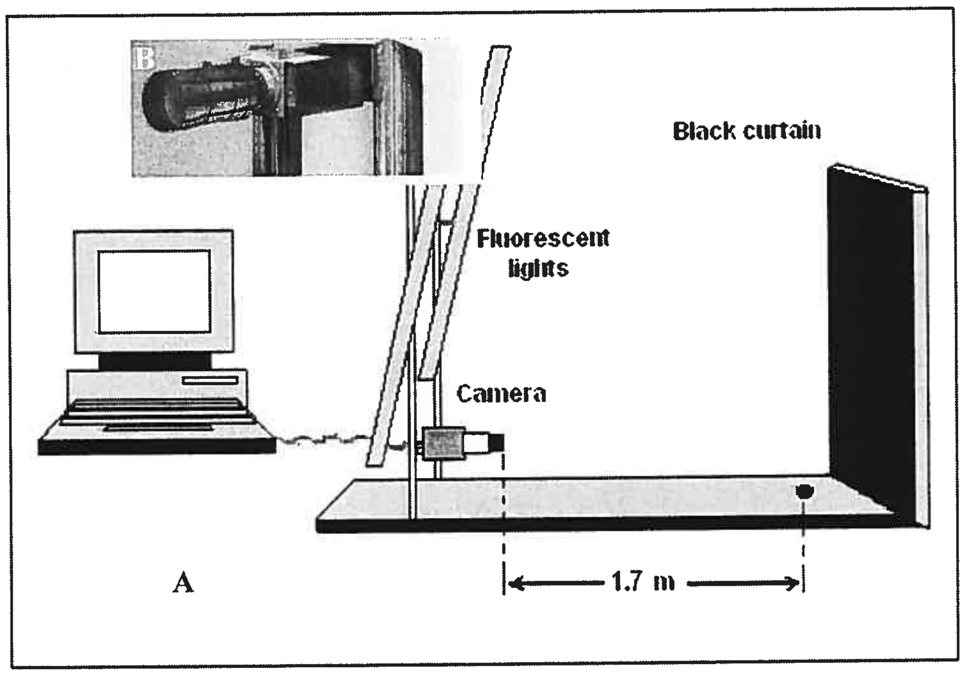


Figure 3.1. A) Color-coded video-based system setting. B) A digital camera is positioned on a vertical rail with two fluorescent lights on its either side. The camera-subject distance is 1.7 meters.

Subjects were asked to maintain a free weight-bearing position to avoid imposing a fixed stance position. For example, using devices to standardize the foot orientation including the distance between the heels could inadvertently modify the configuration of the feet and could lead to an erroneous clinical diagnostic. The subject's lower limbs were uncovered before the acquisition to evaluate the lower leg and feet. To control for parallax, the camera was positioned parallel to the floor with the optical axis directed towards the feet.

Six black and white pictures of the feet were taken with the digital camera in the weight-bearing position as shown in Figure 3.2. Two of these pictures were taken from the antero-posterior and postero-anterior views of both feet together. To control the camera height, the laser point was focused approximately at the level of the leg/foot junction in antero-posterior view. The camera height was controlled by targeting the laser point above the calcaneus bone in postero-anterior view. Another two pictures were of the medial side of each foot separately. In this view, each subject was asked to take a half step backwards with the contralateral foot to expose the medial view of the foot to be photographed while the leg was oriented vertical to floor. To control the camera height, the laser point was targeted immediately above the base of the first metatarsal bone. Finally, the last two pictures show the posterior view of the right and the left foot in plantar flexion weight-bearing position (plantar flexion view). This later view was suggested by a clinician to emphasize and highlight the relative motion or compensation of the hindfoot when the forefoot is relatively fixed on the ground while being partially loaded. The subjects' feet were photographed while the laser point was focused approximately above the heel. These six images form a single trial. The subject repositioned himself or herself for each foot view. All pictures were immediately saved in the PC environment. This whole procedure took less than five minutes.

Figure 3.2. A single trial of images taken by Biovizion system, a) a ntero-posterior view of both feet; b) postero-anterior view of both feet; c) medial view of the right foot; d) medial of the left foot; e) posterior view of the right foot while plantar flexion and f) posterior view of the left foot while plantar flexion.

Using a numerical filter developed by the manufacturer, the pictures were transformed into color-coded images. This original process was applied to highlight the muscle and bone prominences and facilitate the foot angle measurements. Figure 3.3 illustrates the black and white (A) picture of the medial view of the right foot and (B) its corresponding color-coded image.

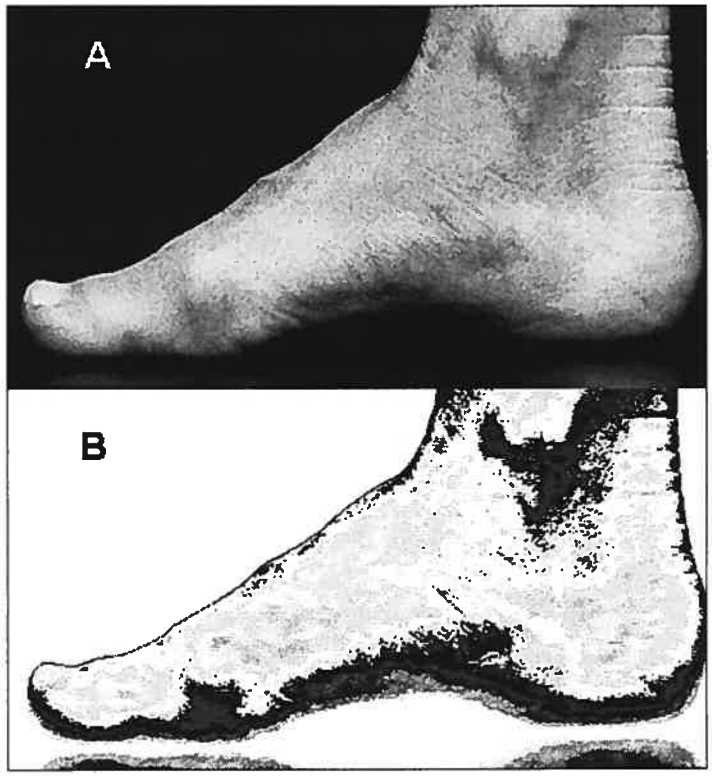


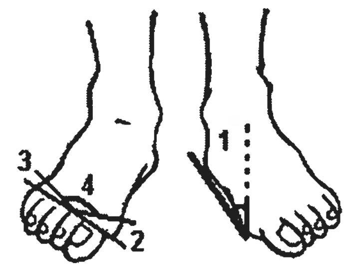
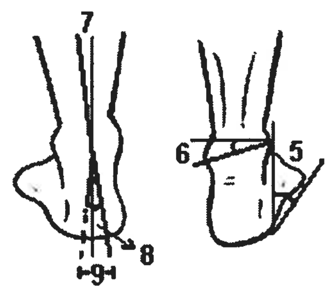
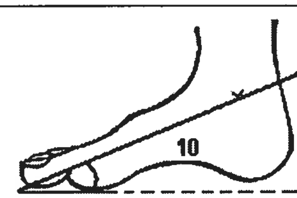
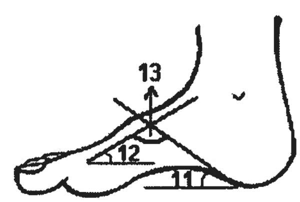
Figure 3.3. The black and white (A) picture of medial view of the right foot and (B) its corresponding color-coded image.

3.2 Angular measurements

In this study, fifteen angles were measured in four anatomical views of the foot to characterize foot types. The angles that are illustrated in Table 3.1 were measured on both feet.

All nine of these foot angles were obtained from the radiographic and the goniometric measurements that were applied to process the foot images. These angles are described in detail in chapter 2. The remaining six angles were developed or modified to improve the geometric description of the foot pathologies.

Table 3.1. The 15 foot angles measured on: antero-posterior (AP); postero-anterior (PA); medial (MED) and posterior plantar flexion (PF) views.

Views	Angles	Images
AP	**1.** Medial base in reference to the vertical axis (Medial base) **2.** Axis of the 1st and the 2nd MTP bones in reference to the horizontal axis **3.** Axis of the 2nd and the 5th MTP joints in reference to the horizontal axis (2^{nd} and 5^{th} MTP) **4.** Meschan	
PA	**5.** Lateral base in reference to the vertical axis (Lateral base) **6.** Malleolus in reference to the horizontal axis (Malleolus) **7.** Bisecting of distal third of the leg to the vertical (Bisect/leg) **8.** Bisecting of calcaneus bone to the vertical (Bisect/heel) **9.** Hindfoot (leg/heel) angle	
MED	**10.** Meary-Tomeno line **11.** Clacaneus inclination in reference to the horizontal axis (Calca-inclination) **12.** The first metatarsal declination in reference to the horizontal axis (1^{st} MTP/Med) **13.** Djian-Annonier angle	 
PF	**14.** Medial heel angle in reference to the vertical (Heel/flex) **15.** Axis of the 2nd and the 5th MTP bones in reference to the horizontal axis (2^{nd} and 5^{th} - MT/flex)	

On the antero-posterior color-coded image, four angles were measured as follows: the Meschan angle as the classical measure of the metatarsal bones' alignment. This angle was formed by two other angles including the first and the second MTP bones' angle and the second and the fifth MTP bones' angle in reference to the vertical axis as illustrated in Figure 3.4.

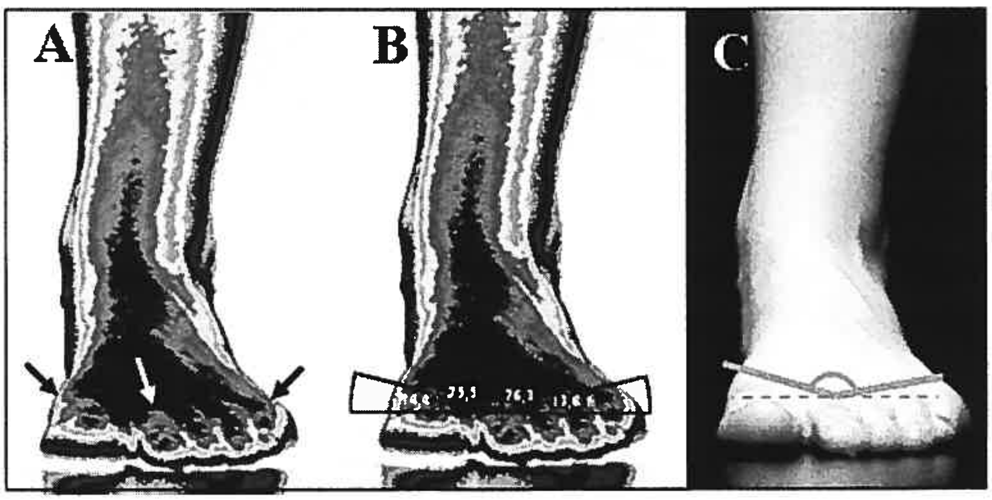


Figure 3.4. The classical foot parameters defining the antero-posterior view, measured on the color-coded image of the left foot: A) references required for measurements; B) angular measurements and C) angles shown schematically on the foot.

In antero-posterior view, the medial base angle formed by the longitudinal axis of the heel and the first metatarsal in reference to the vertical axis was developed to describe the abduction and adduction of the forefoot (Figure 3.5).

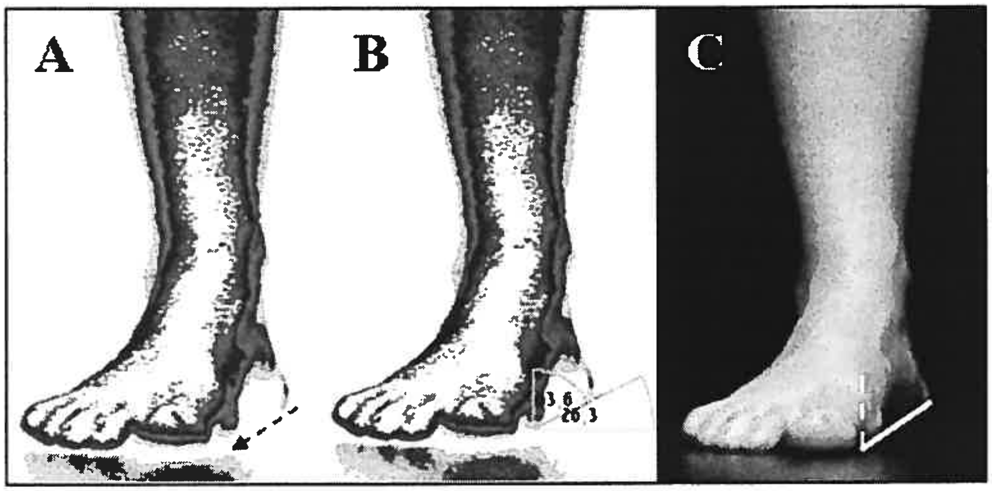


Figure 3.5. The medial base angle in antero-posterior view, measured on the right foot image: A) references required for the measurement; B) angular measurement and C) angle shown schematically on the foot.

On the postero-anterior color-coded image, five angles were measured as follows: the hindfoot angle to describe the supination and pronation as a classical parameter. This angle was formed by two other angles as bisecting the distal third of the leg and bisecting the calcaneus in reference to the vertical axis. These angles were described in section 2.3 of the second chapter. The lateral base angle formed by the longitudinal axis of the heel and the fifth metatarsal in reference to the vertical axis was developed to describe the abduction and adduction of the forefoot. The last parameter was the modification of the tips of both malleoluses (Brage et al., 1997). In this study the malleolus angle is measured in reference to the horizontal axis in order to describe the internal and external tibial torsion related to the foot and ankle. Drawing a line from the medial to the lateral malleolus then to the horizontal axis created the malleolus angle as shown in Figure 3.6.

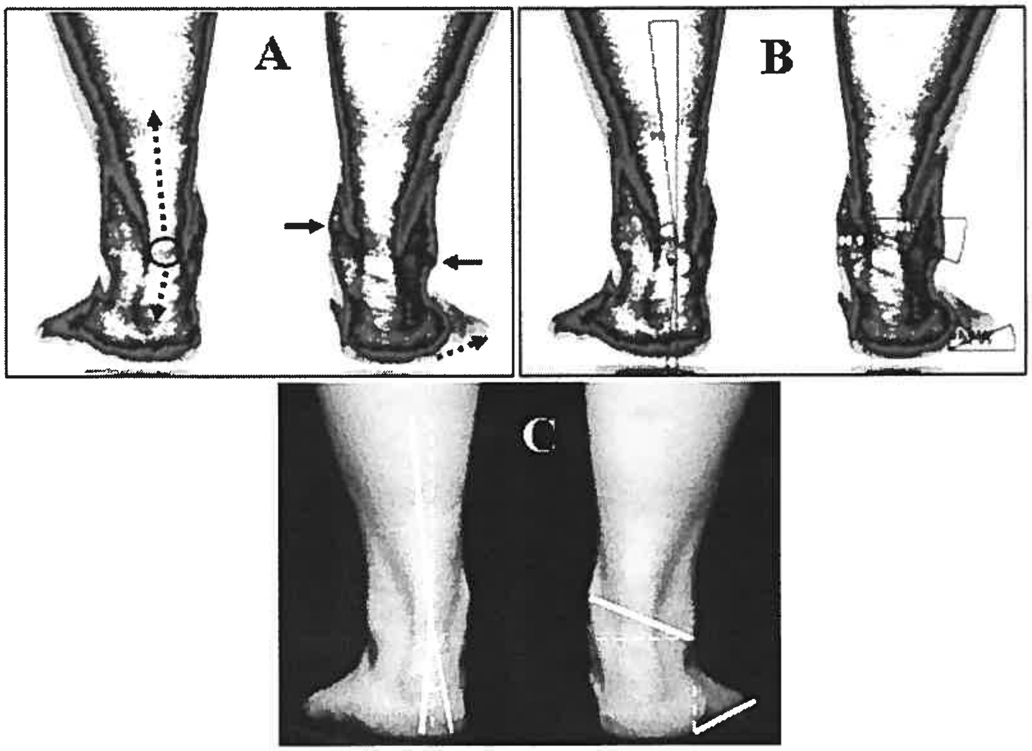


Figure 3.6. The foot parameters defining the postero-anterior view, measured on the color-coded image: A) identification of the references required for measurements; B) angular measurements and C) angles shown schematically on the feet.

