Université de Montréal

Identification of the morphological parameters characteristic of pes cavus and the development of a prediction model

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This thesis entitled:
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Rose-Marie Lèbe	President-reporter
Paul Allard	Research director
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RÉSUMÉ

En milieu clinique, l'examen visuel est souvent utilisé pour identifier les pathologies du pied. Pour améliorer cette méthode qualitative, un outil, appelé Biovizion®, a été développé afin de faciliter la mesure d'angles sur des images numériques du pied, plutôt que sur le sujet lui-même. Pour vérifier si l'utilisation de ce système pouvait permettre de distinguer des pieds pathologiques de pieds sains, une étude a été menée afin d'identifier les angles caractérisant le pied creux, de construire et valider un modèle de prédiction et d'en déterminer la performance.

Trente personnes sans pathologie visible du pied et 30 autres ayant des pieds creux ont participé à cette étude. Huit images numériques de leurs pieds ont été prises puis filtrées pour faciliter la mesure de 16 angles par pied. Des tests-t appariés ont été effectués pour vérifier la symétrie des pieds dans chaque groupe. Ensuite, des ANCOVAs ($p < 0,05$) ont été effectuées pour déterminer quels angles différaient entre les groupes. Ces angles ont été utilisés dans une analyse en composantes principales (ACP). De manière aléatoire, 60% des sujets ont été choisis pour tester le modèle. Les autres sujets ont été utilisés pour la prédiction, dont la performance a été vérifiée à l'aide des tests de Fisher et de Kappa.

Cinq angles caractérisant le pied creux ont été identifiés et associés aux signes cliniques courants de cette pathologie; ils ont permis de construire un modèle de prédiction efficace à plus de 87%, pour lequel les tests de Fisher et de Kappa ont confirmé que les proportions et l'appartenance des sujets étaient conservées.

L’étude a par ailleurs démontré que, pour les sujets avec les pieds creux, les angles caractérisant cette pathologie étaient symétriques. Finalement, les mesures recueillies lors de cette étude à l’aide du système Biovizion® se sont révélées tout à fait adéquates pour la description de la morphologie du pied.

Mots clés : ACP, imagerie numérique, biomécanique, pied creux, modèle de prédiction, évaluation quantitative, symétrie.

ABSTRACT

In a clinical setting, visual assessments are often used to identify foot pathologies. To improve on this qualitative method, a tool called Biovizion® was developed to facilitate the measurement of angles on digital pictures of the foot, rather than on the actual subject. To determine whether this system could distinguish between pathological feet and healthy feet, a study was conducted to identify the angles characteristic of pes cavus, to construct and validate a prediction model, and to determine its performance.

Thirty people with no visible foot pathology and thirty others with pes cavus participated in this study. Eight digital pictures of their feet were taken and then filtered to facilitate measurement of 16 angles per foot. Paired t-tests were done in each group to verify foot symmetry. ANCOVAs ($p < 0.05$) were then done to determine which angles differed between the groups. These angles were used in a principal component analysis (PCA). Sixty percent of subjects were chosen at random to test the model. The other subjects were used for the prediction, whose performance was verified using Fisher and Kappa tests.

Five angles characteristic of pes cavus were identified and associated with common clinical signs of this pathology; they enabled the construction of a prediction model effective at over 87%, for which Fisher and Kappa tests confirmed that the proportions and reference group of the subjects were respected. Moreover, the study showed that the angles characteristic of this pathology were symmetrical in subjects

with pes cavus. Lastly, the measurements taken during this study using the Biovizion® system proved to be completely adequate for the description of foot morphology.

Key words: PCA, digital imaging, biomechanical, pes cavus, prediction model, quantitative evaluation, symmetry.

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LIST OF ABBREVIATIONS

ANCOVA: Analyses of covariance

PCA: Principal component analysis

®: Registered trademark

p: significance threshold

MTP: Metatarsophalangeal

DEDICATION

To my parents, my friends and Philippe. I love you very much.

ACKNOWLEDGEMENTS

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Lastly, I would like to thank my father for his help and support.

1. INTRODUCTION

This chapter will outline the hypotheses and objectives of this study. First, the clinical context will be described in order to confirm the practical relevance of this study in terms of the pathology selected and the system used to evaluate foot morphology. Then, the literature will be reviewed for available measurement methods, the definition of the pathology used for this study, and the analysis methods used to identify the characteristic parameters and for the classification and prediction of a population of subjects into two or more reference groups, according to certain criteria.

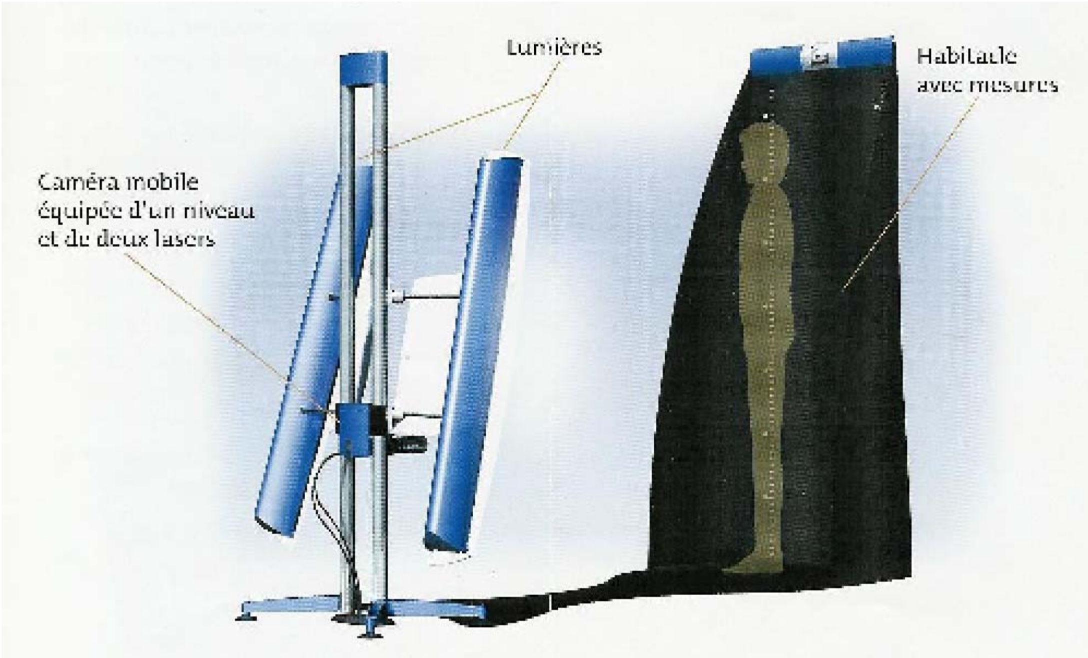
1.1 Clinical context

This section will review the need for quantitative measurement instruments in the clinical setting. Then, it will discuss the relevance of choosing the pathology selected for this study and finally, it will show the need to establish standardized databases for various foot pathologies.

In a clinical setting, foot pathologies are mainly detected and classified by observation, enabling only a qualitative and subjective evaluation of musculoskeletal foot problems. Specialists, such as orthopedic surgeons, podiatrists and physiatrists, can use x-rays to conduct a quantitative evaluation of the feet. But, since this method is limited, invasive and poses a risk to patient health, it is used only occasionally. It is therefore important to promote the development and validation of new, accessible, non-invasive and reliable diagnostic tools for quantifying foot pathologies.

In recent years, an innovative digital imaging system has appeared on the market. Biovizion®, a biomechanical posture assessment system, was developed by Cryos Technologies Inc. (illustrated in Figure 1.1.) Using a camera, a specialist takes digital pictures of the patient's feet placed in different positions. After the pictures are processed with a graphic filter, they are used to measure the characteristic angles of foot morphology (Sadeghi *et al.*, submitted).

Figure 1.1 Recent version of the Biovizion® system enabling biomechanical posture assessment



[Lights; Mobile camera equipped with a level and two lasers; booth with measurements]

This study will focus on pes cavus (Figure 1.2). This choice was motivated by several factors. First, this pathology is quite common, affecting almost 20% of the population (Subotnick, 1985) and is idiopathic in 20% of cases (Fadel and Rowley, 2002). Moreover, the condition of a patient with this pathology can become complicated, since pes cavus can cause locomotion problems (Lavigne and Noviel, 1993). Lastly, a database on a population with this pathology was available.

The use of a quantitative measurement system such as Biovizion® would enable compilation of a database on subjects with and without the pathology. These standardized data would serve as a reference for practitioners. To date, no such reference data exist, specifically on healthy feet and, more specifically, on the existence or non-existence of geometric symmetry between feet. It would be important to study the symmetry of healthy feet, as this would enable better comparison with the symmetry of certain pathologies. The early detection of asymmetries might also help more accurately detect the presence of a pathology.

Clearly, it would be important to be able to quantitatively classify foot pathologies, since this could enable an even easier and quicker general diagnosis. This would be beneficial from a practical standpoint, for both the patient and the evaluator. A more definite diagnosis, a prescription for more suitable orthoses for the patient, and closer follow-up could definitely be beneficial in the long term. Our general objective is to determine whether angles, measured with the Biovizion® system, can be used to distinguish between feet with pes cavus and healthy feet.

1.2 Literature review

First, a literature review will identify the main measurement methods used to diagnose foot pathologies, and demonstrate the importance of having a simple and reliable measurement system to obtain quantitative data on foot morphology in order to eventually establish norms and standards. This literature review will then help establish a definition for the pathology of pes cavus, which will serve as a reference for this study. Lastly, it will explore available statistical analysis methods used in studies aimed at classification and prediction.

1.2.1 Measurement methods for foot morphology

The foot is made up of 26 bones, including the calcaneus and the talus, and has two plantar arches, one medial and the other transverse, which give it its extraordinary strength (Marieb, 1999). Several methods are used to analyze a subject's posture and foot morphology, and thereby help diagnose potential pathologies. These include visual assessment, goniometry, digital imaging, x-rays, foot imprints and pressure measurements. These methods, and their advantages and disadvantages, will be described briefly; Table 1.1. presents a summary.

Table 1.1
Characteristics of the different measurement methods for foot morphology, advantages and disadvantages

Methods	References	Advantages	Disadvantages
Visual assessment	Dahle *et al.* (1991) Cowan *et al.* (1994) Hawes *et al.* (1992)	Inexpensive	Results not very reliable Qualitative
Goniometry	Hunt *et al.* (2000) Astrom and Arvidson (1995)	Inexpensive Reliable	Difficult to use
Digital imaging	Sadeghi *et al.* (submitted)	Quantitative measurements Valid Reliable Easy to use	Fairly expensive
X-rays	Razeghi and Batt (2002)	Accurate Reliable	Expensive Invasive Limited
Foot imprints	Hamill *et al.* (1989)	Valid	Not very reliable Complex calculations
Pressure measurements	Cobey and Sella (1981)	Direct pressure measurements	Mainly dynamic Gives little indication about foot posture

Visual assessment is used by most clinicians in the field of podiatry. While this method is inexpensive and requires no instruments, it is qualitative. Several authors have studied, for example, evaluators' ability to classify feet according to the height of the plantar arch, i.e., whether the arch is low, normal or very high, and the orientation of the rearfoot (Dahle *et al.*, 1991; Cowan *et al.*, 1994 and Hawes *et al.*, 1992). Whereas Dahle *et al.* obtained the agreement of 73% of evaluators, Cowan *et al.* (1994) noted that there was very little agreement between evaluators, especially for high arches. These results suggest that it would be best to use a quantitative evaluation system.