Four foot parameters were measured on the medial view of the processed foot images. The calcaneus inclination and the first metatarsal angles both in reference to the horizontal axis were measured to form the Djian-Annonier angle. These three classical angles were described in section 2.3. Figure 3.7 illustrates the procedure of the measurements of these angles on the color-coded images.

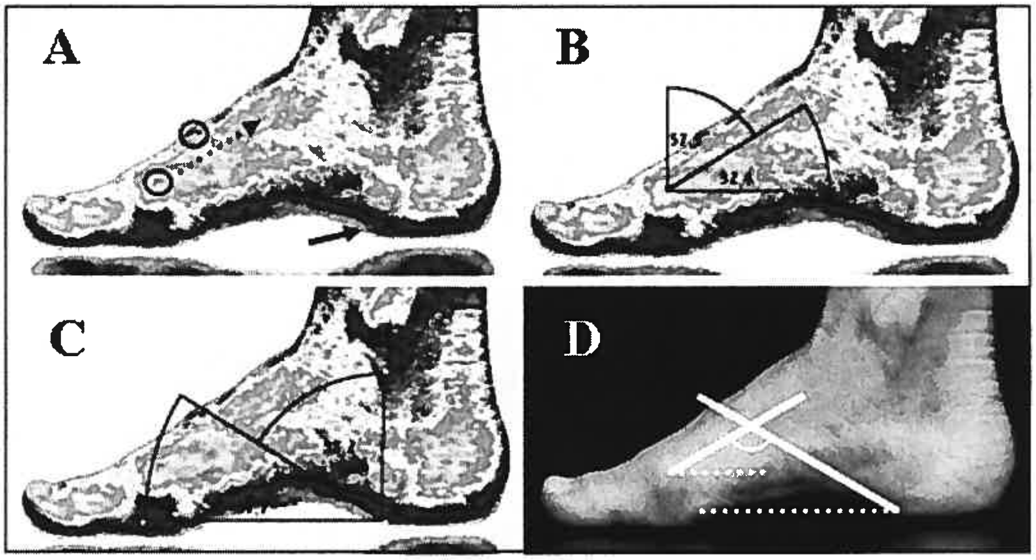


Figure 3.7. Foot parameters defining the medial view, measured on the color-coded image of the right foot: A) references required for measurements; B) first metatarsal inclination; C) calcaneus inclination and D) angles shown schematically on the foot.

In medial view the Meary-Tomeno line was defined as the angle between the axis bisecting the talus and the first metatarsal bone in reference to the horizontal axis (Figure 3.8).

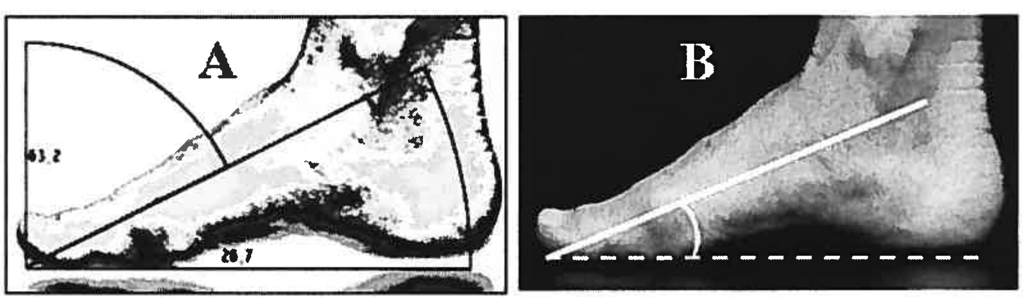


Figure 3.8. The Meary-Tomeno angle on the color-coded image of the right foot: A) angular measurement and B) angle shown schematically on the foot.

Two developed angles were measured on the posterior plantar flexion view of the color-coded image. The medial heel angle of the foot was created and defined as the line drawn tangentially to the medial margin of the heel in reference to the vertical in order to describe varus or valgus of the heel when the forefoot is relatively fixed on the ground while being partially loaded.

The last angle was obtained in the frontal plane from a line taken from the head of the second metatarsal to the fifth metatarsal bone when the foot was loaded (plantar flexion view). This angle was measured to provide information on the functional and compensatory relations between the forefoot and the hindfoot under loading conditions. Figure 3.9 shows the procedure of the measurements of these angles on the left foot color-coded image.

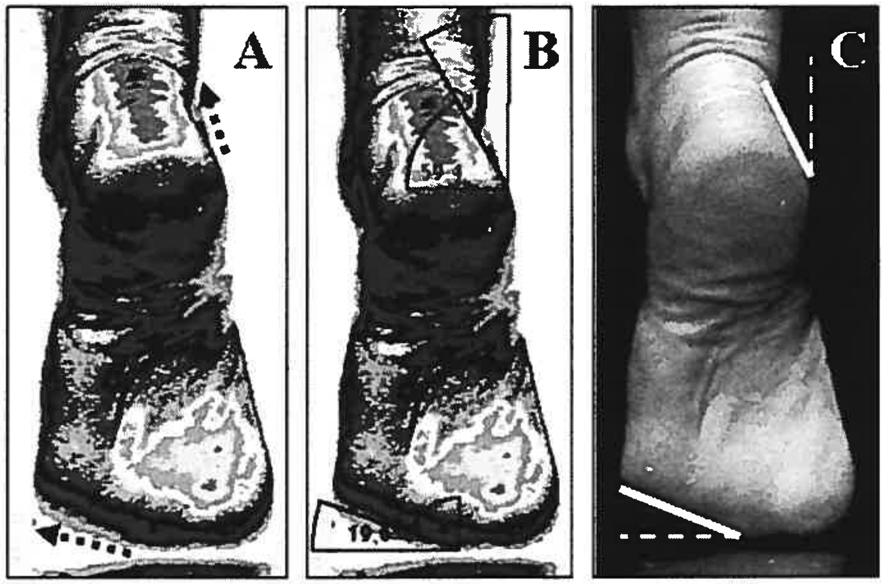


Figure 3.9. The foot parameters defining the posterior plantar flexion view, measured on the left foot color-coded image: A) references required for measurements; B) angular measurements and C) angles shown schematically on the foot.

3.3 Reliability of the color-coded video-based system

Though the classical angles have been routinely used in podiatric clinics for assessing foot disorders and posture, their reliability is still unknown. This section details the procedure to determine the number of required trials, the intertester reliability and the short and long-term reliabilities. The validity of these foot angles has not been addressed in this study and requires an independent study. In validating this technique, there was difficulty in finding both color-coded and radiographic systems in the same clinical setting at the time of the study.

3.3.1 Subjects and preparation

A sample of fifteen able-bodied subjects (11 women and 4 men), having an average age of 21.1±1.8 years was recruited from the Department of Kinesiology at the University of Montreal. The subjects' mean height and mass were 170.5±9.4 cm and 62.5±8.7 kg respectively. No subjects reported a history of musculoskeletal or neurological disorders, nor did they have pain or injury at their lower extremities for a minimum of 6 months prior to the study. Each subject's lower limbs were first uncovered before data acquisition to evaluate the lower leg and feet. Afterwards, the subjects took a few minutes rest to eliminate the effect of pressure from socks and shoes on their feet. Potential subjects were excluded if there were any scars, spots, warts, skin irritations, calluses or other skin signs on their feet. Following an explanation of protocol, subjects gave their informed consent by signing a written consent form for the protocol approved by the University of Montreal Ethics Committee.

3.3.2 Reliability assessment procedure

The effect of subject repositioning for imaging the different foot views was first addressed. All fifteen subjects (30 feet) were included to estimate the intratester reliability of the color-coded video-based system. Each individual was evaluated seven times with a one-minute rest period between each trial. The same examiner measured all of the 15 foot angles for seven trials, using six color-coded images of each foot in each trial. The intra-class correlation coefficient [ICC (2, 1)] was used to estimate the reliability of the system and determine the number of trials required for a clinical evaluation (Shrout and Fleiss, 1979). ICC values vary from -1 to +1 (Bernard and Lapointe, 1998). This study defined excellent reliability as ICC values of 1.00. Sell et al., (1994) defined high reliability as ICC values between 0.90 to 0.99, good reliability as ICC values between 0.80 to 0.89, fair reliability as ICC values between 0.70 to 0.79 and poor reliability as ICC values below 0.69. One-way analysis of variance (ANOVA) for repeated measures with a Tukey post hoc test ($p<0.05$) was used to determine whether there were any significant differences between trials (ICCs for 2 to 7 repetitions). The Tukey test was chosen because it is suitable for unplanned tests and helps to minimize the unwanted family-wise type I error.

In order to investigate the intertester reliability of the system, five different testers were trained by a clinician who was not involved in any part of the experiments. The assessments were conducted by these five testers, all of whom were graduate students in the Human Movement Laboratory at the Sainte-Justine hospital with various clinical experiences in biomechanics. All testers had no experience in the use of the color-coded video-based system before this study. The six images taken from the first trial of the 10 subjects (20 feet) in the intratester experiment were presented to the testers. Using the same method, all testers measured the 15 angles of each foot and then the ICC values were calculated between testers.

Ten out of the 15 individuals (20 feet) participated in the short and long-term reliability assessments. Short-term reliability was determined as the consistency of the measurements repeated within an initial test (baseline) in the morning and a four-hour after baseline session in the afternoon. In the assessment of the long-term reliability of the system the foot angle measurements were performed at the same hour on the baseline day with one week between the two consequent measurements. The same tester measured all of the 15 foot angles for above mentioned occasions. The ICCs were first calculated for all three experimental sessions. Then, the baseline data were compared with those collected four hours after the baseline as short-term ICCs or one week after the baseline as long-term ICCs. Variations in reliability due to the time intervals between baseline and retest occasions were estimated by comparing short-term and long-term ICCs by using a t-test for paired samples.

3.4 Morphological description of foot pathologies

In clinical assessments, quantitative information on the morphological characteristics of the pathological foot is helpful for its accurate identification and classification. To our knowledge, very little information about the morphological description of foot pathologies has been reported in the scientific literature. The available information is often limited to one or two foot pathologies, based on a limited number of feet or a few foot angles.

In this study, 321 feet from 189 subjects were selected to describe five different foot types using 15 foot angles. In some subjects only one foot was affected and in others contralateral feet were differently deformed. For example, the right foot was pronated while the left foot of the same subject was supinated. For this reason the classifications were made based on the feet and not the subjects. The feet were classified by an experienced podiatrist into an able-bodied group (n= 26) and four pathological groups as pes planus (n= 52), pronation (n= 80), pes cavus (n= 115) and supination (n= 48). The able-bodied subjects were different from those participated in the reliability study and selected from students of the department of Kinesiology at the University of Montreal. These subjects had the same inclusion and exclusion criteria mentioned above. Table 3.1 summarizes the information of the selected subjects. Table 3.2 details the demographic characteristics of the subjects according to their foot type.

Table 3.2. Characteristics of 189 subjects (321 feet) by age, height, mass and gender. Values are presented as mean, and standard deviation in parentheses. yrs representative of years; cm representative of centimeter; kg representative of kilograms; M representative of male; F representative of female and n representative of number.

Groups	**Characteristics**						
	Age (yrs)	**Height (cm)**	**Mass (kg) (kg)**	**Gender M**	**Gender F**	**Subject (n)**	**Feet (n)**
Able-bodied	22.4 (4.3)	172.1 (7.9)	70.3 (8.6)	6	9	15	26
Pes planus	38.6 (27.3)	155.6 (9.5)	65.1 (4.9)	8	20	28	52
Pronation	48.8 (18.4)	164.6 (13.1)	71.3 (13.4)	16	33	49	80
Pes cavus	47.7 (17.3)	167.5 (10.1)	73.8 (20.7)	41	26	67	115
Supination	53 (17.2)	163.4 (14.1)	70.9 (12.6)	17	13	30	48
Total				88	101	189	321

Analyses of covariance (ANCOVAs) were performed to analyze between groups differences for each angle. This was followed by Tukey post-hoc comparison to describe in detail each variable across the groups. Finally, a Bonferroni correction procedure was performed to control Type I error by adjusting the p values when analyzing the above angles. All significant differences set at $p<0.05$ level.

3.5 Identification and classification of foot deformities

Classification of foot types requires reliable measurements to identify the main characteristics of each. Principal component analysis (PCA) and stepwise discriminant analysis (SDA) techniques were applied to identify the relevant foot parameters. Then PCA, SDA and Fuzzy logic (FL) were performed to classify foot types. Fifteen angles were measured for all 321 normal and pathological feet to develop the classification models.

3.5.1 Principal component analysis

PCA was performed on a dataset consisting of 15 foot angles taken from 321 feet. Because of some missing data the model used 295 of the feet in the analysis. First, PCA was performed on the complete dataset to reduce the number of foot angles. The first principal component (PC1) accounts for the maximum of the total variance, while the second one (PC2) accounts for the maximum residual variance and so on. Loading values greater than 0.7 and less than -0.7 in each PC were taken to reduce and identify the variables as the most important foot angles in the analysis model (Sharma, 1996). These were then used to classify the five foot types using the PCA technique again.

The first two PC scores were plotted against each other to classify feet in different clusters. Though there is no standard or accepted way to classify cases using PCA, investigators usually separate clusters on the plot using an arbitrary division (Hèberder et al., 2003; Devillers et al., 2004). In order to derive a quantitative classification model with PCA, the score plot area was divided into four equal parts using the vertical and horizontal axes. The five foot types were located in separate parts of the plot. Then the number of cases located in each part were counted and divided by the total number of each group to obtain the percentage of the correct classification.

3.5.2 Stepwise discriminant analysis

A stepwise discriminant analysis was performed to determine the relevant geometric characteristics and classify the feet using the same data set as for the PCA. Because of some missing data, this model used 280 out of the 321 feet in the analysis. This method included all 15 angles to determine those that discriminate between groups. During each step, the model reviews all variables and evaluates which one will contribute most to the discrimination between groups. That variable is included in the model and the model proceeds to the next step. Wilks' Lambda statistic for weighing-up the addition or removal of variables from the analysis was chosen. This study used the Wilks' Lambda test to keep or remove a variable or angle. During each step of adding a variable to the analysis, the variable with largest F value is included. This process is repeated until there is no other variable with an F value greater than the critical minimum threshold value. At the same time, any variable that had been added earlier no longer contributes to maximizing the assignment of cases to the correct groups. In this study, the SDA reduced the number of angles to ten. Afterwards, the model classified the feet in their respective groups.

3.5.3 Fuzzy logic technique

A Fuzzy logic model was developed to classify the 321 feet into five foot types with the success rate of 75%. To develop a fuzzy model, three calculations are required including fuzzification, fuzzy inference and defuzzification (Figure 3.10 A). In this study, the Fuzzy logic toolbox and functions in MATLAB was used to develop the model using two selected foot angles, namely, hindfoot and Djian-Annonier angles.

The values of input angles including the hindfoot and the Djian-Annonier were in crisp form that needed to be converted into fuzzy values using linguistic variables called fuzzy sets. The process of mapping crisp input values into linguistic values is termed as fuzzification (Shahin et al., 2001). Fuzzification of the two above mentioned angles as input variables were established by creating membership functions that indicated the degree to which a particular value belonged to different fuzzy sets. A membership function is a curve that defines how each point in the input space is mapped to a membership value between 0 and 1. Before establishing the membership functions the distribution of feet across the hindfoot and the Djian-Annonier angles was plotted. Then each set of data related to groups was subjectively divided into subgroups to obtain the distribution area that covered most of the feet.

The membership functions defined for the hindfoot angle as illustrated in Figure 3.10 (B) had a value of 0^{o}-10^{o} as a normal range while less than this range represented supination with four subgroups including SU0 to SU4 and higher values than 10^{o} represented a pronation deformity with three subgroups including PR1 to PR3. The membership functions defined for the Djian-Annonier angle had a value of 122^{o} – 130^{o} as normal angle, higher than 130^{o} as pes planus with three subgroups including PP1 to PP3. The angle less than 122^{o} defined as pes cavus with four subgroups including PC0 to PC3.

The fuzzy inference is a set of IF-THEN rule statements that compute an output based on current values of the input angles (Hindfoot and Djian-Annonier). The rules were constructed to formulate the conditional statements that comprise Fuzzy logic. Numbers of the rules are related to the number of possible combinations of the functions of memberships for two above mentioned angles. This part is very difficult to perform because one needs to define and formulate many rules. Because of this, only two angles out of 15 were selected.

The hindfoot and the Djian-Annonier angles were chosen to characterize the four pathological feet to compare them with the able-bodied foot type. These two angles were selected since they were identified as the highest predictors from the main variables following a principal component analysis and a stepwise discriminant analysis. Forty-six reasonable and realistic rules were defined in this study in order to compute five fuzzy output membership functions based on input values of mentioned angles for all feet types.

The defuzzification is the process of transforming a fuzzy output of the fuzzy inference into a crisp output. In this study, five groups of feet were constructed.

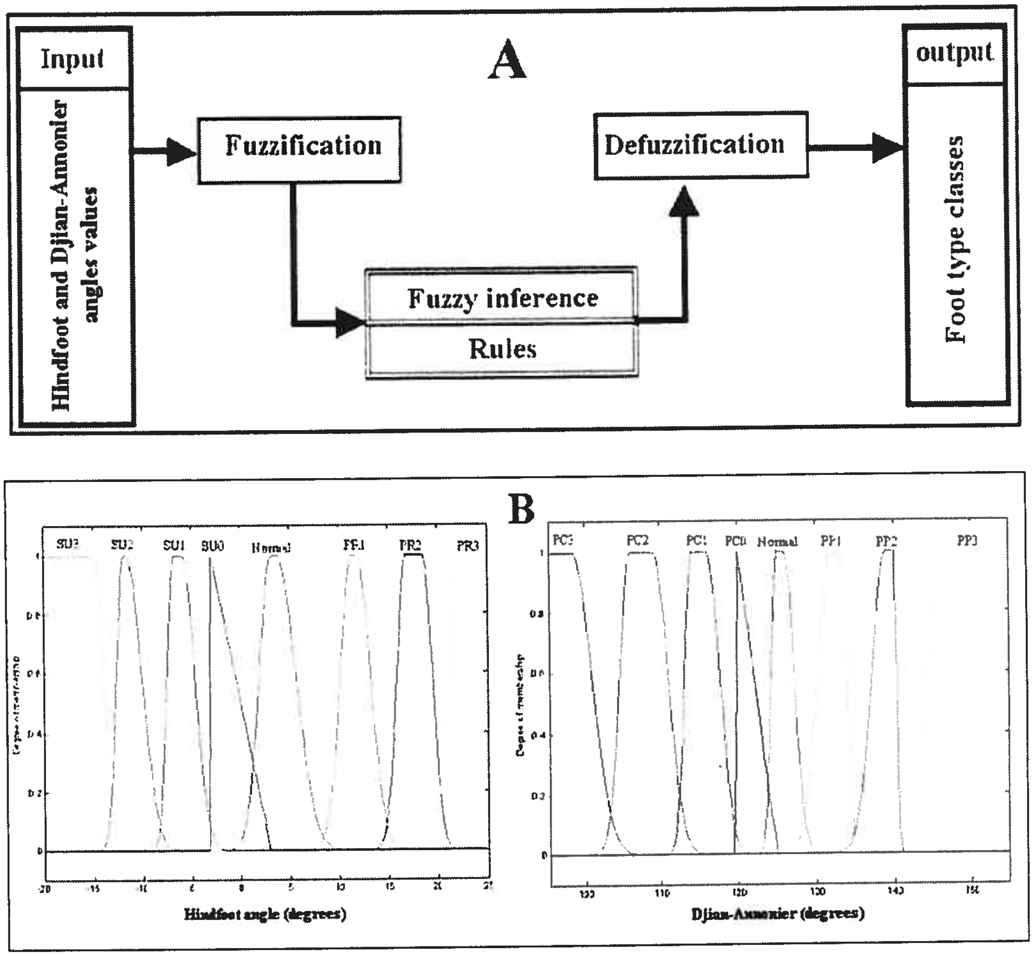


Figure 3.10. **A**) Schematic diagram of stages for foot type classification using fuzzy model and **B**) membership functions for characterization of the pathological feet based on the hindfoot (left) and the Djian-Annonier (right) angles.

Kappa statistics were applied to obtain the relative accuracy of each classification method. This method allows checking the result of the classification with the clinical sorting of the feet performed by the podiatrist. According to Landis and Koch (1977), interpretation of the Kappa values were defined as follows: a value of less than 0.4 indicates poor agreement, values from 0.4 to 0.75 present fair to good and values between 0.76 and 1 indicate excellent agreement.

Chi-square was performed to determine which method produces the best classification by comparing the observed counts of the cases (frequency of feet that were sorted clinically) to the expected counts (frequency of feet classified by models).

3.6 Prediction from new foot values

The prediction capabilities of these three models using new and independent data sets were tested. Ninety-four new feet were first clinically categorized by a podiatrist into five groups including AB (n=16), PP (n=16), PR (n=22), PC (n=28) and SU (n=12). Then the 15 angles were measured from pictures taken with the color-coded video-based system as described above. Afterwards, the PCA SDA and Fuzzy logic models were applied to predict the new data sets. The number of feet was reduced from 94 to 79 only in the PCA model because of some missing data. The Kappa statistics were performed to obtain the accuracy of each prediction method as explained above for classification methods. The Chi-square was also performed to detect which method produced the best prediction by comparing the observed counts of particular cases (frequency of feet that were sorted clinically) to the expected counts (frequency of feet predicted by models).

Chapter 4

4. RESULTS

This chapter first details the results of the reliability assessment of a computer-aided color-coded video-based technique for the evaluation of foot morphology. This is followed by the identification of the morphologic characteristics of four pathological foot conditions and their comparisons with asymptomatic feet. Then, the classification of 321 feet into five different foot types based on PCA, SDA and Fuzzy logic techniques are presented. Finally, using new data from 94 feet, the capability of these three models for foot type prediction is compared.

4.1 Reliability analysis

The reliability of the color-coded video-based system is presented in three parts. The first part reports on the number of trials required for reliable information in the clinical examination of the feet. This is followed by the intertester reliability results. Finally, the short-term (morning and afternoon of the same day) and the long-term (1 week interval) reliabilities are presented.

4.1.1 Intratester and number of trials reliability tests

The mean ICC values for all 30 angles measured on both feet (15 for each foot) were calculated for the first two trials to all seven trials and are presented in Figure 4.1. The mean ICC value for the first two trials to all seven trials was 0.89±0.03 with a range varying from 0.83 to 0.92. The highest mean ICC values were found for trials 1-7 while trials 1-2 had the lowest mean. The mean ICC values of twenty out of the thirty measured angles (15 angles for each foot) for all trials had ICC values of 0.90-0.98. Seven angles had ICC values ranging from 0.83 to 0.88. Two of them had ICC values of 0.72 and 0.73. The Meschan angle of the right foot had an ICC value of 0.60.

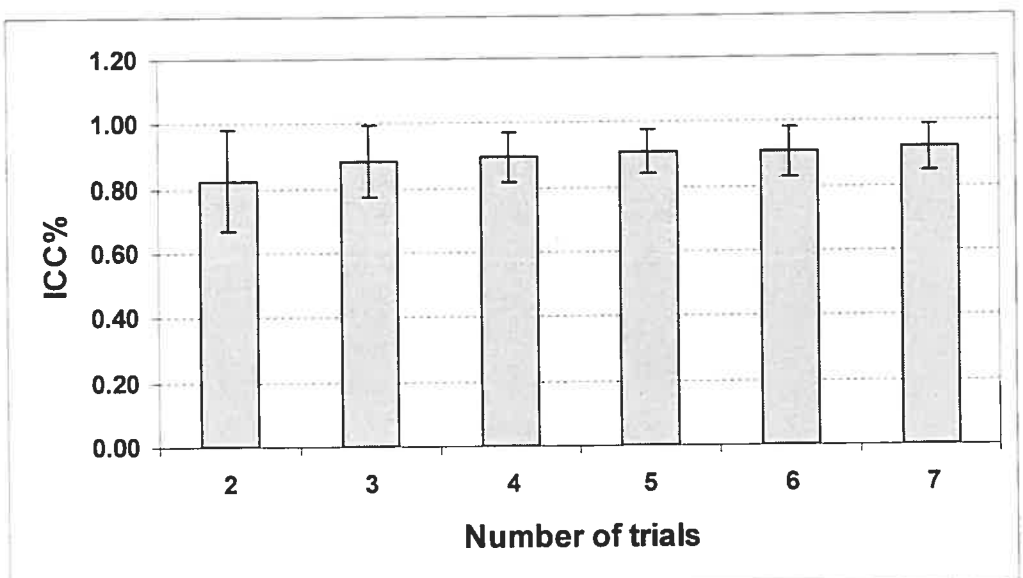


Figure 4.1. The mean of the ICC values for all parameters for first two trials up to all seven trials.

Figure 4.2 shows the mean ICCs for all four views of both feet which were calculated for the first two trials to all seven trials. The overall average was 0.88±0.04. The highest (ICC=0.93) value was found for the postero-anterior view while the lowest ICC value (0.84) was found for the antero-posterior view.

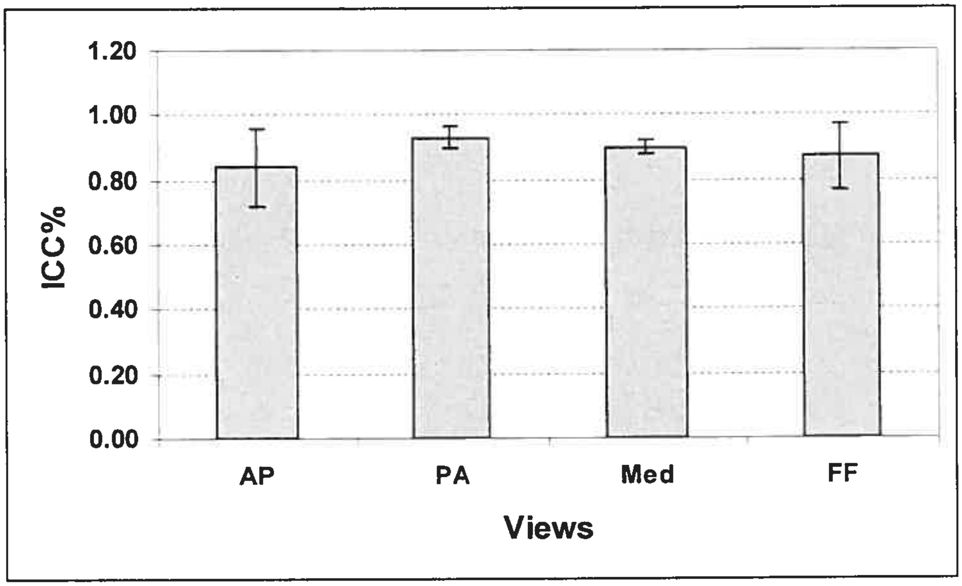


Figure 4.2. The mean ICC values of the foot angular parameter, measured in all four views of the foot. AP, (antero-posterior); PA, (postero-anterior); Med, (medial), and PF, (plantar flexion).

4.1.2 Intertester reliability

Figure 4.3 represents the mean ICC values when all of the 30 angular parameters in both feet were included in the evaluation of two to five testers for ten subjects. As shown in Figure 4.3 the overall mean and highest ICC values for all the testers was 0.91. While the lowest ICC value (0.80) was obtained for the 1-2 testers.

When the angles were grouped according to view, the highest ICC value (0.97) was found for the foot plantar flexion view while the lowest ICC value (0.83) was seen on the antero-posterior view. The average ICC value for the right and the left feet were similar in all views.

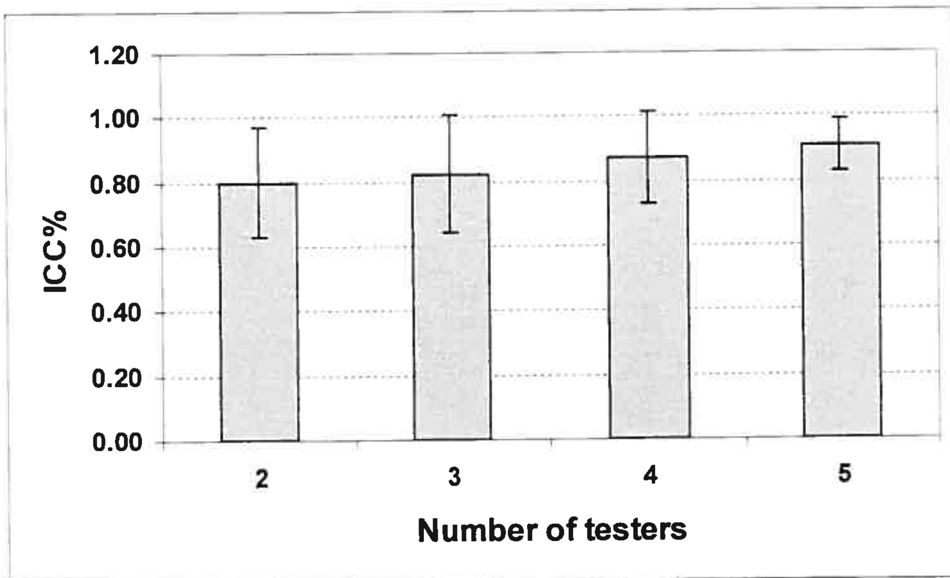


Figure 4.3. The mean ICCs for all of the 30 angular parameters of both feet of 10 subjects that were obtained by two to five testers.