Goniometry is used to measure the angles of the foot itself. It can also measure the medial arch and the orientation of the rearfoot (Hunt *et al.*, 2000 and Astrom and Arvidson, 1995). It is mainly used to measure the position and range of joint movements. A goniometer is inexpensive, but requires direct assessment on the patient's foot, which is long and uncomfortable, for both the patient and the evaluator. It is quite difficult to locate the joints, and an irregular-shaped foot makes using the goniometer even more complicated.

Digital imaging, such as that used by the Biovizion® system, uses a computer system equipped with a digital camera and specialized processing software. This system is used to view the mechanical limitations of the legs using a graphic filter and to quantitatively analyze the shape and alignment of body parts quickly and easily (Sadeghi *et al.*, submitted). This system is reliable, moderately expensive and available to all specialists.

X-rays accurately measure several angles of the feet, but are invasive, expensive and poorly justified for normal subjects (Razeghi and Batt, 2002). Moreover, because of the superposition of bones, their use is limited to only a few views of the foot.

Footprints are used to indirectly quantify the height of the medial arch of the foot, using different calculations. They show where the foot touches the ground and are used to measure the length and width of the foot. According to Hamil *et al.* (1989), this method would simply be used to determine whether or not the foot touches the ground. Calculations to arrive at a result are quite complex, which limits the clinical use of footprints.

Systems to measure foot pressures provide information only on pressures under the patient's feet or on the footprint (Cobey and Sella, 1981). They provide no information on the posture of the foot, other than its shape and areas of high pressure. They can also be used in the same way as footprints, by deducing the height of the plantar arch through calculations, although their use for feet with a pronounced arch is debatable (Razeghi *et al.*, 2002).

Razeghi *et al.* (2002) analyzed four assessment methods used to classify foot types: Qualitative visual assessment, anthropometric measurements, footprints and x-ray assessment. They concluded that there was a lack of standardized data, thereby making comparison difficult. A standardized measurement system would help in the diagnosis and treatment of foot pathologies, but also in conducting more extensive research in the field. The Biovizion® system could be an appropriate, effective tool for quantifying foot pathologies and suggesting standardization. This is why this system was selected for this study.

1.2.2 Clinical definition of pes cavus

Idiopathic pes cavus is the most common type of pes cavus. It develops after age 3 and affects as many men as women (Turek, 1977). It is mainly characterized by a high medial plantar arch. Pes cavus differs from other pathologies in that it is not caused by a neurological disease and its mechanism of onset is unknown (Turek, 1977). This pathology has several degrees. This study will examine the least serious degree. Simple, or first-degree, pes cavus presents with forefoot equinus, weight equally distributed on all metatarsal heads, and heel in neutral position or slightly in valgus (Turek, 1977). People with this pathology experience heel pain and stress fractures due to the foot's poor ability to absorb shocks and its small area of contact with the ground (Franco, 1987). This pathology can cause foot complications such as hallux valgus and hammer toe (Verleysen, 1982). It can affect only one foot (Dwyer, 1975) or both feet. However, there are no studies showing that both pathological feet in the same subject are systematically identical.

Figure 1.2 Picture of pes cavus

Pes cavus can be treated with plantar orthoses, objects often made of plastic that are inserted into the shoe like an insole. They also align and stabilize the body, as well as reduce or equalize pressure exerted on the soles of the feet, thereby re-establishing normal movement that had been affected by the pathology. A plantar orthosis used to correct the biomechanical changes caused by pes cavus should feature an anterior transverse elevation to modify support for the forefoot (Delagoutte and Bonnel, 1989). According to Claustre (1982) and Bourdiol (1980), the orthoses must feature a metatarsal component, which is a retrocapital bar placed under the metatarsal heads to relieve them during contact. A plantar orthosis is necessary to relieve the pain caused by this pathology and to prevent subsequent complications.

The definition of pes cavus given in the literature is qualitative in nature and is not suitable for statistical analyses used to set standards. However, it will be used as a reference to interpret the quantitative data stemming from this study.

1.2.3 Classification and prediction methods

Several methods were used to classify a population into two or more groups. These methods were used to classify pathologies related to feet, but also to the back and hips, and were also used in different contexts such as sports, chemistry and medicine. The most common methods will be presented and their performances specified.

1.2.3.1 Ascending discriminant analysis and logistical regression

Peach and McGill (1998) classified low back pain using electromyographic (EMG) parameters. They wanted to determine whether healthy subjects differed from pathological subjects based on parameters previously identified as being characteristic of back pain. They used two classification methods, i.e., ascending discriminant analysis and logistical regression, with five of the nine EMG parameters they had measured. They developed their model with 28 subjects and verified performances with a test group of six subjects. Using discriminant analysis, 93% of the pathological subjects and 100% of the healthy subjects were correctly classified. With logistical regression, 92% of subjects were classified in their reference group, and 100% of pathological subjects and 75% of healthy subjects in the test group. No test was done with data independent of the model to verify performances.

Marras *et al.* (1995) used a similar methodology to classify the same low back pain problems. Based on standardized parameters of upper body movements, the four statistical analysis methods, i.e., discriminant analysis, classification and regression trees, classification using splines and modified classification using splines, enabled them to classify 171 subjects with back pain, with a percentage of error between 4.9 and 8.6%. They also used a test group of 37 subjects, which represented 22% of their pathological population. Bezold *et al.* (1998) used logistical regression and obtained results of 92% on average in distinguishing two groups in a prediction of the progression of subaortic stenosis in a population of only 41 children. These results are good, but the test group could have been put to better use.

1.2.3.2 Neuronal modeling and linear classification

Bishop *et al.* (1997) used neuronal modeling in a study on the characteristics of dynamic movements in subjects with back pain. They obtained 86% classification for the 375 movement tests done on the 75 subjects used for their model, and classified 72% of the 110 movement tests done on the 22 subjects in their test group. However, the results were not verified by a complementary statistical analysis used to determine their validity.

Few studies have been done on feet. Using a pressure measurement system and an unspecified linear classifier, Bertani *et al.* (1999) classified 28 children with flat feet and 28 children with no pathology, all with an average age of 11. The estimated classification error was at least 15%. No results validity tests were done.

1.2.3.3 Principal component analysis

Principal component analysis (PCA) is used for several purposes, but mainly to reduce a certain number of correlated variables into uncorrelated variables; this analysis can also be used for classification and prediction. Its usefulness in reducing variables will be described first. Blin *et al.* (1995) used PCA to reduce the number of variables they used in a discriminant analysis to separate molecules according to their category of activity. Sultan *et al.* (2003) used PCA, and then a multivariate analysis to classify rats according to neuron morphology. Other authors, such as McKeown and Ramsay (1996) used it initially to find variables for differentiating brain cancers and, then, to find variables for use in their neuronal modeling and for classification. Olney *et al.* (1998) used PCA to group the variables describing the gait of people having had a cerebrovascular accident and to graphically analyze the positioning of their subjects with respect to these new variables. Accordingly, this analysis can be used to reduce variables and as a visual tool to study certain characteristics for comparison between subjects.

Principal component analysis has also been used as a classification method in several contexts and numerous studies. For example, in the study by Kollias *et al.* (2001), it was used to compare the individual performances of several athletes in different sports on a vertical jump. Yamamoto *et al.* (1983) also used it to classify their subjects with hip diseases. Their principal components represented different variables describing the gait of patients distributed according to treatment intervention. This method can therefore be used to compare subjects.

However, few studies with PCA have focused on the prediction of classification of subjects or have verified the results. Bermejo-Barrera *et al.* (2002) used PCA successfully to distinguish between drug abusers (100%) and drug-free subjects (94%) and to distinguish between those using one drug (73%) or several drugs (68%). These researchers also used soft independent modeling of class and analogy, based on a principal component analysis by group, to make their prediction and obtained 94% for the classification and 84% for the prediction. The results obtained by these authors are convincing, especially for the prediction.

With an efficacy comparable to other available analyses, PCA has the advantage of enabling uses other than classification. It can also be complemented by tests to verify the performance of results, which is why this statistical tool was selected for this study.

1.2.4 Verification of the efficacy of classification

The performance of a prediction model can be validated by appropriate statistical tests. Accordingly, two statistical tests are relevant. The first, Fisher's exact test, is a non-parametric statistical test used to determine the strength of the relationship between two variables, i.e., the probability of obtaining results as or more extreme than those observed. The critical value of this test depends on the significance level and varies between 0 and 1. This statistical analysis was used by Oeffinger *et al.* (2000) to compare diagnoses made based on pressure measurements with those made based on x-rays of subjects with flat feet, and by Goldberg *et al.* (2001) to evaluate differences between changes in the Cobb angle and surface topography in patients with scoliosis. Finally, the Kappa test, whose value varies between 0 and 1 (Rosner, 2000), is used to determine the level of agreement between methods, observers, evaluators or variables studied. It is frequently used in classifications, i.e., of back pain (Fritz and George, 2000), foot pathologies (Wainwright *et al.*, 2002) or scoliosis (Xue *et al.*, 2001). It was also used by Dahle *et al.* (1991) to evaluate the similarity between the prognoses of three evaluators for foot pathologies and by Goldberg *et al.* (2001) in the same capacity as Fisher's exact test. These same tests were therefore used to verify the performance of our subject classification prediction model.

The literature review enabled a positioning of the methodology used in this study with respect to the measurement systems and statistical analyses. It also yielded the definition of pes cavus, that of Turek (1977), used as a reference to validate the results obtained. In the process, it also became apparent that it would be important to conduct a foot symmetry analysis on the two study groups.

1.3 Study hypotheses and objectives

Clinical practice proposes a definition of pes cavus for which little quantitative data are available; therefore, it would be important and relevant to quantitatively characterize this pathology in order to have a reference for future studies and to have a reliable and effective prediction model to help clinicians detect and correct foot pathologies.

This study has three objectives. The first is to identify, among the sixteen angles measured on the pictures of each foot taken with the Biovizion® system, those which differentiate feet with pes cavus from the control feet (no observable pathology and asymptomatic). First, the symmetry between the right and left feet of the control and pathological subjects will be checked to qualify this possible additional source of variability. Then, the statistically different angles between subjects in the control group and in the group with pes cavus will be deduced for subsequent use in the prediction model. The hypothesis related to this objective is that there are a certain number of angles among the sixteen measured that characterize pes cavus and that correspond to the definition stated in the literature.

The second objective consists in verifying whether all the angles selected can actually be used to distinguish subjects with pes cavus from control subjects. We will first have to build a model for classifying people's feet. To do this, principal component analysis will be used. A sensitivity analysis of the model with different combinations of characteristic angles will be done to reduce their number even further, if possible. More specifically, the prediction model will retain the angles that enable preservation of the proportions of each group after classification, and according to which the largest number of feet will be correctly classified in their respective groups. It must be possible to build this model and to correctly classify at least 80% of the subjects using principal component analysis.

The last objective consists in estimating the performance of the prediction model. Feet with no visible pathology and feet with pes cavus, which will not have been used in developing the model, will be classified using the prediction model. The same criteria as those in the previous step will be used to evaluate the performance of the prediction model. This performance should prove good if it is around 80%.

This prediction model could prove to be a key clinical tool, by providing (among other things) a visual means of graphically positioning a subject with respect to groups presenting with the reference pathologies. Foot specialists could use it to make quick and efficient diagnoses.

2. METHOD

This chapter describes the population selected for this study, the characteristics of the data acquisition system, and the statistical analyses that were used.

2.1 Description of the population

Sixty participants were recruited to participate in this study. Half of them, with no pathology, comprised the control group and the other half, the group with pes cavus. The 30 subjects were volunteer students from the Kinesiology Department at Université de Montréal. They had no pathology that had been diagnosed by a specialist, podiatrist or orthopedic surgeon, and no foot anomaly, such as slight supination or pronation. Nor did the subjects complain of foot or leg pain. This group comprised 23 women and 7 men, with an average age of 23.5 ± 7.6 years, average height of 168.5 ± 8.25 cm and average weight of 61.7 ± 7.4 kg.

The 30 pathological subjects were diagnosed by a podiatrist as having first-degree pes cavus in both feet, i.e., the least serious degree. Pes cavus is mainly characterized by a high anteroposterior vault. At this first stage of the pathology, pes cavus requires no surgery and the symptoms can be relieved by plantar orthoses (Lavigne and Noviel, 1993). Half of the feet presented with one or two associated pathologies such as supination, pronation or hallux valgus. All of the subjects wore orthoses, prescribed by the same podiatrist, to correct their pathology. This group of subjects was recruited at a podiatry clinic in the Montreal area. The 19 women and

11 men in the group had an average age of 47.8 ± 12.8 years, height of 168.3 ± 11.2 cm and weight of 69.4 ± 14.8 kg.

The subjects in both groups had similar heights and weights, but the control group was younger and comprised mainly of women. The 60 subjects in this study were all over age 18 and signed a consent form approved by the Université de Montréal ethics committee. Individuals under age 18 were not considered for this study because, as their bones have not finished growing, a foot pathology can return to normal after treatment.

2.2 Data acquisition

The machines and techniques used in the biomechanical posture assessment with the Biovizion® system will be described. This system was developed by Cryos Technologies Inc. (Joliette, Quebec) to enable better diagnosis and to facilitate the prescription and manufacture of plantar orthoses.

The Biovizion® system is used to measure angles from digital pictures of patients' feet and not directly on the patients, which significantly facilitates the evaluator's task. Figure 2.1 shows the machine and the position adopted by the subject during an assessment. This machine has three parts, i.e., an acquisition booth in which the subject stands, a digital camera, and image acquisition and processing software.

The 2-m high booth has three black walls and an opening facing the digital camera. The floor measures 1 m^2 and features a small marker in the middle, indicating where the subject must stand in order to be 2.7 m from the camera. The booth is lit by two fluorescent lights, installed in the ceiling of the booth, which maintain uniform lighting of 84 lux, enabling pictures with good contrast.

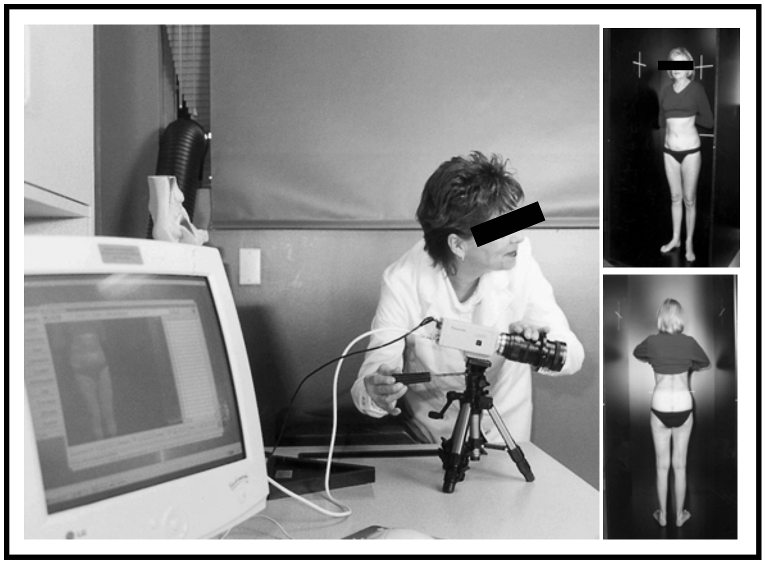


Figure 2.1 Position of the subject in the acquisition booth, facing the digital camera, which is connected to the computer equipped with the Biovizion® software

The subject is assessed while standing. He/she stands facing the camera, unclothed on the areas exposed to the camera's field of vision. For this study, the subject was undressed from the feet to the knees. He/she must adopt eight positions in five views, as illustrated in Table 2.1, i.e., one position in posterior view, one in anterior view and, for each foot, one in medial view, one in lateral view and one in plantar flexion, of which digital pictures are taken. The view in plantar position is innovative, since it shows movements or compensations by the heel with respect to the weight-bearing forefoot.

No device was used that required the subject to adopt a predetermined position, since this could mask the pathology. For example, a template for normalizing the orientation of the feet or the distance between the feet could modify the abnormal posture of the feet. This would prevent diagnosis of certain posture anomalies in the subject.

The pictures of the feet are taken using a *Panasonic WV-BP334* digital camera, which takes pictures in black and white, as shown in Figure 2.2a. This camera is connected to a computer, and the pictures are stored in the subject's folder in the Biovizion® software. Then, a graphic filter is applied to the pictures, enhancing the anatomical structures by giving a different colour to each of the shades of gray formed by the reflection of light on the skin (Figure 2.2b). Once the pictures are processed, it is possible to measure sixteen angles that quantify foot morphology. These angles are illustrated in Table 2.1. Thirteen angles are measured directly on the pictures and three others are calculated from them.

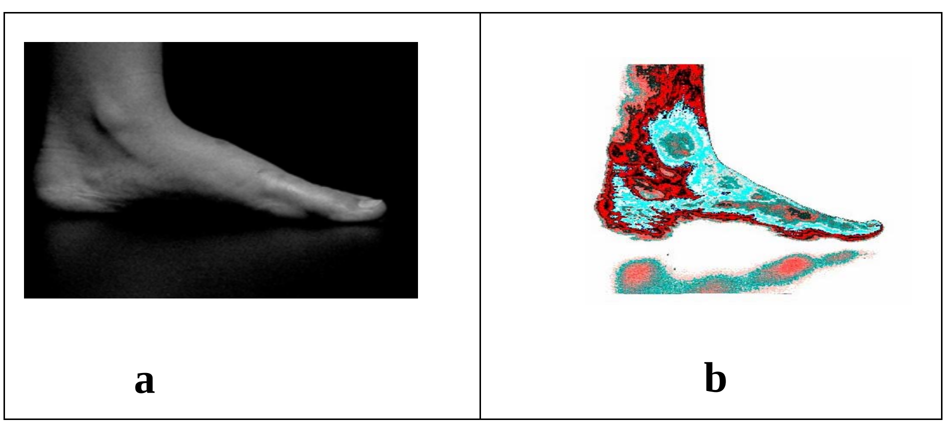
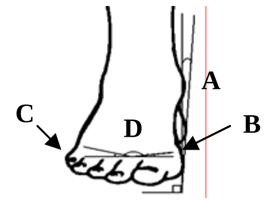
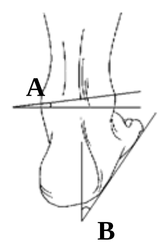
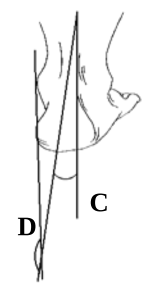
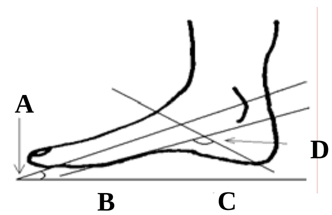
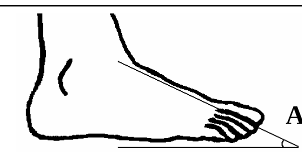
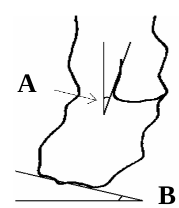


Figure 2.2 **a)** Black and white digital picture of the foot **b)** Picture of the foot filtered by the Biovizion® system

These sixteen angles are part of the clinical protocol developed by Cryos Technologies Inc. and validated by Sadeghi *et al.* (submitted). Two of them are classic angles: the Meschan angle and the Meary-Tomeno line. The Meschan angle corresponds to the angle between the line joining MTP 1 and 2 and the line joining MTP 2 and 5, as measured in the frontal plane, and the Meary-Tomeno line is measured on the medial and lateral side of the foot, and indicates the slope of the metatarsal bones with respect to the horizontal plane. The sixteen angles are not all necessarily used to identify the postures of a pathological foot. Each pathology has its own characteristics and can be described by a limited number of angles. The difficulty rests in identifying the relevant angles and determining their respective role in distinguishing a pathological foot from a healthy foot.

Table 2.1
Views of angles measured or calculated, and their pictures

Views	Angles	Pictures
Anterior	A) Medial base with respect to the vertical axis B) Axis of MTP 1 and 2 with the horizontal plane C) Axis of MTP 2 and 5 with the horizontal plane D) Meschan	
Posterior	A) Axis of the malleoli with the horizontal plane B) Lateral base with respect to the vertical axis C) Middle of the leg and heel with respect to the vertical axis D) Internal malleolus and middle of the heel with respect to the vertical axis E) Pronation (C + D)	 
Medial	A) Meary-Tomeno line B) MTP 1 with respect to the horizontal plane C) Calcaneus, foot fold with respect to the horizontal plane D) Djian-Annonier	
Lateral	A) Meary-Tomeno line	
Plantar flexion	A) Medial heel with respect to the vertical axis B) Axis of MTP 1 and 2 with respect to the horizontal plane	

2.3 Statistical analyses

This study includes several types of successive analyses involving various populations of control subjects and individuals with pes cavus. To clarify the process, an organizational chart is presented in Figure 2.3.