Out of the 30 angles for both feet, as is detailed in Table 4.1, two angles had an ICC equal to 1; twenty were between 0.90-0.99; six were between 0.80-0.89 and two were between 0.70-0.79. The lowest ICC value (0.72) was located in the antero-posterior view for the Meschan angle of the left foot to identify abnormality of the metatarsal bones.

Table 4.1. Mean intertester ICC values of all 15 angles for the right and left feet separately. Views and angles abbreviations are given previously in chapter three (Table 3.1).

Views	**Angles**	**ICCs**	
		Right foot	Left foot
AP	Medial base	1.00	1.00
	1st and 2nd MTP	0.74	0.82
	2nd and 5th MTP	0.80	0.90
	Meschan	0.86	0.72
PA	Malleolus	0.95	0.92
	Lateral base	0.98	0.99
	Bisect/leg	0.83	0.94
	Bisect/heel	0.99	0.99
	Leg/heel	0.93	0.93
MED	Meary-Tomeno	0.97	0.91
	1st MTP/Med	0.86	0.95
	Calca-inclination	0.90	0.81
	Djian-Annonier	0.92	0.93
PF	Heel/flex.	0.99	0.96
	2nd and 5th MTP/flex.	0.96	0.97

4.1.3 Short and long-term reliabilities

The mean ICC values of the short- and the long-term evaluation of ten subjects conducted by one tester are presented in Figure 4.4. The subjects were evaluated in the morning (baseline), in the afternoon of the same day (short-term) and one week after at the same time of the initial evaluation (long-term) by the same tester. The short-term evaluation had a mean ICC value of 0.83, and similarly the long-term evaluation had an average ICC value of 0.81. Variations in reliability due to the time intervals between baseline and retest occasions were estimated by comparing short- and long-term ICC values by using a dependent t-test. The dependent student t-test did not reveal any significant difference between the short and the long-term measurements in comparison to the baseline measurements.

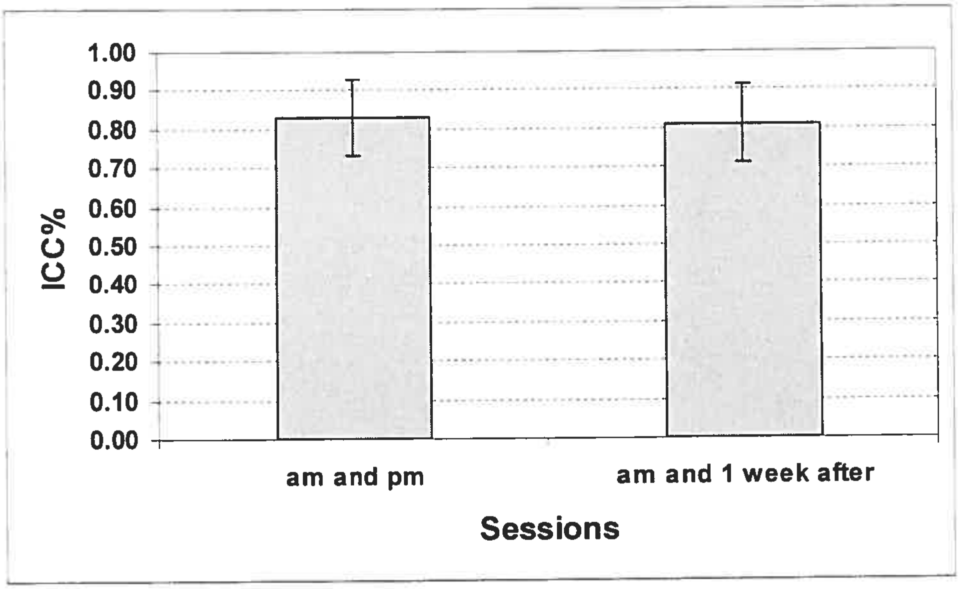


Figure 4.4. The mean ICC values for short-term (am and pm) and the long-term (am and one week after) of 10 subjects evaluated in the morning, in the afternoon of the same day and after a one week interval.

4.2 Identification of the foot parameters

This section deals with the identification and description of four pathological foot conditions and their comparisons with asymptomatic feet based on the 15 angles. Descriptive statistics for all of these 15 angles measured in four views are given in Table 4.2 for five different foot types. Because of significant differences of weight and height between groups, analysis of covariance (ANCOVA) was used in this study. This was followed by Tukey post-hoc tests to compare the angles between the pathologies and the able-bodied groups with weight and height as covariates.

Comparing the pathological conditions with able-bodied feet enables the characterization of each foot condition. The purpose here was to identify which angles are abnormal for a particular foot condition. For this reason, univariate statistical methods were applied. Comparing foot pathologies among themselves would lead to a multitude of differences difficult to interpret. It is the purpose of multivariate analyses to describe these associations between foot pathologies. Principal component analysis and stepwise discriminant analysis as well as fuzzy logic method were used in this thesis.

Table 4.2. Mean and standard deviations of the angles measured in degrees for all five foot types. Views and angles abbreviations are given in Table 3.1. SD represents for standard deviation.

View	Angles	Groups				
		Able-bodied Mean (SD)	Pes planus Mean (SD)	Pronation Mean (SD)	Pes cavus Mean(SD)	Supination Mean (SD)
AP	Medial base	34.3 (28.2)	32.2 (16.4)	32.2 (13.7)	32.2 (16.4)	40.7 (14.8)
	1st and 2nd MTP	6.1 (1.6)	7.3 (3.9)	10.5 (4.1)*	4.7 (5.6)	10.0 (2.6)*
	2nd and 5th MTP	4.9 (2.3)	14.2 (6.8)*	15.6 (3.7)*	11.9 (4.6)*	15.3 (2.9)*
	Meschan	169.0 (2.3)	158.4 (8.4)*	153.7 (4.5)*	162.5 (6.7)*	154.7 (2.9)*
PA	Malleolus	13.0 (3.7)	13.0 (4.5)	13.1 (3.4)	15.7 (5.1)	13.4 (5.1)
	Lateral base	70.0 (10.7)	50.6 (16.3)*	47.7 (14.3)*	51.9 (14.2)*	56.5 (20.3)*
	Bisect/ leg	0.4 (3.4)	0.6 (5.4)	0.0 (6.6)	1.1 (5.9)	2.6 (5.8)
	Bisect/heel	0.4 (2.6)	2.1 (9.4)	2.6 (9.3)	0.8 (5.6)	3.8 (9.2)
	Leg/heel	4.2 (2.6)	11.6 (6.6)*	14.5 (4)*	3.2 (5.5)	-3.9 (3.4)*
MED	Meary-Tomeno	25.6 (2.1)	21.7 (3.0)*	20.2 (2.4)*	22.7 (3.1)*	21.2 (1.9)*
	1st MTP/Med	25.4 (2.2)	21.9 (3.2)	21.5 (10.0)	27.0 (2.7)	25.9 (8.3)
	Calca-inclination	30.6 (3.1)	24.0 (3.6)*	23.2 (11.3)*	34.4 (3.5)	36.7 (4.1)*
	Djian-Annonier	124.2 (2.8)	134.1 (5.1)*	131.2 (6.1)*	119.2 (8.2)*	116.4 (5.4)*
PF	Heel/flex	23.2 (7.8)	15.9 (6.0)*	15.5 (6.3)*	18.1 (6.5)	16.2 (5.4)*
	2nd and 5th MTP/flex	21.0 (6.4)	15.1 (7.1)*	12.1 (4.2)*	11.8 (5.0)*	8.8 (3.7)*

* Significant differences $p<0.05$, between the able-bodied group and the four pathological groups of feet.

Pes planus is one of the foot pathologies in which the medial longitudinal arch is decreased in mild cases or severely flattened in advance pes planus. Our results showed that in pes-planus feet the Djian-Annonier angle was 134.1° ± 5.1°, which is about 10° greater than that of able-bodied feet (p=0.000). This large Djian-Annonier angle represents a flattening of the medial longitudinal arch of the foot and is also expressed by a decrease of 6° (p=0.002) on the calca-inclination and 4° on Meary-Tomeno (p=0.000) angles. We also observed that in a weight-bearing position of the pes planus feet the heel was tilted in a valgus direction resulting in an increase of about 7^{0} on the related leg/heel angle (p=0.000).

In the pes planus foot type the lateral base angle was decreased by about $19.4^{0} \pm 16.3$ (p = 0.000) compared to the able-bodied group, implying reduction on the forefoot abduction. This finding was supported by a decrease of about 6^{0} on 2^{nd} and 5^{th} MTP/flex angle in pes planus feet (p=0.000). This could partially be explained by an internal leg rotation, which is associated with the pes planus foot type. We also found a decrease of 11^{o} on Meschan angle (p=0.000) that is related to the metatarsal deformity in the forefoot.

In a clinical setting, the pronated foot is characterized by the heel valgus combined with a decrease on both the medial longitudinal arch height and the forefoot abduction. In the present study, we observed that the leg /heel angle in the pronation group of the feet was 14.5^{o}, which is about 10^{o} greater than that of able-bodied feet representing a valgus heel (p =0.000). The Djian-Annonier angle in pronated feet was increased about 7° (p=0.001) representing a lower medial arch height than the able-bodied feet. We also observed a 22° decrease of the lateral base angle of the pronated feet compared with the able-bodied feet (p=0.000). This represents more adduction in the pronated feet compared to the able-bodied feet. These findings are in agreement with the decrease of the 2nd and 5th MTP/flex angle of this pathological foot type by about 9° (p=0.000) that also shows forefoot adduction. There was a 15° decrease on the Meschan angle which was statistically significant (p=0.000) showing an abnormal foot shape in the metatarsal region.

Pes cavus foot is characterized by a raised medial longitudinal arch. The results showed that the Djian-Annonier angle in this type of foot pathology was slightly (5°) smaller than in the able-bodied foot, which was not statistically significant.

It is explained in the literature that claw toes and forefoot equinus in relation to the hindfoot are also other characteristics of the pes cavus foot. The amount of claw toes was not measured but will be included in future studies. Forefoot equines can be visualized by the increased 1st MTP/Med angle. Our data did not show any significant increase in this angle among pes cavus feet. The inverted forefoot and heel may also be present in subjects with pes cavus foot deformity. Results showed that the lateral base angle in pes cavus feet was decreased by about 18^{o} in comparison to that of able-bodied feet (p=0.000). This represents a significant inverted forefoot in patients with pes cavus feet. This was supported by a reduction of about 9^{o} of the 2nd and 5th MTP/flex angle (p = 0.000). However, our data did not show a significant inverted heel in this type of foot pathology. Instead there was a decreased value of Meschan angle in this group representing metatarsal abnormality.

The lack of statistical differences between the pes cavus group and able-bodied feet support our hypothesis that foot disorders need to be quantified by several geometric parameters grouped together rather than taken individually. Furthermore, foot pathology can be present even if morphologic changes are subtle, and because of this, various pathologies having similar symptoms may be confused.

Supination is characterized by inversion of the calcaneus, adduction and plantar flexion in relation to the talus together with a forefoot varus or adduction. The results indicate that in the supination group, the leg/heel angle was -3.9^{o} which deviated from the related angle in the able-bodied group by about 8^{o} (p=0.000). The negative direction indicates the inverted position of the heel.

Supinated feet also showed an 8^{o} reduction on Djian-Annonier angle with respect to that of able-bodied feet (p=0.000). It has been shown that supinated feet are associated with the knee extension and the external rotation of the leg. In patients with supinated feet, there were significant reductions on their lateral base angle, 2nd and 5th MTP/flex angle and Meschan angle by 13.5° (p=0.014), 12.2° (p=0.000) and 14.3° (p=0.000) respectively.

4.3 Foot type classification

This section deals with the use of PCA, SDA and Fuzzy logic techniques for the classification of able-bodied and pathological foot conditions. This is followed by comparison of these three methods for successful classification.

The PCA method was carried out on the complete data set of 15 foot parameters including 321 feet to reduce the number of angles and classify the five different foot types. In this study, five PCs were extracted from application of PCA to the data. Kaiser's criteria (Kaiser, 1960) were adopted to decide appropriate number of PCs to be retained. Consequently, principal component analysis yielded five principal components (PCs) explaining 63.5% of the total variance in the data as presented in Table 4.3. These five PCs were retained because the eigenvalues of them were greater than one (Sharma, 1996). The first PC represented only 21% of the variance while the first two PCs accounted for 36.1% of the total variance. As outlined in the methods section, loading values of ±0.7 and higher correlation identified the main angles. Out of the 15 angles, the PCA identified 9 angles.

Table 4.3. Correlation coefficients in the loading values for the first five principal components (PCs) of the 15 measured angles. Views and angles abbreviations are given in Table 3.1.

View	Angles	PC1(21.0%)	PC2(15.1%)	PC3(12.4%)	PC4 (8.3%)	PC5 (6.7%)
AP	Medial base	0.009	-0.365	0.764	-0.085	0.100
	1st and 2ndMTP	0.087	-0.339	-0.532	-0.413	-0.181
	2nd and 5thMTP	-0.115	-0.852	0.042	-0.138	-0.038
	Meschan	0.59	0.818	0.272	0.301	0.126
PA	Malleolus	0.162	0.191	0.045	0.489	0.002
	Lateral base	0.141	0.016	0.609	0.232	-0.112
	Bisect/leg	0.029	-0.181	-0.019	0.761	-0.158
	Bisect/heel	0.058	-0.012	-0.082	-0.112	0.916
	Leg/heel	-0.722	0.025	-0.233	-0.144	-0.059
MED	Meary-Tomeno	0.451	0.555	-0.052	-0.329	-0.137
	1st MTP/Med	0.734	0.113	-0.066	-0.169	0.103
	Calca-inclination	0.836	0.015	0.065	0.219	0.055
	Djian-Annonier	-0.814	0.032	-0.021	-0.106	0.124
PF	Heel/flex.	0.073	0.244	0.623	-0.179	-0.140
	2nd and 5thMTP/flex.	-0.181	0.636	-0.042	-0.240	-0.104

Four out of the nine angles were found in the first PC. Three out of the four were in the medial view and included the calca-inclination, Djian-Annonier and 1st MTP/Med angles. The last angle was related to the postero-anterior view and was the leg/heel angle. The angles observed in the medial view are used to describe the arch height while the last angle found in the PA view was associated with the hindfoot angle.

In the second PC, the 2nd and 5th MTP and Meschan angles were found in the antero-posterior view. The medial base angle in the PC3 was found in the antero-posterior view. These angles were associated with the forefoot to describe abnormal metatarsal bone alignment.

In the fourth and fifth PCs, two angles were observed in the postero-anterior view. These were bisect/leg and bisect/heel angles, which are used to describe hindfoot position as normal, pronated or supinated.