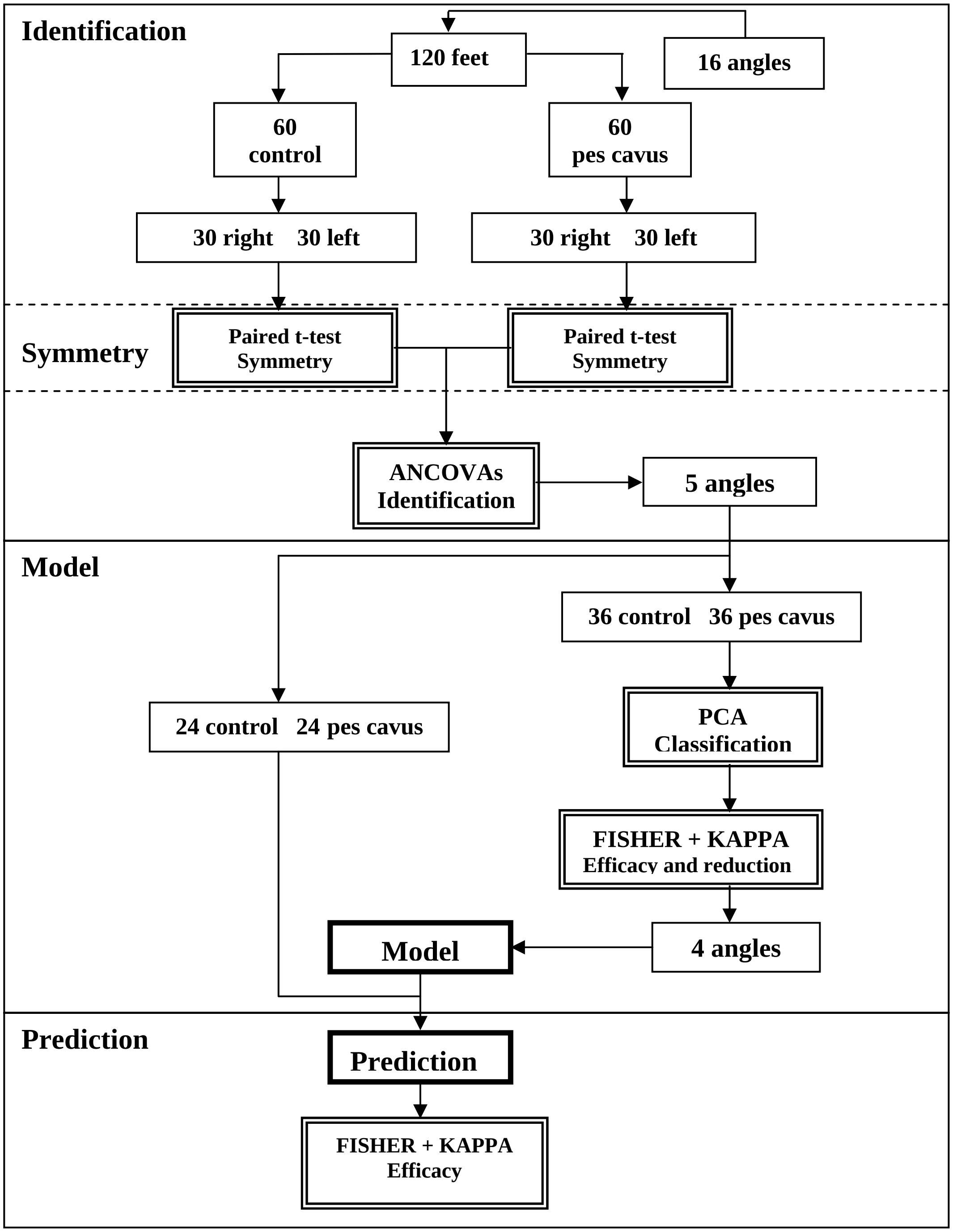


Figure 2.3 Organization chart of statistical analyses

In total, 16 angles on 120 feet were analyzed. There were as many control feet as pes cavus feet. Seventy-two feet were selected at random from each group in order to provide sufficient data to develop the classification model, and the rest were used for the prediction. The *Statistica* software (Oklahoma, USA) was used in this study. The results given to illustrate the methodology used will be discussed later in this section.

2.3.1 Foot symmetry and identification of characteristic angles

Part of the first objective consisted in determining whether or not there was symmetry between the right and left feet in terms of the values of the sixteen angles measured or calculated. Paired t-tests were done for each of the groups. The significance threshold (p) was 0.05. Each p value was rectified by a Bonferroni correction (Neter *et al.*, 1996) to take into account the number of tests done. This was also repeated in the subsequent analyses.

The main part of the first objective was to identify the characteristic parameters of pes cavus. A single-factor analysis of covariance (ANCOVA) ($p < 0.05$) was used, since this analysis takes into account covariables such as age, height, weight and gender. This analysis therefore enables better comparison between the groups. Tukey tests were then done *a posteriori* on significantly different angles. All of the feet, i.e., 60 per group, were included in these analyses. ANCOVAs were used to isolate five statistically different angles.

2.3.2 Development of a prediction model

The second objective was to develop a model for correctly classifying subjects' feet using the set of angles found previously. To do so, PCA was used on a population of 36 control feet and 36 feet with pes cavus. First, single-factor variance analyses with a significance threshold of 0.05 were done to check that the groups used to build and test the model were similar.

PCA, in our case based on the correlation matrix between the variables, enabled us to reduce the number of these correlated variables by combining them into independent variables. The variables had to be correlated from the outset. The variables found were orthogonal compared with each other and each explained a certain percentage of variance. It would have been possible to rotate the variables to try to explain an even greater variance, but a rotation was not necessary, since a very large proportion of the variance was explained by the first two variables. The latter were retained and used as axes in a two-dimensional graph on which the coordinates of each foot were represented by a symbol.

Once the classification was completed, the results were compared with the real distribution of subjects. Two non-parametric tests verified the performance of the classification model. These analyses determined whether the classification was effective; a non-significant value ($p > 0.05$) on the bilateral Fisher test indicates that the proportions were maintained and a value between 0.61 and 0.8 on the Kappa test indicates that the correctly classified subjects are substantially related to their reference groups—almost perfectly, if this value exceeds 0.81 (Landis and Koch, 1977).

It is also possible to use Fisher and Kappa tests to evaluate the performance of the model built from previously identified angles and to reduce the number of these angles, if possible. We had to find the combination of angles that would correctly classify the most feet with the principal component analysis and with good results on the Fisher and Kappa tests. To do this, we had to do 25 analyses representing all possible combinations of two or more angles. The values of the results of an analysis had to exceed those of the five parameters found previously in order for the analysis to be considered more effective. A combination of four angles proved more effective than the five found previously and was therefore used as the basis for the prediction model for classifying feet.

The angles of the subjects' feet held in reserve, i.e., 24 control feet and 24 feet with pes cavus, were then used in the model developed above to predict their reference group. Fisher and Kappa tests verified the predictive quality of the model.

3. RESULTS

In this section, the results of the different steps in the study will be presented. First, the overview of the symmetry analysis between the right and left feet of subjects in each group will be described. Then, the angles characteristic of pes cavus, identified with an ANCOVA, will be listed and the results of an initial classification of subjects according to their reference group using principal component analysis will be presented. Then we will list the results of the sensitivity analysis and the reduction of characteristic angles. Finally, the results of the prediction generated by the model will be presented, with the reduced parameters, as well as the results of the efficacy tests.

3.1 Symmetry between right and left feet

The mean values of the 16 angles noted on the right and left feet are presented in figures 3.1-3.4 for the control group and figures 3.5-3.8 for the subjects with pes cavus. The paired t-tests done for each angle on the subjects' left and right feet showed that there were three statistically different angles, two of which are common to both groups.

In the control subjects, these angles are the pronation angle, the medial Meary-Tomeno line and the angle between MTP 2 and 5 with the horizontal plane in plantar flexion. These angles, measured on pictures taken in posterior, medial and plantar flexion views, are 8.28° (5.2%, $p = 0.00005$), 0.81° (3.1%, $p = 0.02000$) and 5.97° (41.2%, $p = 0.00020$) greater in the left feet, respectively.

In the pes cavus group, the differences are observed in the posterior and plantar flexion views, as illustrated in figures 3.6 and 3.8. The angles are the same, except that the Meary-Tomeno line is replaced by the angle between the line connecting the middle of the leg and the middle of heel with respect to the vertical plane. The latter is 2.47° (46%, $p = 0.000600$) greater in the right feet, the pronation angle is 7.83° (29.3%, $p = 0.000006$) greater in the left feet, and the angle between MTP 2 and 5 with the horizontal plane in plantar flexion is also 5.61° (34.6%, $p = 0.040000$) greater in the left feet.

For the other angles, the differences are rarely more than 4º between feet. In the control subjects, five angles are greater in the right feet, three are greater in the left feet, and five have very similar values. In the subjects with pes cavus, five angles are greater in the left feet, four angles are smaller than the corresponding angles in the right feet, and four angles are similar.

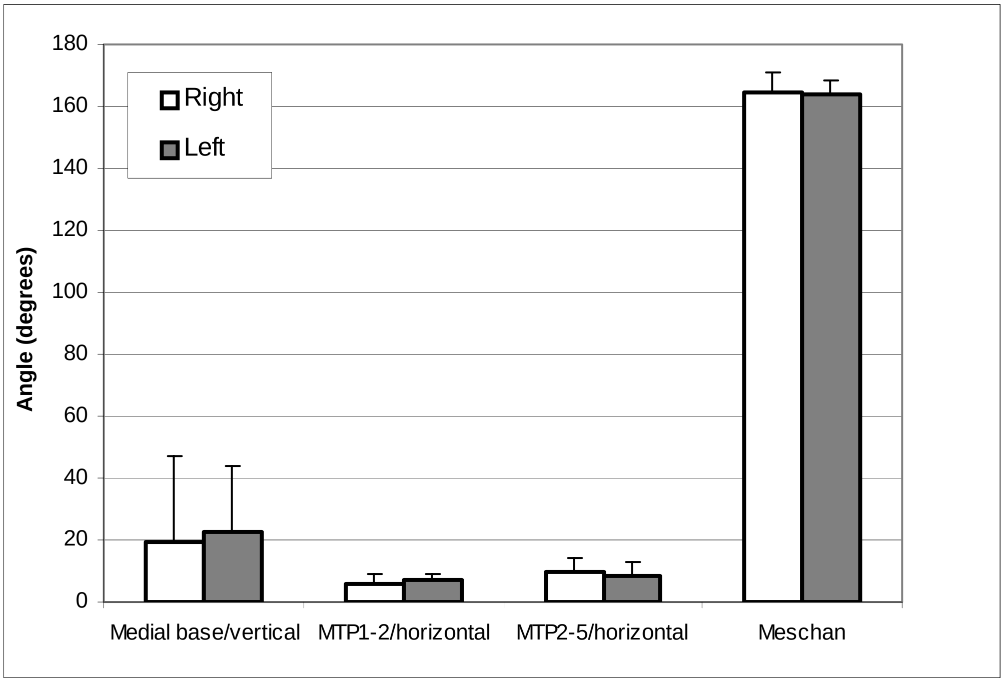


Figure 3.1 Angles in the right and left feet of control subjects measured in anterior view

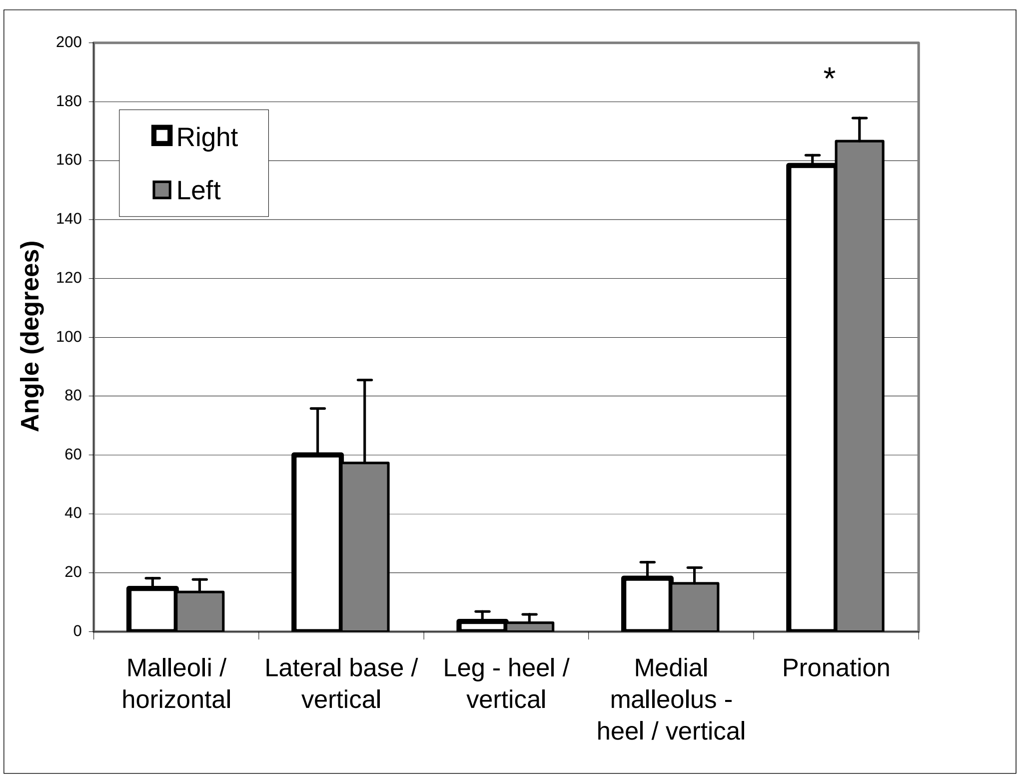


Figure 3.2 Angles in the right and left feet in control subjects measured in posterior view (* = p <0.05)

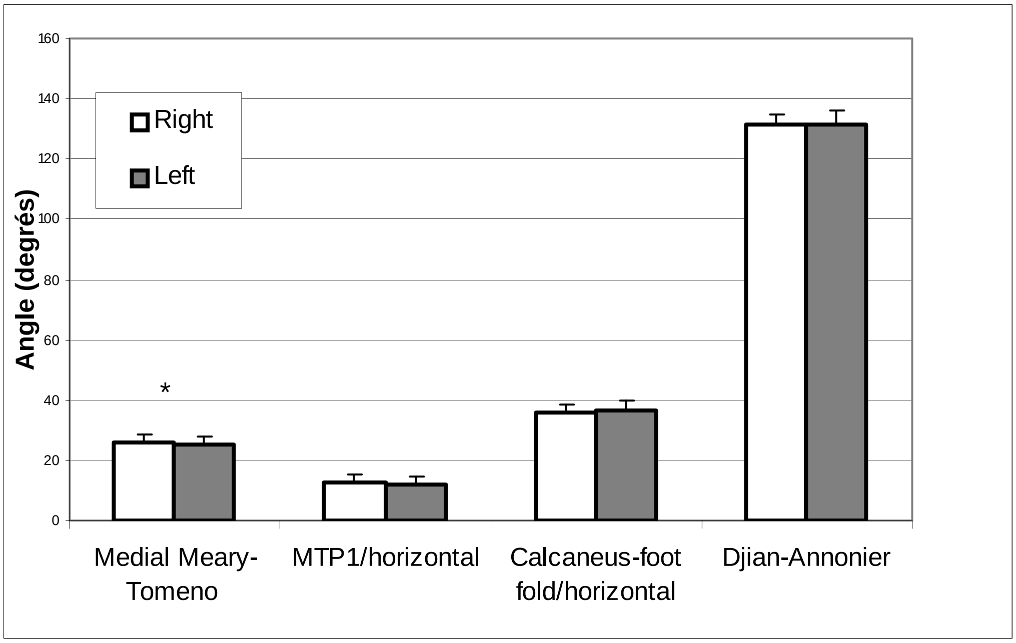


Figure 3.3 Angles in the right and left feet in control subjects measured in medial view (* = p <0.05)

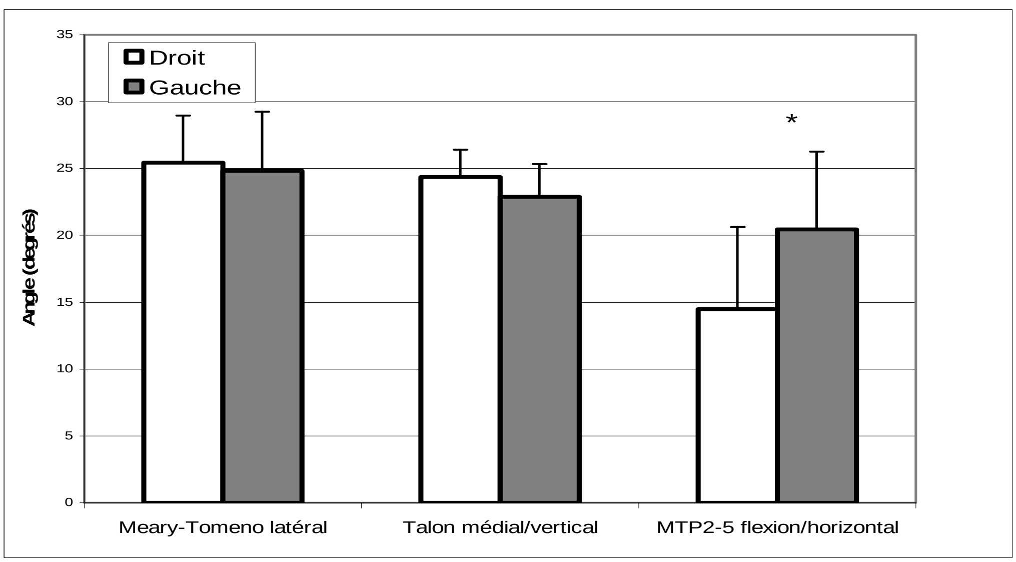


Figure 3.4 Angles in the right and left feet in control subjects measured in lateral and plantar flexion views (* = p <0.05)

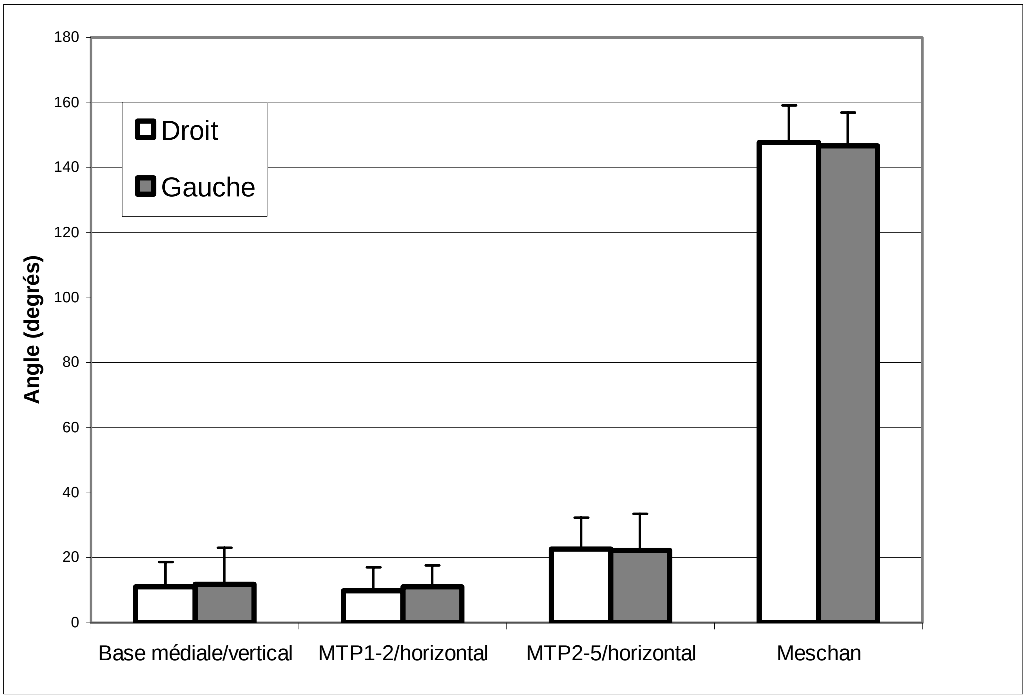


Figure 3.5 Angles in the right and left feet in subjects with pes cavus measured in anterior view

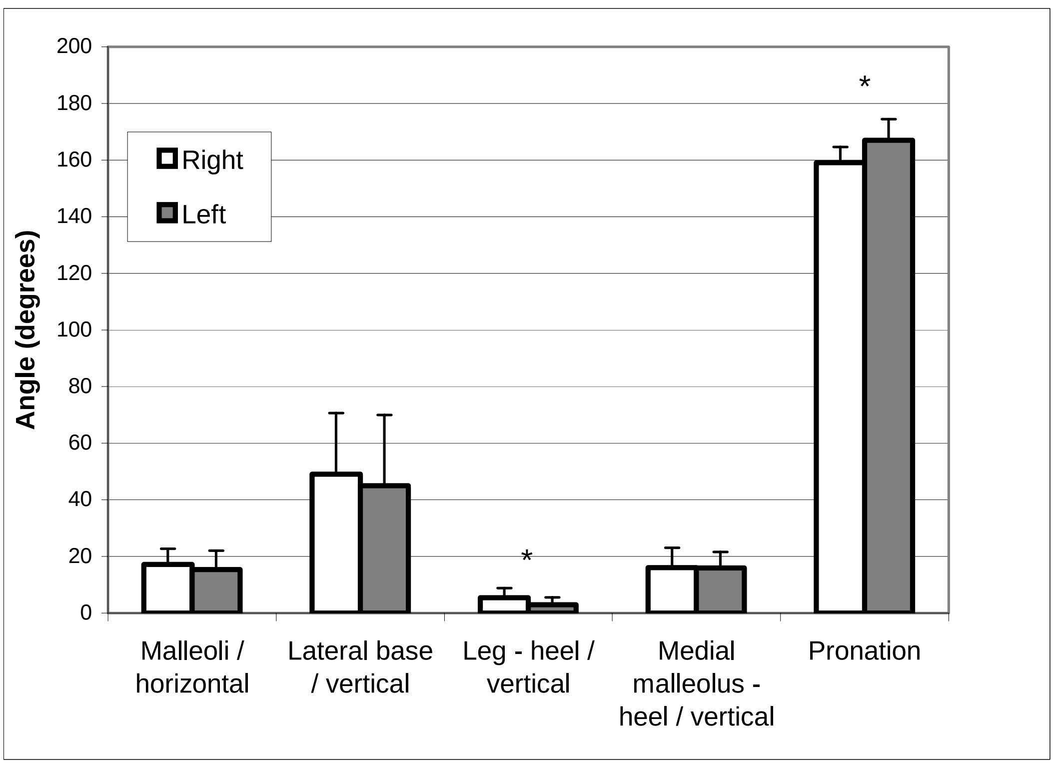


Figure 3.6 Angles in the right and left feet in subjects with pes cavus measured in posterior view (* = p <0.05)

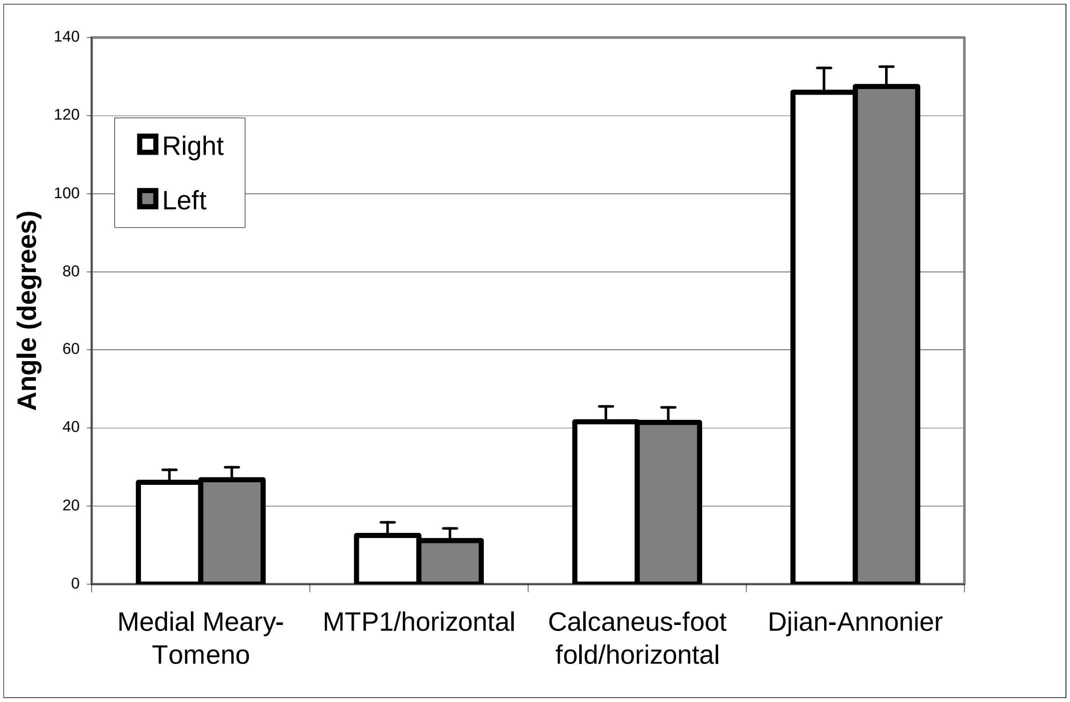


Figure 3.7 Angles in the right and left feet in subjects with pes cavus measured in medial view