Figure 4.5 displays the clusters of all five foot groups using the first two PCs. The following general observations can be made from visual inspection. For better visualization, the reader is referred to Figure 4.6 where the location of each foot type shown separately. Two separate clusters can be observed. The pes planus and pronation groups are located on the right-hand side of the figure while the others (pes cavus, supination and able-bodied groups) are on the left-hand side of the graph. The top part of the right-hand side is formed in the main by the pronation group while the bottom part constitutes the pes planus feet. The supination group is located in the main in the top part of the left-hand side while the able-bodied group is located in the bottom part of this side. The bulk of the pes cavus group is found between the supination and able-bodied groups. As shown in Figure 4.5, the majority of the cases within the pes cavus group are distributed in the left part of the plot between -1 to 1 of the vertical axis. Fig 4.5 shows a clear cluster in which the groups are almost separated. In general the PCA method presented a good aspect for classification of pathological feet, but not a clear identification for the PC group from the able-bodied and supination groups of feet.

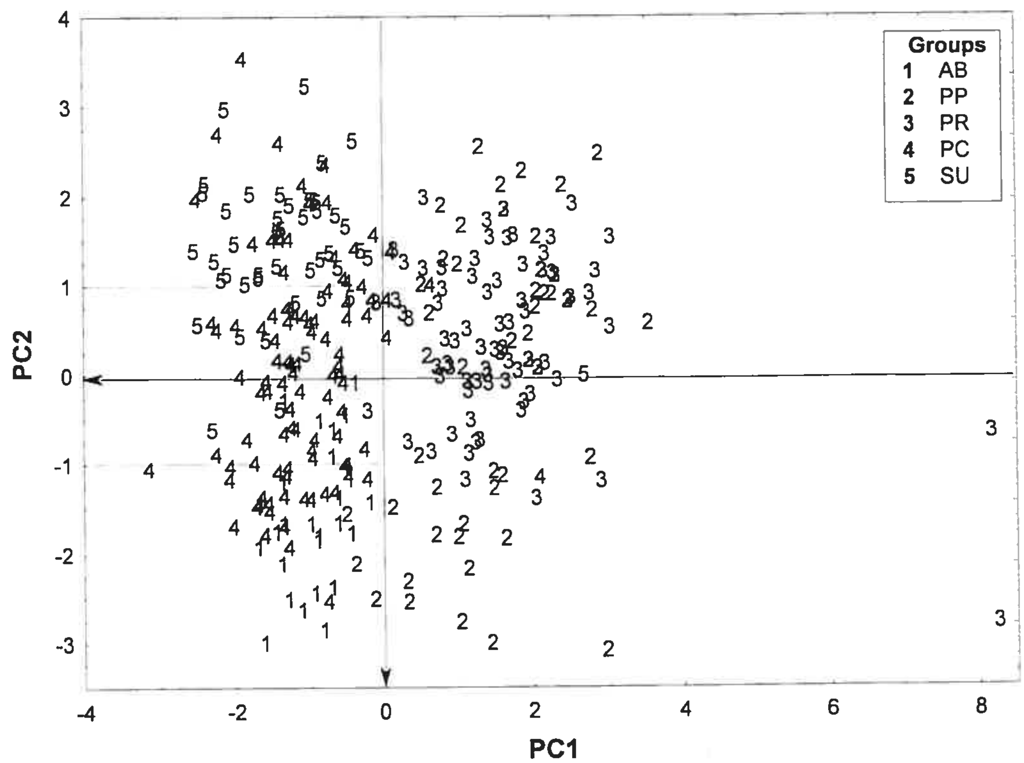


Figure 4.5 . Plot of the first and second principal component scores for all five foot types using a PCA. Abbreviations: AB, (able-bodied); PP, (pes planus); PR, (pronation); PC, (pes cavus) and SU, (supination).

Based on score plot areas explained above for Figure 4.5, the numbers of cases located in their own parts were counted. Dividing the explained number by the total number of feet in each group and then multiplying this value by 100, the success rate in the classification of foot types was calculated using the PCA method. On average 62.7% of all the feet were classified correctly. The best results (80.0%) were obtained for the able-bodied group and the worst (38.8%) for pes planus group. For the others the success rate was 73.9% for supination, 64.9% for pronation and 56.1% for the pes cavus group. However, pes planus feet were more likely to be classified as pronation in 26 of 46 feet. This was due to the majority of the cases in PP group having pronation in their heel and vice versa. Out of 98 pes cavus feet, 23 feet were classified as able-bodied and 15 feet as supinated. The misclassification of PC in the supination group could be related to the presence of the supinated heel in the majority of the cases in the pes cavus group and vice versa. The misclassification of the PC with AB group might be related to the small value (less than 5°) of Djian-Annonier angle with a relatively large standard deviation in the PC group.

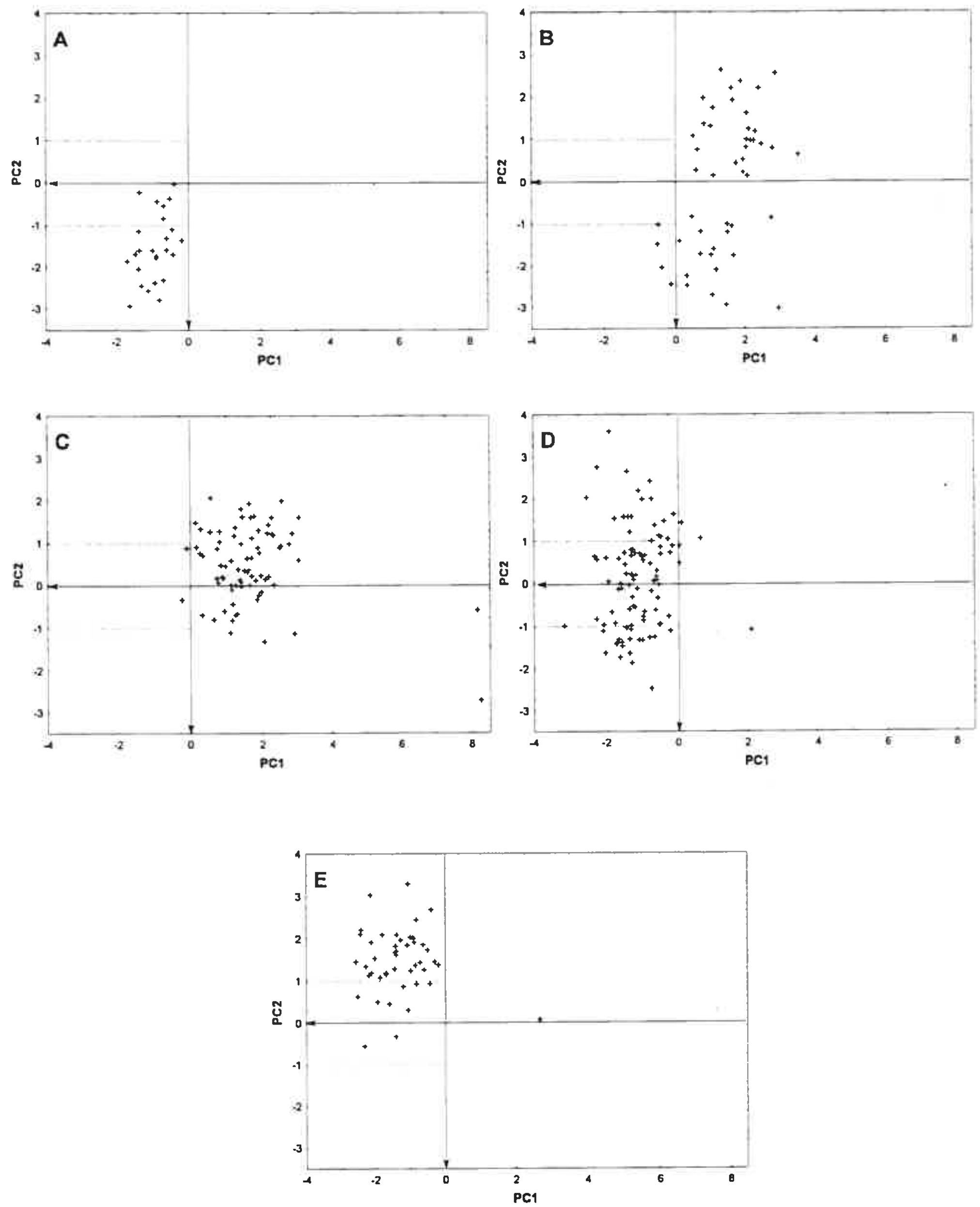


Figure 4.6. Plot of the first against second principal component scores for individual groups are presented for: A) able-bodied; B) pes planus; C) pronation; D) pes cavus and E) supination using PCA for classification.

The second model is based on a stepwise discriminant analysis (SDA). It revealed four significant functions ($p<0.01$) that are presented in Table 4.4. Based on Wilks' lambda and eigenvalues, the two first discriminant functions accounted for 91.9% of the variance. The structure matrix which is a table of pooled within groups correlations between the discriminating angles and the functions are given in Table 4.4. The table shows that the SDA model identified 10 angles out of the 15. The model used these 10 angles in the analysis to classify feet into their appropriate groups. The criteria for selecting an angle is based on the F test values as described in the Methods section. The first function was based on angles in the postero-anterior (leg/heel) and medial (calca-inclination) views respectively. The first angle is a measure to describe the hindfoot position and the second angle is a clinical measure of medial longitudinal arch height (Saltzman et al., 1995). The second function was based on two angles from the antero-posterior view. These are the Meschan and 2^{nd} and 5^{th}MTP angles. In the plantar flexion view, the 2^{nd} and 5^{th} MTP/flex angle; in the medial view, the Meary-Tomeno and in the postero-anterior view, the lateral base angle was identified. The third function was based on two angles; in the antero-posterior view the 1^{st} and 2^{nd}MTP angle and in the postero-anterior view the malleolus angle, while the last function was based on the Djian-Annonier angle, obtained from the medial view.

Table 4.4. Structure matrix of four discriminant functions. Views and angles abbreviations are given in Table 3.1.

View	Angles	Function			
		1 (68.1%)	2(23.8%)	3 (6.5%)	4 (1.6%)
AP	Medial base (a)	-0.06	-0.04	0.08	0.22*
	1st and 2nd MTP	0.15	-0.22	-0.63*	-0.33
	2nd and 5th MTP	0.14	-0.56*	0.08	0.51
	Meschan	-0.21	0.59*	0.36	-0.09
PA	Malleolus	-0.10	-0.02	0.32*	-0.21
	Lateral base	-0.11	0.26*	-0.23	0.03
	Bisect/leg (a)	-0.06	-0.13*	0.08	-0.00
	Bisect/heel (a)	-0.12*	0.06	-0.03	0.03
	Leg/heel	0.72*	0.11	0.47	-0.37
MED	Meary-Tomeno	-0.18	0.43*	0.08	-0.13
	1st MTP/Med (a)	-0.32*	-0.03	0.03	-0.10
	Calca-inclination	-0.46*	-0.10	0.09	-0.08
	Djian-Annonier	0.48	0.14	-0.01	0.61*
PF	Heel/flex (a)	-0.09*	0.05	0.08	0.08
	2nd and 5th MTP/flex.	0.07	0.51*	-0.07	0.27

* Largest absolute correlation between each angle and any discriminant function. [(a)] This angle has not used in the analysis.

Figure 4.7 illustrates all five foot types plotted using the first two functions of the SDA. For better visualization, Figure 4.8 reproduces the location of each foot type group separately. There was a strong cluster for able-bodied feet located on the top left-hand side of the scores area. There was also a good cluster for the supination group located on the bottom left-hand side and for the pronation group on the right-hand side. Pes planus feet overlapped with the pronation group and in many cases pes cavus feet were mixed with the supination group.

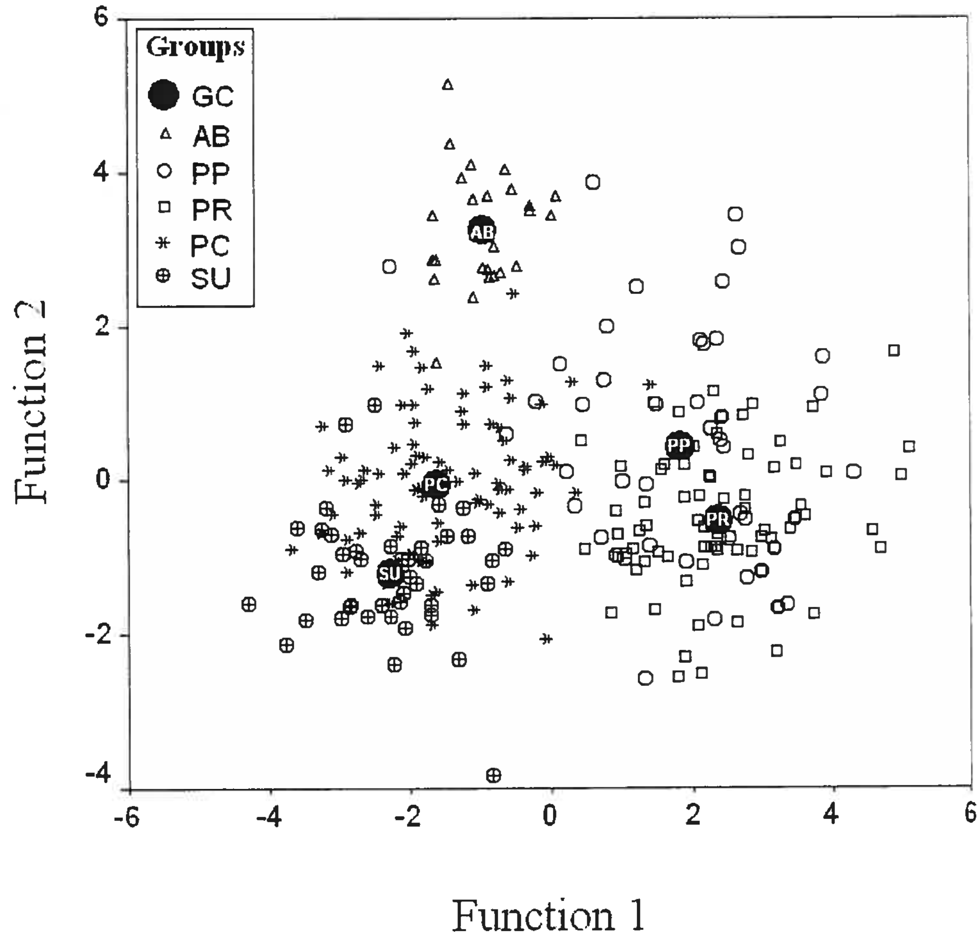


Figure 4.7. Plot of first and second functions of the discriminant analysis method for all five groups. Abbreviations for groups were described in Figure 4.5. New abbreviation: GC, for group centroid with identity of each group.