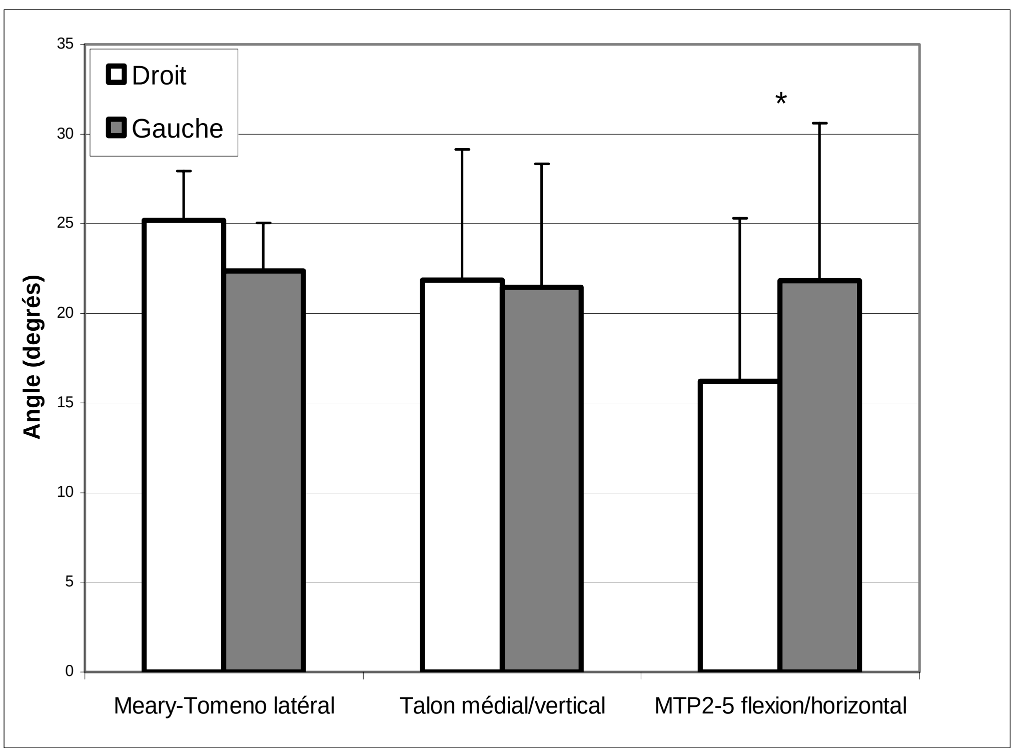


Figure 3.8 Angles in the right and left feet in subjects with pes cavus measured in lateral and plantar flexion views

3.2 Identification of characteristic angles

To identify the angles characteristic of pes cavus, an analysis of covariance was used. For 14 angles, the standard deviation is greater in the subjects with pes cavus than in the control subjects. The angle of the lateral base with the horizontal plane has the greatest standard deviation at 24.47°.

The results of the analysis of covariance are presented in Table 3.1. This analysis enabled identification of five significantly different angles between the control group and the group with pes cavus. These results are detailed in figures 3.9-3.12. As indicated in Figure 3.9, in the anteroposterior plane, three of these statistically different angles are the angle between MTP 1 and 2, the angle between MTP 2 and 5 with respect to the horizontal plane, and the Meschan angle. The differences between the two groups for these angles are 3.9º, 13.4º and 17.3º with p values of 0.00190, 0.00190 and 0.00150, respectively. Figure 3.11 shows two other angles that differ between the groups, i.e., the angle between the calcaneus and the foot fold with respect to the horizontal plane, and the Djian-Annonier angle. The differences are 5.3º and 4.7º, and the p values are 0.00058 and 0.00640, respectively. These five angles were used in the next step to classify subjects.

Table 3.1
Angles selected with ANCOVA and significant p values

Angles selected	p
A) MTP 1-2 with respect to the vertical plane	0.00190
B) MTP 2-5 with respect to the vertical plane	0.00190
C) Meschan	0.00150
D) Calcaneus, foot fold with respect to the horizontal plane	0.00058
E) Djian-Annonier	0.00640

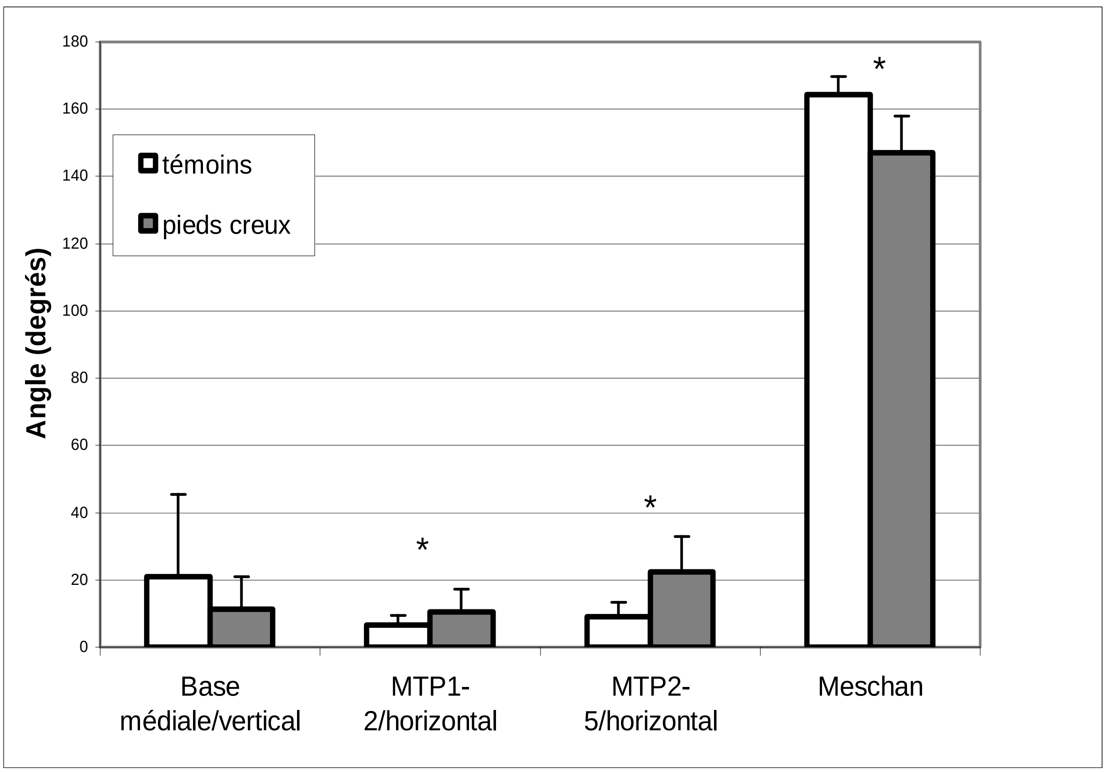


Figure 3.9 Angles in the control feet and the feet with pes cavus measured in anterior view (* = p <0.05)

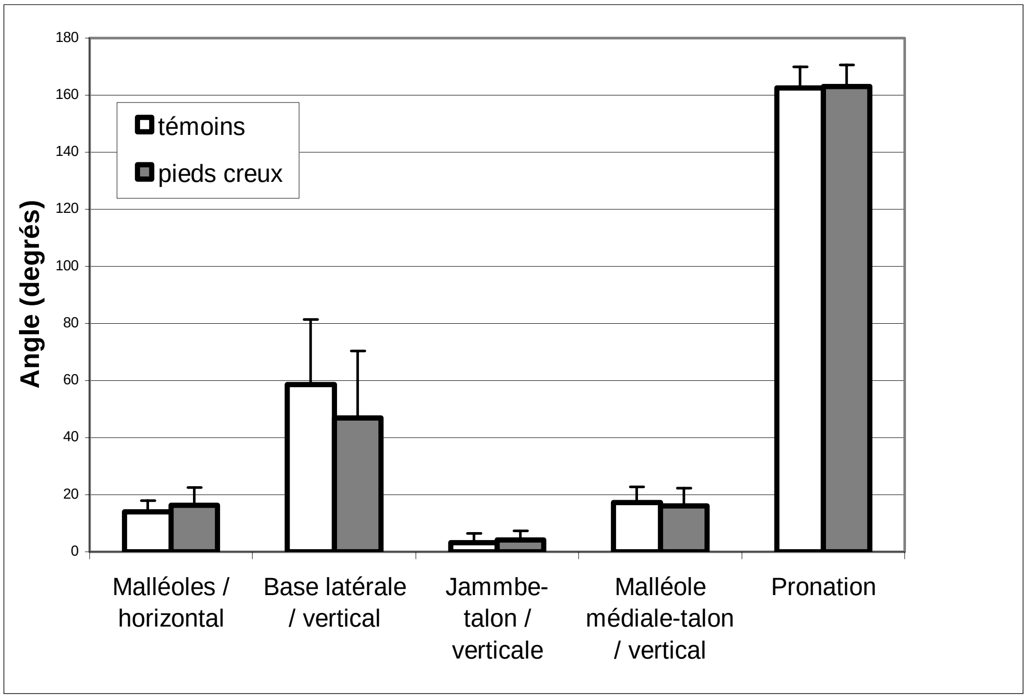


Figure 3.10 Angles in the control feet and the feet with pes cavus measured in posterior view

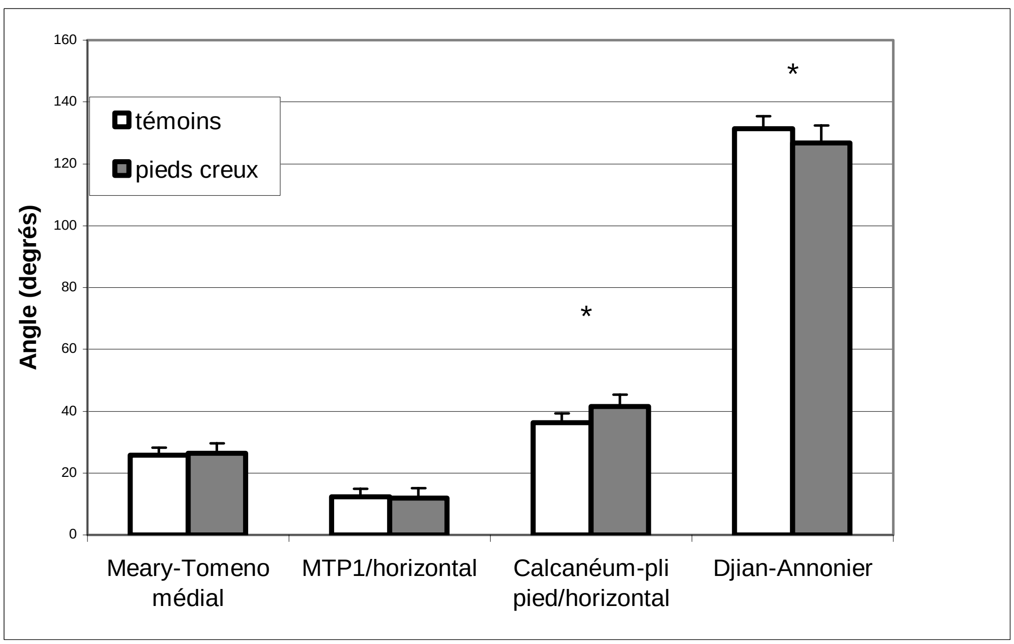


Figure 3.11 Angles in the control feet and the feet with pes cavus measured in medial view (* = p <0.05)