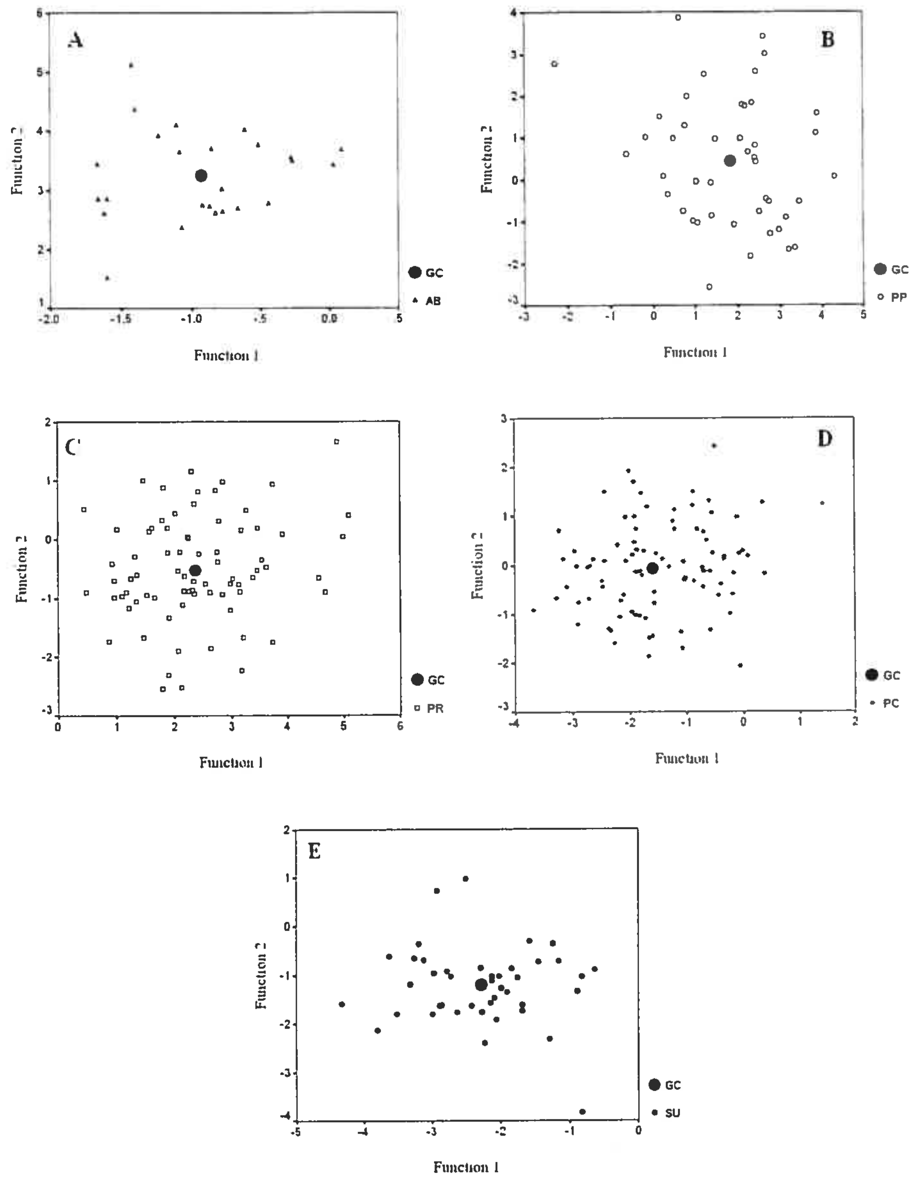


Figure 4.8. Plot of the first against second functions scores for individual five groups are presented for : A) able-bodied; B) pes planus; C) pronation; D) pes cavus and E) supination using SDA for classification. Abbreviations: GC, for group centroids, which are identified for each group separately.

Stepwise discriminant analysis classified all feet into five groups with an overall success rate of 78.7%. More specifically, the success rate was 96.0% for the able-bodied group; 84.8% for supination; 81.3% for pronation and 78.9% for pes cavus. The pes planus was the worst classified group by this model with 52.3% of success. Using this model, 17 of the 44 pes planus feet were incorrectly classified as pronation. But the model classified PP feet within their respective group with a higher mean success (13.5%) than the PCA model. In general, SDA represented a higher success of classification (16%) for all groups than PCA.

The overall correct classification using the Fuzzy logic technique was 88.8%. The successful identification of supination, pes cavus and pes planus were similarly about 95.8%, 94.8%, and 94.2%. The success rate for the pronation foot (90.0%) was about 4% smaller than that of supination, pes cavus and pes planus. A much lower success rate was found for able-bodied feet (69.2%). Five of the 26 able-bodied feet were incorrectly classified as pes cavus feet.

In summary, Figure 4.9 expresses the ability of the three modeling techniques to identify the five different foot types. The highest mean of the successful identification (88.8%) was found in the Fuzzy model, and the lowest mean (62.7%) for PCA model. SDA showed the largest success rate (96.0%) of classification for the able-bodied group while the worst technique for this group was Fuzzy logic with a success rate of 69.2%. Fuzzy logic was the best method for classification of all the pathological groups of feet with a mean success rate of 93.5%. This was followed by the SDA and the PCA methods with success rates of 74.3% and 58.4% respectively.

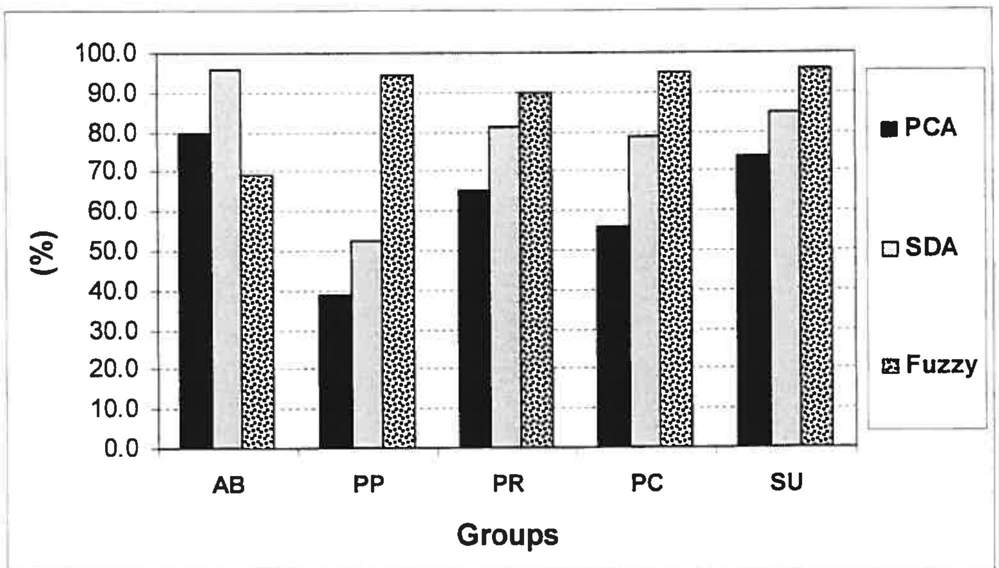


Figure 4.9. Classification of foot types using PCA, SDA and Fuzzy logic techniques. Abbreviations of groups were described in Figure 4.5.

The Kappa test was used to determine the accuracy of the three models for the classification of 321 feet into five groups. Excellent results was obtained with the Fuzzy logic technique having a Kappa value of 0.89; while the classification ability of the SDA and the PCA methods were judged as good and fair respectively with Kappa values of 0.71 and 0.49 respectively.

Chi-square was performed in order to examine the success rate of the three models in the classification of the pathological feet. A Chi-square value of 9.49 is needed at the 95% confidence level to obtain a statistical difference. Only the Fuzzy logic classification model was non-significant between the observed and expected values (Table 4.5).

Table 4.5. Chi-square values for classification of foot types using PCA, SDA and Fuzzy logic models. Abbreviations of groups were described in Figure 4.5. New abbreviations: Significant (sig), Non-significant (NS).

Technique	Observed					Expected					Chi-square value	Result	p value
	Groups					Groups							
	AB	PP	PR	PC	SU	AB	PP	PR	PC	SU			
PCA	25	49	77	98	46	20	19	50	55	34	101.1	Sig	0.000
SDA	25	44	75	90	46	24	23	61	71	39	28.75	Sig	0.000
Fuzzy logic	26	52	80	115	48	18	49	72	109	46	4.94	NS	0.283

The largest differences (8) between the observed and expected frequencies for the able-bodied group were found with the Fuzzy logic technique. Both SDA and PCA had small differences of 1 and 5 respectively between observed and expected frequencies for the able-bodied feet. For pathological foot classification, Fuzzy logic showed the lowest differences (3, 8, 6 and 2 for PP, PR, PC and SU respectively) between observed and expected frequencies. The SDA method showed smaller (21, 14, 19, and 7 for PP, PR, PC and SU respectively) differences as compared with PCA, which showed 30, 17, 43 and 12 differences respectively.

4.4 Foot type prediction

This section represents the results of the PCA, SDA and Fuzzy logic models to predict foot types from 94 new feet. This is the first time that a prediction model was tested with new data from both able-bodied and pathological feet. This is followed by a comparison of the success rate of these three methods to predict all five foot types.

Figure 4.10 shows the score plot obtained from the PCA model while Figure 4.11 displays individually the able-bodied feet and four pathological groups. Pes planus and pronation groups were located on the right-hand side of the plot while the three other groups were on the left-hand side. Some pes planus and pronation feet were mixed together as with pes cavus and supination feet.

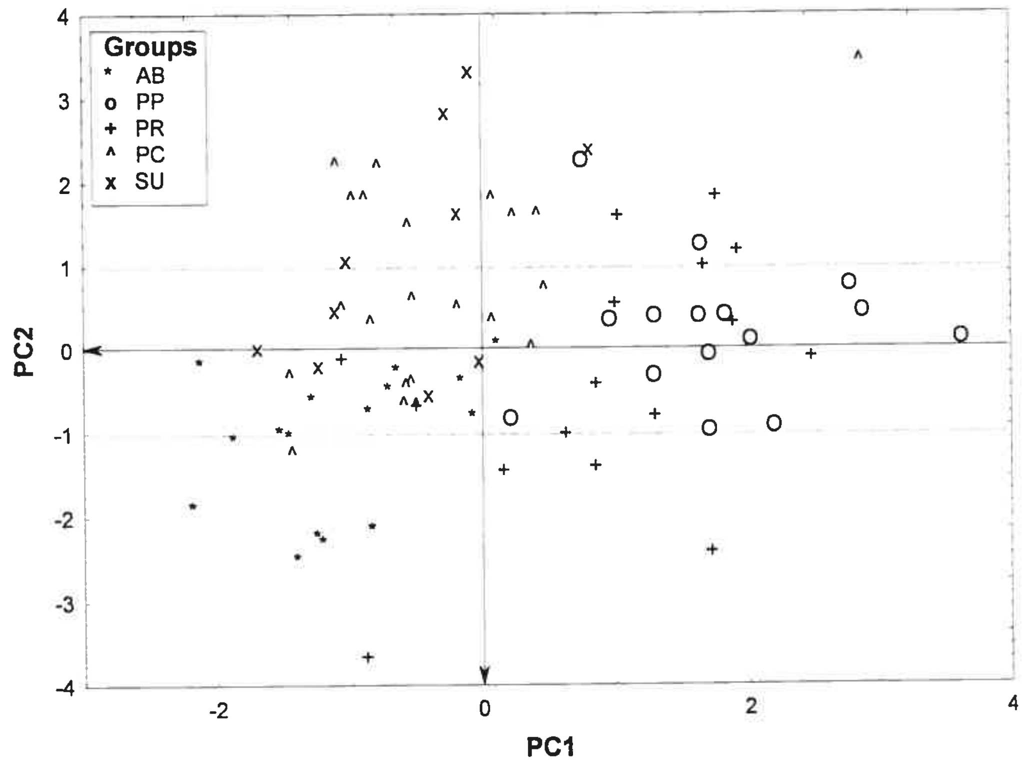


Figure 4.10. Plot of the first and the second principal component scores for foot types prediction with PCA. Abbreviations for the groups were described in Figure 4.5.

Distribution of the feet into five groups was similar to the classification results with the PCA method but with a much reduced classification success. On average, 39.1% of the feet were correctly predicted. The PCA model predicted correctly 43.8% of the able-bodied feet, 40.9% of the pes cavus and 40% of the supinated feet. Slightly lower values were obtained for pronation (37.5%) and pes planus (33.3%). Eight of the 16 able-bodied feet were misclassified into the pes cavus group. Ten of the 15 pes planus feet were misclassified as pronation. Similarly, 7 of the 16 feet in pronation were predicted to be in the pes planus group. Incorrectly predicted pes planus feet were mostly located in the pronation and supination (6 and 5 of 22 feet respectively) groups. Finally, five of the ten supination feet were incorrectly predicted as pes cavus feet.

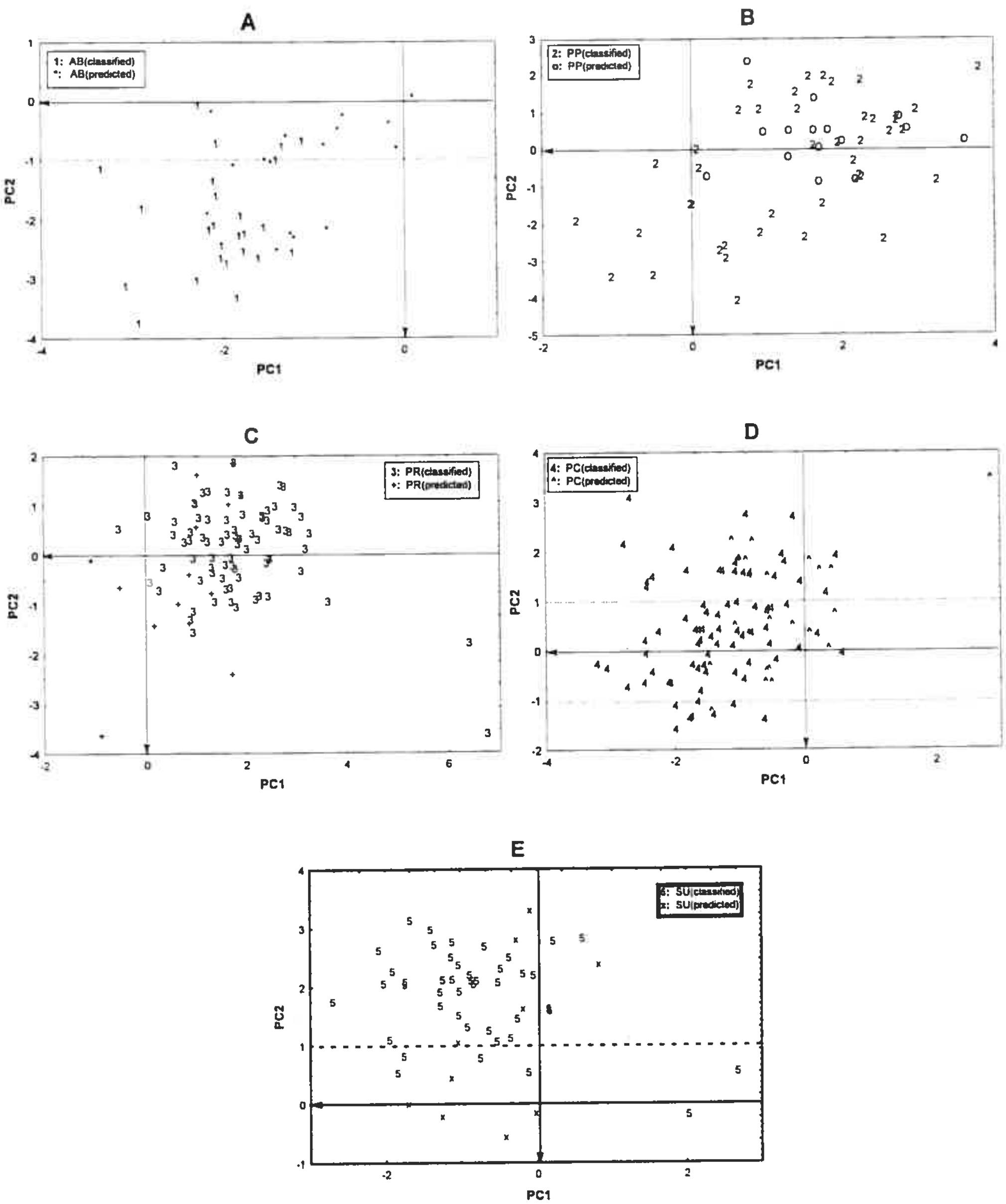


Figure 4.11. Individually plotted first and second principal component scores for prediction of A) able-bodied, B) pes planus, C) pronation, D) pes cavus and E) supination groups.

Using discriminant analysis modeling, 53.8% of the feet were correctly predicted. This predicted value is about 24.9% lower compared with the classification results and is now similar to that of the PCA. The highest prediction was for the pes cavus group at 82.1%.This success rate was dropped by 12% at 68.2% for the pronated feet. The prediction success rate was reduced to 50% for the supinated feet and 43.8% for the pes planus feet. The able-bodied feet were predicted with the poorest success rate at 25%. Ten of the 16 able-bodied feet were incorrectly predicted as pes cavus feet. Nine of the 16 pes planus feet were incorrectly located in the pronation group. Out of 22 pronation feet, four feet (18%) were predicted as pes cavus and three feet (14%) as pes planus feet. Three of the 28 pes cavus feet were mispredicted as supination. Finally, for supination 6 feet out of the 16 were incorrectly predicted as pes cavus.

The Fuzzy logic model had the highest average success rate at 78.3%. This value was reduced by about only 10.5% in comparison with the success rate of the Fuzzy logic model when used for classification purposes. The best result was obtained for the pronation group with a success rate of 86.4%, and then the pes cavus and able-bodied groups were predicted with the success rate of (82.1%) and 81.3% respectively. It was slightly lower for the pes planus group at 75% and very low for the supination group (66.7%). This model mispredicted three feet in the supination group as pes cavus feet. Two of the16 able-bodied feet were incorrectly predicted in the pronation group. Three of the 16 pes planus feet were located incorrectly in the pronation group while three out of the 22 pronation feet were classified as pes planus feet. Two of the 28 pes cavus feet were incorrectly predicted in the AB and PP groups. Finally, three of the 12 feet in the supination group were incorrectly predicted as being in the pes cavus group.

In summary, Figure 4.12 compares the ability of the three different techniques to classify feet with respect to their pathologies. The highest mean of correct classification was found for the Fuzzy model (78.3%) while PCA exhibited the lowest mean (39.1%). Fuzzy logic showed the largest success rate of prediction (81.3%) for the able-bodied group while the worst technique was the SDA with a 25% success rate. For pathological feet, Fuzzy logic was the best method for prediction with a 75.5% mean success rate for all four pathologies. The Fuzzy logic had highest success rates for all four pathologies separately except for the pes cavus group that was similar to the SDA method (82.1%).

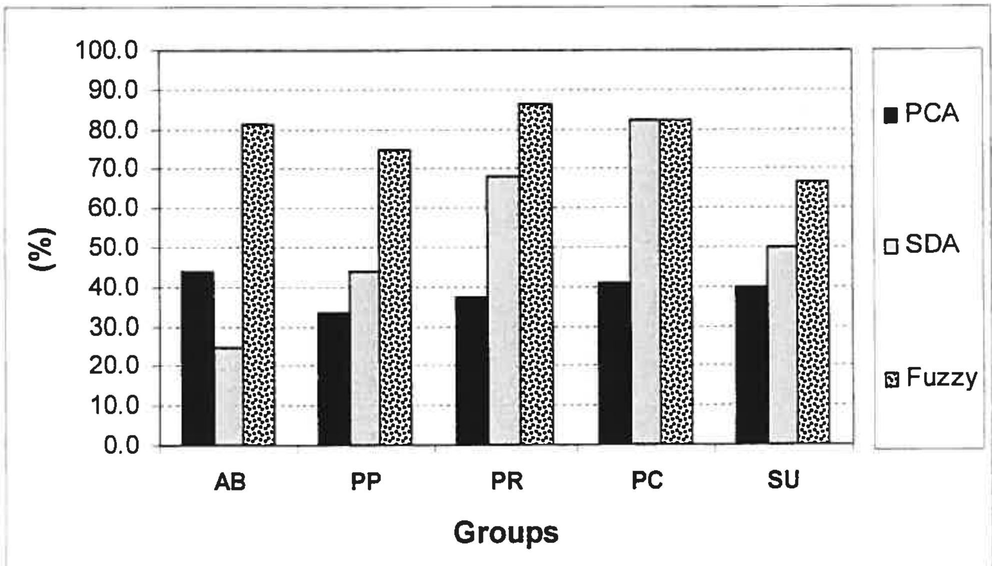


Figure 4.12. Percentage of accurate prediction of foot types with PCA, SDA and Fuzzy logic techniques. Abbreviations of groups were described in Figure 4.5.

The Kappa test was applied for testing the accuracy of all three methods for prediction of the new feet into five groups. A good result was obtained for the Fuzzy logic technique with a Kappa value of 0.74 while a fair result was obtained for SDA with a Kappa value of 0.45 and a poor result obtained for PCA with a Kappa value of 0.23.

A Chi-square test was performed to determine the prediction performance of each model. A critical value of 9.49 was needed at the 95% level of confidence to have a statistical difference. Only the Fuzzy logic method had a non-significant difference between the observed and expected cases (Table 4.6). In general, for the prediction of the able-bodied group, the lowest difference between observed and expected frequencies was for Fuzzy logic. It dropped by 9 for PCA and 12 for SDA between observed and expected frequencies for the prediction of able-bodied feet. For pathologies, the highest differences (10, 10, 13 and 6 for PP, PR, PC and SU respectively) between observed and expected frequencies for pathologies were found for PCA. These dropped by 9, 7, 5 and 6 respectively for SDA and were respectively 4, 3, 5 and 5 for the Fuzzy logic technique. Therefore, the most successful method of prediction was Fuzzy logic, followed by SDA and PCA.

Table 4.6. Chi-square values for prediction of foot types using PCA, SDA and Fuzzy logic models. Abbreviations were described in Table 4.5.

Technique	Observed					Expected					Chi-square value	Result	p value
	Groups					Groups							
	AB	PP	PR	PC	SU	AB	PP	PR	PC	SU			
PCA	16	15	16	22	10	7	5	6	9	4	76.1	Sig.	0.000
SDA	16	16	22	28	12	4	7	15	23	6	57.8	Sig.	0.000
Fuzzy logic	16	16	22	28	12	13	12	19	23	8	5.6	NS	0.232

Chapter 5

5. DISCUSSION

This chapter deals first with the reliability of a color-coded video-based system as a technique for assessing foot deformities. The intratester reliability is assessed to establish the minimum number of repetitions required for foot assessment and intertester reliability. Short and long-term reliabilities will also be discussed in relation to other clinical methods. This will be followed by a description of able-bodied feet and four foot deformities. Then the accuracy in distinguishing five different types of feet from three classification models will be presented followed by the ability of these models to predict foot types. Finally, the limitations of this study are discussed and suggestions for further studies are offered.

5.1 Reliability of a color-coded video-based system for foot assessment

Using a color-coded video-based system, the subject's morphology was immediately recognizable providing a better insight for qualitative clinical evaluation of foot problems. However, as a part of clinical evaluation, the number of trials required is a primary concern, particularly when a diagnosis is made or a treatment is planned. Consistency of the measurements at different times and with several evaluators is important in order to apply this system in a clinical setting.

The first objective of this study was to determine intratester reliability for establishing the minimum number of trials required to achieve a clinically acceptable reliability of 15 foot parameters from six images taken from four different anatomical views. Intra-class correlation coefficient values were used to determine whether measurement errors or natural physiological differences between individuals caused variations. A clinically reliable value is the minimum number of trial with an ICC of 0.8 and above. The mean ICC values of all 15 angles were well over 0.83 and ranged from 0.83 to 0.92. Sell et al., (1994) reported that ICC values over 0.8 could be considered good to high. The mean ICCs did not vary with additional trials and there were no significant differences between trial sets. Our findings were better than those of Jonson and Gross (1997) who reported ICC values ranging from 0.65 to 0.97 on nine lower extremity skeletal measures such as hindfoot angle, arch height and ankle dorsiflexion using a goniometer. Åström and Arvidson (1995) also reported intratester reliability of joint motion and foot alignment using a goniometer with a mean ICC value of 0.91 (0.66-0.98). Our findings were more consistent than their findings. These superior results were obtained because of the different techniques we applied.

All 15 foot angle measurements had high intra- and intertester reliability (ICCs= 0.89 and 0.91 respectively). Intratester (ICC=0.94) and intertester reliability (ICC=0.93) were high for the leg/heel angle in both feet. This angle represents the hindfoot or subtalar joint position, which is clinically used to assess foot and ankle position because of the high incidence of lower extremity dysfunction (Knutzen and Price, 1994). In the literature, subtalar joint position is usually shown with a goniometer (Picciano et al., 1993; Elveru et al., 1988b) or inclinometer (Sell et al., 1994). According to the above studies, the hindfoot angle reliability ranges from 0.68 to 0.91 using the goniometry technique while our study showed higher values (ICCs= 0.94 and 0.93) for intra- and intertester reliabilities. Our values were also higher than those of Jonson and Gross (1997) for the hindfoot angle (ICCs= 0.88 and 0.68) who used a goniometer for measuring this angle. Our intra and intertester reliability findings were higher than those of Åström and Arvidson (1995) reported for hindfoot (ICC=0.89) and Bicect/leg (ICC=0.66) angles. Consequently, the system used in this study can be more useful than the goniometer or inclinometer method and can be an alternative technique to goniometry for measuring hindfoot position with high reliability.

Calca-inclination intratester (ICC=0.88) and intertester (ICC=0.86) reliabilities were good. Bryant et al. (2000) reported intratester reliability (ICC= 0.87) for the same angle from radiographic measurement. They also reported intratester reliability (ICC=0.87) for 1st MTP/Med to describe first metatarsal declination angle on radiographic film. Our finding for the same angle represents higher intratester reliability with an ICC value of 0.91. These two angles are used to describe the medial longitudinal arch. Our study presents intratester (0.92) and intertester (0.93) ICCs for describing the medial arch structure using the Djian-Annonier angle. We did not find any studies for the Djian-Annonier angle to compare with the results of the present study. However, our findings indicate that the color-coded video-based system could be considered as an appropriate non-invasive technique for measuring medial foot parameters.

Intratester (0.74) and intertester (0.79) ICCs were fair for the Meschan angle in the antero-posterior view. Bryant et al. (2000) reported high intratester reliability (ICC=0.92) for this angle measured from dorsoplantar radiographs. Our finding for the Meschan angle is satisfactory in comparison with the radiography technique which has the lowest ICC value of this study. The value could be increased by changing the view from which the foot is captured to dorsoplantar in coordination with the radiographic technique.

For determining the short and long-term reliability of the evaluation system, the baseline data (in the morning acquisition) were compared with those collected in the afternoon of the same day (short-term) and one week after the baseline (long-term). The mean ICC values were above 0.80 for both the short-term and the long-term intervals. Benvenuti et al., (1999) collected posturographic measurements using a video-based kinematic data acquisition system to test the reliability of the measurements while quiet standing. They reported the mean ICC values of 0.76 and 0.67 for short- and long-term reliability respectively. Li et al., (2004) tested the short-term and long-term reliability in sonographic measurements of maximum and mean of the splenic lengths. They found ICC values of 0.87 and 0.94 for the short-term reliability of the maximum and the mean splenic lengths respectively. The ICC values were 0.61 and 0.76 for the long-term reliability of maximum and mean splenic lengths. In addition, findings of this thesis for the short-term and the long-term reliability of the foot measurements were better than above studies. Our results confirm that the system provides accurate assessment of the foot parameters if used in different periods of the time.

In summary, our results support the hypothesis that a single set of measurements is sufficient for foot assessment using the color-coded video-based system. Therefore this study presents a non-invasive technique that can provide quick and reliable assessment of foot disorders. It also demonstrates that having the subject stand freely and not constrained to a standard position by means of a floor fixture did not introduce excessive variability. Furthermore, the reliability is high when measurements are taken at different time periods and when different evaluators assess the same subject.

5.2 Foot angles

The second objective of this study was to compare four pathological foot types with able-bodied feet. Nine out of 15 angles were needed to characterize all four pathological foot types. In MED, PA and AP views, six of these angles have been classically measured with radiography or goniometry techniques by clinicians to describe the foot pathologies. It is interesting to note that more than one or two angles, also from different views, can be used to characterize some foot disorders.

Pes planus is described by a flattening of the arch on the medial side of the foot as measured by the Djian-Annonier angle (Djian et al., 1968). Normal arch height ranged between 120°-128°. A value higher than 128° is typical of pes planus. Jarde et al. (2002) reported an average value of 134° for the Djian-Annonier angle in adults. This is in agreement with our findings (134.1°). Since we used several angles rather than a single one, we found a valgus heel in pes planus as noted well by Jarde et al. (2002) and Burns (1996).

We did not find any report on the relationships between the forefoot and the hindfoot angles in the weight-bearing condition to compare with our results. We presented a novel morphological angle (2nd and 5th MTP/flex angle) to quantify the functional interaction between forefoot and hindfoot and highlight any compensations or rigidity. A 6.3° everted forefoot in the frontal plane for the pes planus group was observed when the foot was in the weight-bearing condition (foot flexion view). Forefoot eversion and inversion are defined in the frontal plane while the foot is in non weigh-bearing position. In the weight-bearing position we defined that a smaller 2nd and 5th MTP/flex angle in reference to the horizontal axis refers to an inverted forefoot. The bigger angle refers to an everted forefoot angle. According to this definition, an everted forefoot for planus feet was observed in comparison with cavus feet. This everted forefoot could be associated with internal rotation of the tibia and/or everted metatarsal heads alignment (Tiberio, 1988) because of the structure of the medial side of the foot.

Pronation feet were characterized by subtalar joint valgus (Aquino and Payne, 2001). Our results show that a pronated foot is usually combined with a decrease of 7^{o} in arch height (Root, 1971; Greisberg et al., 2003). Forefoot valgus or everted metatarsal heads alignment was observed in comparison with supination feet while the foot is loaded in the plantar flexion view. According to Root et al. (1977), forefoot varus is the most common frontal plane deformity in abnormal pronation. They note that this deformity is compensated at the subtalar joint by heel valgus in the weight-bearing position. There was no published data on forefoot position in the frontal plane relative to the hindfoot other than those reported here. We found a greater (3.3^{o}) 2nd and 5th MTP/flex angle in the pronation group in comparison with supination feet. This greater angle could be related to internal rotation of the leg and existing flattened foot in the majority of feet in the pronation group.