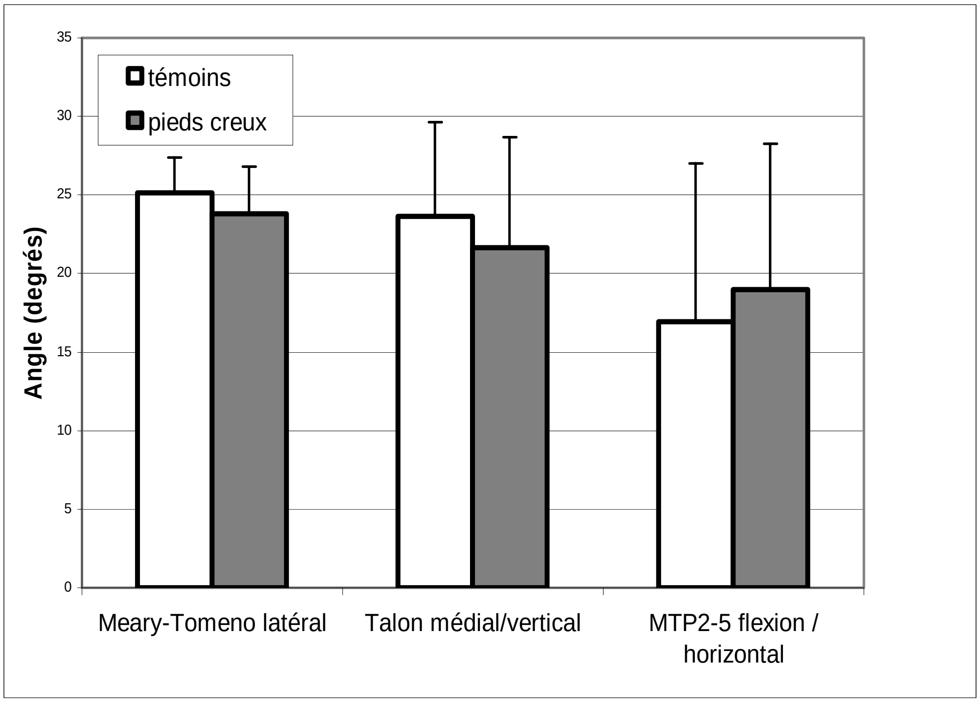


Figure 3.12 Angles in the control feet and the feet with pes cavus measured in lateral and plantar flexion views

3.3 Development of a prediction model

For this step, 72 feet among the 120 available were chosen at random. The classification of this population into two groups using the principal component analysis enabled the five angles to be grouped into four independent and orthogonal variables. As shown in Table 3.2, 79.89% of the variance was explained by the first two principal variables and 96.83% by the first three. As the eigenvalues of the first two variables were higher than 1, these variables were used as orthogonal axes on the graph presented in Figure 3.13. During this first classification, 89% of the control feet and 86% of the feet with pes cavus were correctly classified into their reference group, with the axis of ordinates being the separation point between the groups.

Four control feet were not classified into their reference group. These were two pairs of feet belonging to two subjects. One of them presented with greater-than-average MTP 1 and 2 angles with respect to the horizontal plane and the line linking the calcaneus and the foot fold with respect to the horizontal plane. The other had a higher-than-average angle of the calcaneus and the foot fold with the horizontal plane and the Djian-Annonier angle. For the pathological subjects, the five incorrectly classified feet all belonged to different subjects. Accordingly, there were no problematic subjects, since in no case was the same person found to have two problem feet. However, the values of their Meschan and Djian-Annonier angles are closer to the means for the control feet than the pes cavus feet.

The results of the Fisher and Kappa tests are presented in Table 3.3. The results of the Fisher test show, with a value of 1, that the proportions are maintained. The subjects correctly classified are substantially related to their reference group with a k of 0.75 on the Kappa test.

Table 3.2
Percentage of variance explained, eigenvalue, and characteristic angles for each principal variable with their respective eigenvector

	Component 1	Component 2	Component 3	Component 4
Variance explained (%)	51.71	28.19	16.94	3.16
Eigenvalue	2.585	1.410	0.847	0.158
A) MTP 1-2/vertical	0.342	-0.181	-0.877	0.016
B) MTP 2-5/vertical	-0.421	-0.589	-0.251	-0.019
C) Meschan	0.516	0.459	-0.124	0.024
D) Calcaneus, foot fold/horizontal	-0.481	0.432	-0.264	0.716
E) Djian-Annonier	0.457	-0.472	0.288	0.697

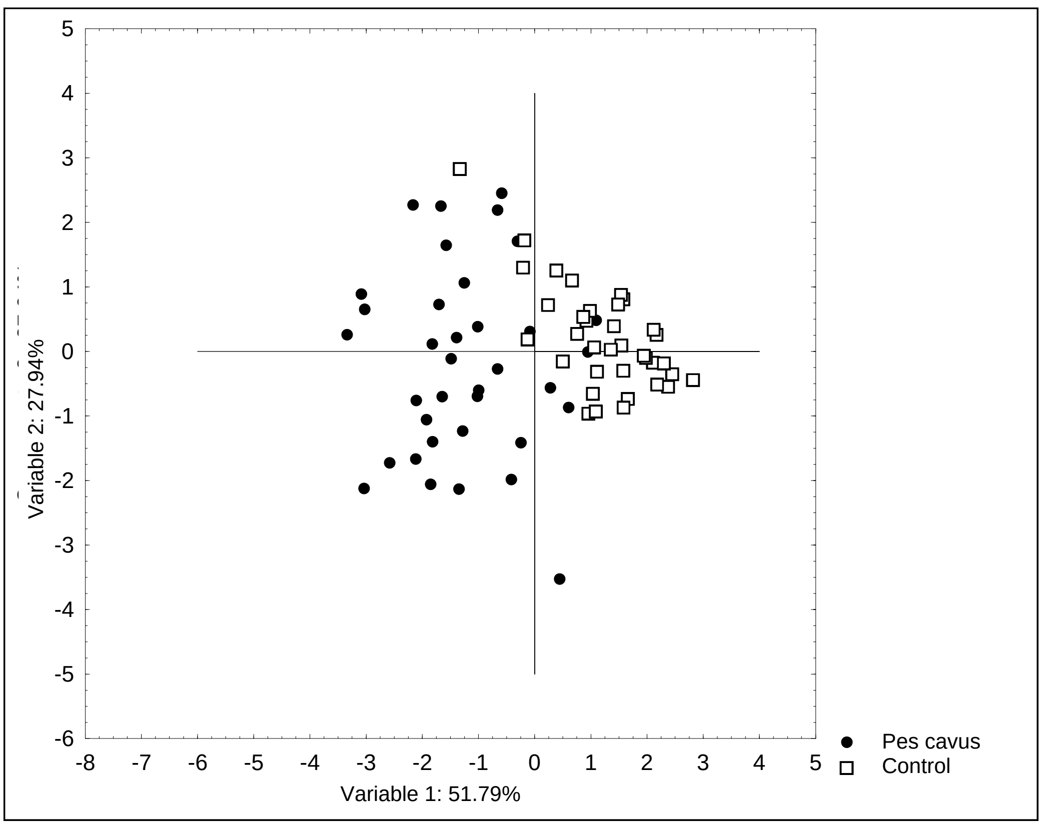


Figure 3.13 Classification of the control feet and the pes cavus feet according to the first two variables calculated from the five characteristic angles

Table 3.3
Results of real classifications and by principal component analysis (PCA) in each group as well as the values from Fisher and Kappa tests associated with the classification

	Classification			
Classification	Control	Pes cavus		
Real	36	36	Fisher	Kappa
With PCA	32	31	1	0.75

To reduce the number of angles and increase the performance of the model, a sensitivity study was done with the five angles found previously. A principal component analysis was done with each of the possible 25 combinations. Four angles yielded better results than the five found previously, with the Kappa value increasing from 0.75 to 0.78. A combination of four angles rather than five would therefore be better to classify subjects according to their reference group.

Since the two angles in medial view are strongly correlated with an r = 0.8, the two combinations of four variables yielded the same results. These are combinations ABCD and ABCE. The percentage of feet correctly classified and the results of the Kappa are better than with five angles and are equal for both combinations of four angles. As shown in Table 3.4, only one control foot and seven feet with pes cavus were incorrectly classified, i.e., their angle values differed from the values for their reference group. The Fisher test yielded 0.4 and the Kappa test 0.78 for both combinations of four angles.

Table 3.4
Results of real classifications and by principal component analysis (PCA) in each group, and Fisher and Kappa tests values associated with the prediction model

	Prediction model			
Classification	**Control**	**Pes cavus**		
Real	36	36	**Fisher**	**Kappa**
With PCA	35	29	0.4	0.78

The choice of the best combinations of angles was determined from the proportion of variance explained by the first two principal variables, which is greater than 0.75% for the combination including three angles in anterior view and the angle between the line connecting the calcaneus to the foot fold and the horizontal plane. The values are 82.74% compared with 81.99% for the combination that includes the Djian-Annonier angle. The angle between the line connecting the calcaneus to the foot fold and the horizontal plane is therefore better than the Djian-Annonier angle for classifying feet.

A classification by principal component analysis was repeated with these four angles and the 72 subjects. Figure 3.14 shows the results. The first two principal variables (of a total of three) explain 82.74% of the variance. A total of 97% of the control feet and 81% of the feet with pes cavus were correctly classified. Accordingly, only one foot was not correctly classified among the control subjects. The seven feet that were incorrectly classified in the pes cavus group belong to six different subjects. Accordingly, there was only one subject whose two feet were incorrectly classified.

The angle between the axis of MTP 2 and 5 with respect to the horizontal plane is 11.4º smaller compared with the mean and the Meschan angle is 18º greater.