Pes cavus is characterized by a high arch. Jarde et al. (2001) using the Djian-Annonier angle reported a value of 108° on the average. Though our finding for Djian-Annonier was greater (119°) than what Jarde and coworkers reported (108°), it was lower than the normal arch angle at about 124°. In the frontal plane, pes cavus is associated with the heel varus. A study by Ledoux et al. (2003) showed that patients with pes cavus have an inverted calcaneus. They did not present quantitative information for this, but our results showed an inverted heel one degree smaller in pes cavus than those in able-bodied feet. There was an inverted forefoot in frontal plane among cavus feet in comparison with pes planus. This could be associated with external rotation of the leg and about 8.4° greater inverted heel than in planus feet.

Supination is characterized by hypermobility of the calcaneus and an inverted heel (Donatelli, 1987; Hunter, 1995). In this study there was a high arch height defined by a Djian-Annonier angle of 116.4° combined with 3.9° of heel inversion. The hindfoot was associated with changes in the ankle and the subtalar joint. Inversion of the heel with a large calcaneus inclination of 6.1° was responsible for an increased arch height of 7.8°. Supination is usually characterized by a forefoot adduction of 3.5° in comparison with our able-bodied group. Supination feet had an inverted forefoot in the plantar flexion view in comparison with the pronation group. This smaller (3.3°) 2nd and 5th MTP/flex angle is related to heel varus and external rotation of the leg.

In general, foot types are usually described by a single angle in the literature. A novel approach was developed in this study to quantify foot types based on means of several angles taken in different planes. Some foot pathologies can be described by similar foot angles such as pes cavus and supination or pes planus and pronation. Our findings reported significant changes in some novel foot parameters particularly for the description of the compensatory relations between the hindfoot and the forefoot while the foot is loaded. It was interesting to note that all pathologies had smaller 2nd and 5th MTP/flex angles in comparison with the able-bodied group.

5.3 Foot types classification methods

The third goal of this study is related to the classification of five groups of feet using more than a single geometric foot parameter. The principal component analysis method, the stepwise discriminant analysis technique and the Fuzzy logic methods were tested to classify the five foot types using 321 feet.

Principal component analysis was performed as the first attempt in this study to identify and classify foot types. PCA identified nine angles to classify foot types. These angles included all the important clinical parameters. They were related to all three parts of the foot rather than a particular section such as the midfoot. Based on the above nine angles, the PCA model presented an acceptable classification for the able-bodied group and two of the pathological groups, pronation and supination. This was expected because pronation and supination are foot deformities that are at each other's opposite, namely, low and high arches respectively. The PCA method could not adequately classify the pes cavus and pes planus feet since the majority of pes planus feet had some pronation. The same reasoning can be applied to the poor classification of the pes cavus and supination feet.

Our application of the PCA method is novel since few if any studies make use of several foot parameters to describe foot pathologies. Our results presented the PCA as a powerful tool for variable reduction (Perez and Nussbaum, 2003; Du and Sun, 2004). These findings also confirmed that using several parameters from different views would better identify foot types. Nonetheless, the PCA method was unable to classify foot disorders with a high success rate due mainly to similarities between some pathologies such as pes cavus and supination or pes planus and pronation.

The second attempt at foot type classification was the application of the stepwise discriminant analysis model. This technique identified 10 out of 15 angles as the best variables for the differentiation of five different foot types.

These angles were similar to those found with the PCA model with the 9 angles. SDA presented an acceptable classification for the able-bodied group and three pathological foot types including pronation, supination and pes cavus. The classification was in agreement with the PCA method except for the pes cavus. SDA achieved a better overall accuracy than PCA by 78.7%, but still there is a problem in dissociating PP from PR groups of feet. This is reasonable since these two foot pathologies both have a low arch. To our knowledge, only Song et al. (1996) used this method to classify foot types based on the center of pressure excursion index and malleolar valgus index. They reported 100% and 90.9% correct classification for pes planus and able-bodied groups respectively. They compared only 11 able-bodied feet with 10 pes planus pathological feet. The SDA method was unable to classify pes planus feet with a high success rate due mainly to a similar low arch in both pes planus and pronation groups.

The third and final technique that was applied as first attempt at classification by this study was the Fuzzy logic method. The present study is the first that applies Fuzzy logic for foot classification. This method presented a better classification with higher accuracy than PCA and SDA by 88.8%. This technique presented excellent classification ability for all pathological groups but a lower rate of classification success for the able-bodied group. One possible explanation for misclassification of most able-bodied feet in the pes cavus group could be the small variation of the leg/heel angle among different foot types.

Since techniques other than radiography involve larger errors, this misclassification of the small angle is expected. This angle represented the subtalar joint position as one of two main parameters that were selected to develop the Fuzzy logic model.

In summary, this study is the first to use several parameters to successfully classify foot pathologies and has highlighted the importance of using different foot views to characterize a foot disorder. Consequently, this study is the first to employ two multivariate analysis methods and an artificial intelligence technique for identification and classification of foot types. Although all three methods classified pronation and supination groups with high accuracy, the Fuzzy logic performed optimal classification of foot types with excellent accuracy for pathologies. This was the first effort to apply the Fuzzy model to classify foot types with a higher rate of success than SDA and PCA. The poor reliability of the Meschan angle that is used in both SDA and PCA methods might explain the lower success rate of these two methods on the classification of foot pathologies compared with the Fuzzy logic method. Furthermore, univariate and multivariate analyses provide a single yes or no answer according to the variability in the data. The fuzzy logic method is based on probabilities rather than certainties. The rules are set up according to low, medium and high probabilities. Accordingly, a foot can be correctly classified with a medium probability with the fuzzy logic method and misclassified in a multivariate analysis. However, PCA and SDA proved to be accurate techniques to characterize relevant foot geometric parameters for distinguishing foot types. Moreover, the SDA method presented an acceptable model for classification of five different foot types based on multivariate parameters.

5.4 Foot types prediction

This study aimed to test the ability of each classification model to predict foot type. Therefore, the principal component analysis, the stepwise discriminant analysis and the Fuzzy logic models were applied on 94 new feet in order to determine their ability to predict foot types. All three models had lower prediction accuracy than classification ability. The average success of prediction for Fuzzy logic was 78.3% while it was 53.8% and 39.1% for SDA and PCA respectively. Since this study was the first study to attempt to predict foot type using two multivariate models and Fuzzy logic, we did not find any published work to compare with our findings.

PCA had the worst accuracy (33.3%) when performed for pes planus feet. This poor performance may be associated with existing valgus heel among the majority of the planus feet, as seen in the classification results. There was the same performance of model when applied to predict the pronation feet. Seven pronated feet out of 16 were predicted as planus feet. The PCA model predicted some supinated feet as cavus feet because of a combination of a high arch with an inverted heel in some feet. In the prediction of pes cavus 22 feet were predicted as supination and as pronation feet. This incorrect prediction could be related to inverted and everted heel among the pes cavus group (Gould, 1988).

The highest rate of prediction (44%) was found for the able-bodied feet but the majority of feet were predicted as pes cavus feet. This incorrect prediction may be related to a small difference (0.8^{o}) of leg/heel angle between AB and PC groups. The difference of this angle ranged from about 5^{o} to 9^{o} for other pathological feet. Despite the prediction pattern, the feet were similarly classified, but PCA could not predict efficiently the feet in their respective groups. The results demonstrated the weakness of the PCA model for foot type prediction.

The second model for the foot type prediction was SDA. This method predicted 54% of the foot types correctly and had the best success rate, predicting 82% of the cavus feet correctly. There was no acceptable success rate (ranged from 25% to 68%) of prediction by the SDA model for other foot types. The lower values of success of prediction in comparison with the classification ability are reasonable, because the classification model was used for prediction of a new data set.

The final method was the Fuzzy logic technique. It presented an acceptable prediction of all foot types except for the supination group with a

67% success rate. The Fuzzy logic presented a better average of success for prediction than SDA by 24.5% and PCA by 46.4%. This was because the Fuzzy logic model presented a better classification than the SDA and PCA. Nonetheless, our results confirmed the Fuzzy logic model as an accurate method for prediction of foot types.

In summary, three previously developed models for classification of foot types were applied for prediction of new feet. All three models presented worse results for foot type prediction except Fuzzy logic. To our knowledge, this study is the first to evaluate the performances of PCA, SDA and FL models for prediction of foot types. This study is the first to present prediction results using data that were not used to develop the model. According to the prediction results, Fuzzy logic can be used as an artificial intelligence technique for foot type prediction.

5.5 The study limitations

The results of this study need to be interpreted within the bounds of its limitations. The first is related to the PCA method to classify the five groups of feet. This method showed a poor classification for the pes planus and the pes cavus groups. This could be associated with interpretation of clusters on the plot that is both arbitrary and based on visual inspection. Only the first two PCs were plotted against each other in order to display the feet on the scatter plot. These two PCs representing only 36% of the total variance were used to interpret the performance of the classification. Though it could have an effect on the distribution of the clusters, this is a common procedure (Cañeque et al., 2004) and a simple way to classify feet into five groups. It also provided useful supplemental information for development and interpretation of the SDA model.

A second limitation is related to the number of variables for developing the Fuzzy logic model. To establish the membership functions, a large number of rules are formulated with respect to parameters. This is a complex part because one needs to define and formulate many rules. For this reason only two parameters, namely the leg/heel and Djian-Annonier angles based on the PCA analysis, were chosen. These two angles were also identified as the highest predictors from the main variables following stepwise discriminant analysis. Despite using two main selected variables, the Fuzzy logic model presented an accurate and reliable method for classification and prediction of foot types.

Another limitation is related to the reliability of the Meschan angle. This angle had the lowest ICC value for both intra (0.60 for right foot) and intertester (0.72 for left foot) reliability, due to the camera angle in taking the antero-posterior image. In this image the second metatarso-phalangea joint did not clearly appear. To solve this problem, we suggest using a dorsoplantar view when the camera angle is located at 15° in reference to the vertical axis. Despite finding only a fair reliability for the Meschan angle, it had a better value than some other angles reported by Jonson and Gross, 1997.

5.6 Future studies

The present study attempted to test the reliability of a color-coded video-based system as a non-invasive system for the assessment of foot disorders. There is a need, however, to compare this system with other known techniques currently used for foot assessment, such as radiography, in order to validate it. At the time of this study, there was difficulty in finding both a color-coded system and radiographic equipment in the same clinical setting. Podiatrists are gradually equipping themselves with both systems. This validity experiment could be possible in the near future.

An attempt was made in this study to discriminate between five different foot types based on several foot geometric parameters from different anatomical views. Three classification models were applied to these parameters for classifying 321 feet in their appropriate groups. In general, this study indicated the applicability of these parameters to better describe foot disorders. However, to be used in a clinical setting, it would be necessary to extend these models to other foot pathologies such as bunions, first ray hyper mobility, hammer toe and claw toe.

There was a low accuracy rate for principal component analysis as a classification method. Improvements in the classification models could include the use of other relevant parameters, using anthropometric measures such as the navicular drop to describe excursion of the navicular bone, although this parameter may reflect excessive hindfoot pronation (Gross, 1995). Footprint indices such as arch and footprint indices are other possibilities. Using other types of discriminating procedures such as a neural network could be more effective than the present models.

Many studies consider the effects of foot structure and function on the risk of injuries (Razeghi and Batt, 2002; Williams et al., 2001; Hamill et al., 1992; Tiberio, 1988). Even so, few studies have attempted to establish relationships between static parameters and lower extremity movements (Cavanagh et al., 1997), and very little research has addressed the relationship between foot types and their commensurate foot function. Studies which have addressed such a relationship have focused on only one or two pathologies: pes cavus and/or pes planus (Song et al., 1996; Hamill et al., 1989). Further research is required to investigate whether foot type could yield distinguishable differences in dynamic foot function. Demonstration of such a relationship may help to establish the effectiveness of treatments. Even so, it could be hypothesized that foot type results in significant differences in foot kinetics during walking.

Although postural stability has been the subject of many studies (Wollacott and Shumway-Cook, 2002), few have actually investigated the effect of foot types on postural control (Hertel et al., 2002). There is no published research to report on the five different foot types that were the focus of the present study. Analysing the effect of foot types on postural control can provide clinicians with important information about postural control. Foot types can then be assessed and sorted out using the approach presented by this study.

Chapter 6

6. CONCLUSIONS

A novel approach for the assessment of foot posture parameters related to foot pathologies is proposed. The proposed method is simple and provides quantitative information for assessing foot disorders. The characterization and classification of foot types is based on several foot geometrical parameters rather than using one or two and several views rather than one. Furthermore, these geometric parameters were considered simultaneously using multivariate analysis. To our knowledge, this study is the first investigation to describe five different foot types using several parameters taken from several anatomical views at the same time.

According to the first objective, the color-coded video-based system can be used as a quick tool for assessing foot ailments. The results demonstrated that a single set of images is sufficient for measuring foot angles. The system is reliable by means of both intra- and intertester and can be used in the assessment of foot ailments.

Based on the second objective, the study distinctively differentiated and described four foot pathologies in comparison with the able-bodied group using several foot parameters. Based on these differences, a description of differences between angles was established across the groups. Our findings support the hypothesis that each pathological foot should be described by its own specific parameters. It is also reported that different pathologies such as PP and PR have similar characteristics which can result in diagnostic confusion, justifying the use of several morphological parameters to clearly identify the specific pathology.

The third objective was to determine the best geometric parameters for distinguishing an able-bodied group from the four pathological groups. This study developed two multivariate statistical models to identify the best foot geometric parameters for distinguishing an able-bodied foot from four pathological groups of feet. According to the results, the principal component analysis and the stepwise discriminant analysis are both important models to determine the best relevant foot parameters required to interpret and characterize foot types. PCA provided a powerful model to distinguish relevant foot parameters, which is in agreement with clinical findings in the literature. SDA also provided an acceptable model to discriminate initial geometric parameters. These multivariate analyses demonstrate the need to simultaneously consider several measurements to characterize foot disorders rather than using several angles individually.

For the first time, this study applied the PCA, SDA and Fuzzy logic models for foot type classification. Five foot types were classified in their respective groups using distinguished geometric parameters. Fuzzy logic technique as a novel approach provides an accurate and powerful model to classify foot pathologies. SDA enhances discrimination between groups, which improved classification over PCA. Therefore, both Fuzzy logic and SDA models provide useful and unique information about foot type classification.

In summary, the reliability of the color-coded video-based system varied from good to high, making it a good clinical tool for foot assessment. PCA and SDA identified several foot angles from different planes to better characterize foot pathologies than one angle from a single view or plane. Therefore, there is a need to use multivariate analyses for classification purposes. PCA had poor classification results and SDA classified foot types in their respective groups based on several angles with an acceptable accuracy while the Fuzzy logic method had an excellent accuracy. However, using the two multivariate models for prediction of the foot resulted in a low accuracy rate while Fuzzy logic presented an acceptable performance.

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