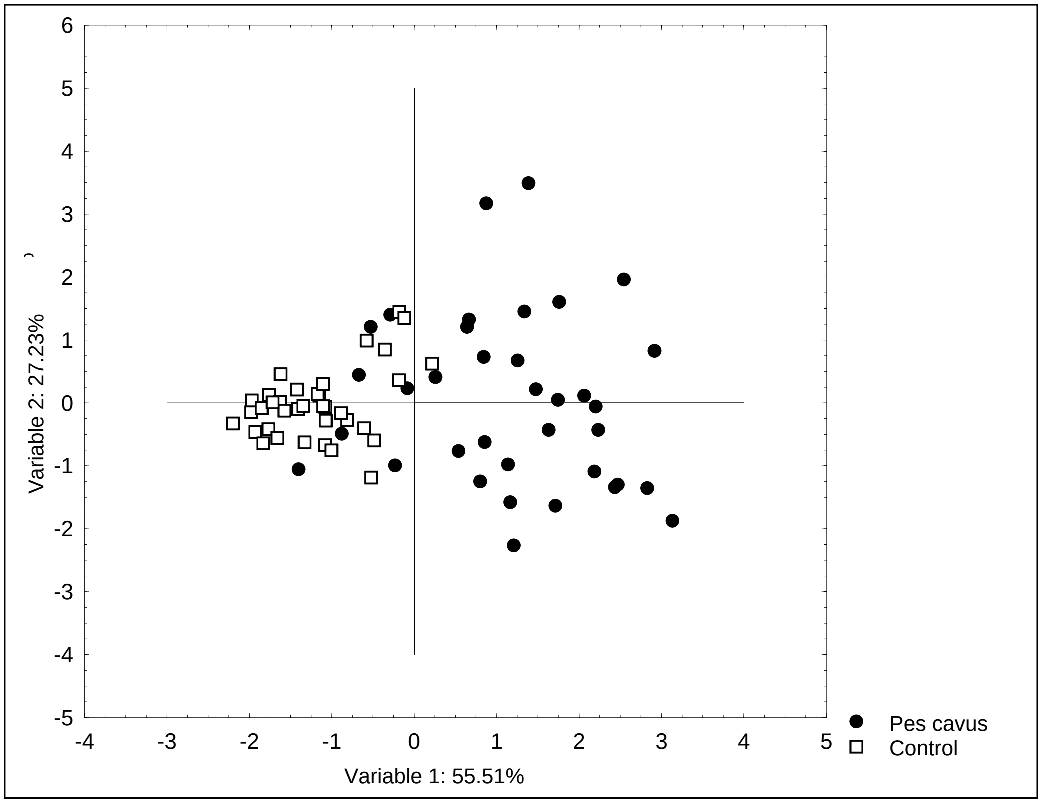


Figure 3.14 Classification of the control feet and the feet with pes cavus according to the first two variables calculated from the four angles forming the prediction model

3.4 Prediction model test

According to a single-factor variance analysis with a significance threshold of 0.05, done to compare the two groups, the 48 remaining feet presented no significant differences from the group used to establish the model. This population of 48 feet was used to make the prediction. Figure 3.15 illustrates the position of the control feet and the pes cavus feet, with the first two variables as axes. One foot with pes cavus was eliminated from the prediction, since the values of its angles in anterior view could not be calculated (they could not be distinguished due to picture quality). Classification of a large portion of the feet was correctly predicted, i.e., 96% of the control feet and 79% of the feet with pes cavus.

Only one control foot and four feet with pes cavus were incorrectly classified. The incorrectly classified control foot was not the same as that during the first classification, and its values were 6.6° higher than the mean for the three angles in anterior view. The four feet with pes cavus belonged to four different people. Their Meschan angle was 18.6° higher than the group mean. Again, Table 3.5 shows the results of the Fisher test as being non-significant (0.68). The Kappa test shows substantial classification quality (over 0.81 is considered almost perfect) (Landis and Koch, 1977).

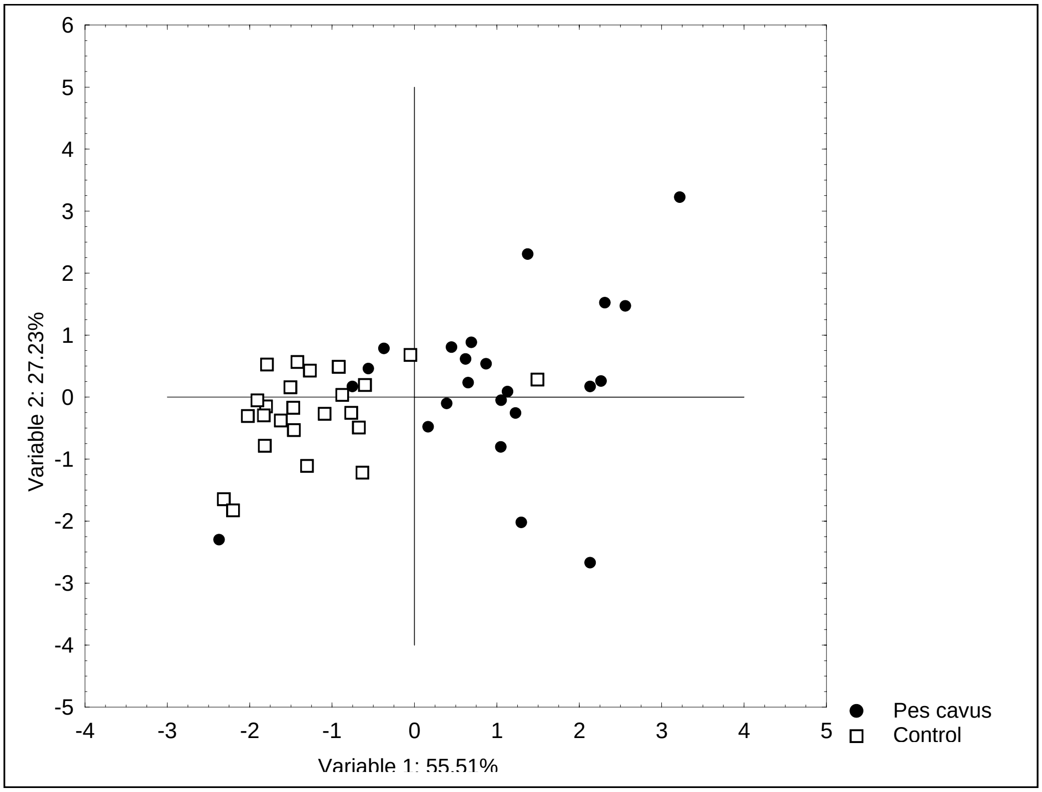


Figure 3.15 Prediction of the control feet and the feet with pes cavus according to the first two variables calculated from the prediction model

Table 3.5
Results of real classifications and by principal component analysis (PCA) in each group, and values for Fisher and Kappa tests associated with the prediction

	Prediction			
Classification	**Control**	**Pes cavus**		
Real	24	23	**Fisher**	**Kappa**
With PCA	23	19	0.68	0.79

4. DISCUSSION

In this chapter, the measurements gathered using the Biovizion® system will be examined, and the results of the symmetry tests between the right and left feet discussed. The feet with pes cavus will be described using angles measured with the Biovizion® system. The results of the classification and the prediction will be compared with similar studies in order to assess the performance of the model and its possible application in identifying pes cavus. An assessment will be made of this project's contribution to podiatry and, to conclude, the limitations of this study and its possible follow-ups will be presented.

4.1 Value of angles measured with the Biovizion® system

One of this study's important contributions was to establish a database of asymptomatic feet and feet with pes cavus. To our knowledge, no other study has been done on the quantitative characterization of foot morphology. The measurements obtained with the Biovizion® system are within the range of values generally reported in the literature. According to Montagne (1980), a foot with no pathology should have a Djian-Annonier angle between 120° and 125°, whereas a foot bordering on pes cavus would have an angle of 118º. These data were obtained using an x-ray in medial view. The control subjects in our study had values between 131° and 137° for the same angle, whereas subjects with pes cavus had a higher value than that found by Montagne (1980), but smaller than that of the control feet. Montagne (1981) observed a Meschan angle of 140º in normal feet compared with 164º in this study. The difference between the control group and the group with pes cavus is similar to that found in the literature. It is understandable that the same absolute values were not found, since our measurements were taken from digital pictures of feet and not x-rays.

Levy and Hetherington (1990) also studied x-rays in medial view and determined the normal values for the angle of inclination of the calcaneus. They determined that this angle should be between 15º and 30º, but they do not give the values for pes cavus. The study by Didia and Dimkpa (1999) showed that, on average, the feet in their population of healthy Nigerians had a calcaneal angle between 28º and 38º. Our control group had a mean value of 36º for the angle between the calcaneus and the foot fold, i.e., slightly greater than that measured by all these authors. However, for the calcaneal angle, McClay and Bray (1996) obtained a value on x-rays—between 43º and 48º, on average—similar to that in our study. Again, comparison was difficult, since the angles were not measured using the same method.

In summary, we can state that the values of the angles measured with the Biovizion® system are often slightly greater than those obtained using x-rays, although the range of their values is similar to that of x-rays. It would be interesting to do more advanced comparative studies to definitively confirm these hypotheses.

4.2 Foot symmetry

A second important contribution of this study was to identify the nature of the symmetry between feet for a large number of subjects. Although symmetry is predictable in the feet of the control subjects, it is not clear whether it exists in subjects with idiopathic pes cavus, even though this pathology most often manifests simultaneously in both feet. Few studies have confirmed the nature of the symmetry that exists between the angle values in the left and right feet, and these studies (unlike this one) are often limited to a maximum of nine measurements.

Didia and Dimkpa (1999) compared only the calcaneal angle of the feet of non-pathological subjects, and concluded that the feet were symmetrical. Astrom and Arvidson (1995), using a goniometer, measured nine angles on healthy active subjects. These authors found a one-degree difference in eversion of the calcaneus between the right and left feet, which corresponds to our study. Using calculations on footprints, Forriol and Pascual (1990) found differences in the medial arch between the right and left feet of healthy subjects aged 3-17, which were not found in this study. It is therefore possible to find asymmetries in healthy subjects, although this aspect is not covered in detail in the literature. Moreover, there is nothing to indicate that feet with pes cavus could present with asymmetries.

The results of this study show that the majority of the angles measured are symmetrical. Only three angles proved statistically different between the right and left feet in each group of subjects in the posterior, medial and plantar flexion views. The differences in the control subjects appeared in the medial Meary-Tomeno angle, the pronation angle and the angle between MTP 2 and 5 with respect to the horizontal plane in plantar flexion. The means for these angles differed by at least 3%. Note that the first two angles are not the only ones that characterize the inclination of the metatarsals and the position of the rearfoot. For feet with pes cavus, the differences appeared in the angle of the line linking the middle of the leg to the middle of the heel with respect to the vertical plane, the pronation angle and the angle between MTP 2 and 5 with respect to the horizontal plane in plantar flexion. The differences in the means between the two feet were 5%, 29% and 59%, respectively. The differences were noted in two angles indicating the posture of the rearfoot and one angle indicating the position of the forefoot.

In general, there is a good level of symmetry, since 80% of the angles proved symmetrical. Moreover, no asymmetry was noted in the angles characteristic of pes cavus. In both groups, the angles of the metatarsals in plantar flexion were asymmetrical. This could be due to problems holding the necessary position while taking the pictures. The clinical protocol for this angle should be reviewed to verify the cause of these systematic asymmetries in the two groups. For the group with pes cavus, two angles indicating the posture of the rearfoot are asymmetrical. This could confirm the presence of secondary pathologies observed in 50% of the subjects, i.e., pronation or supination. In these subjects, the two opposing positions are present, since when one foot is in supination, the other is in pronation.

The asymmetries noted therefore had no impact on the rest of the study. But the fact of having found asymmetries could be useful in a clinical setting. In fact, foot symmetry could be checked frequently, which would determine whether or not the pathology is progressing systematically in both feet. Asymmetrical progression could result in more targeted clinical follow-up or even specific treatment for each foot.

4.2 Angles characteristic of pes cavus

The first objective of this study was to identify the morphological parameters characterizing pes cavus. An analysis of covariance identified the angles characteristic of pes cavus. An explanation will follow about how these angles, determined from pictures of feet taken with the Biovizion® system, compare with those in the literature.

According to Turek (1977), pes cavus is characterized by a high anteroposterior vault caused by contraction of the plantar fascia, a lower first metatarsal, a rearfoot in supination and dorsiflexion, and a forefoot in pronation.

Pes cavus is identified by the Djian-Annonier angle, which is 4.7° greater in the control feet, and the angle of the line between the calcaneus and the foot fold with respect to the horizontal plane, which is 5.3° greater in feet with pes cavus. These two angles indicate a high plantar arch, as stated by Turek (1977). The Djian-Annonier angle indicates a high inclination of the metatarsals. The angles between MTP 1 and 2 and MTP 2 and 5 with respect to the horizontal plane, which are 3.9° and 13.4° greater in feet with pes cavus, and the Meschan angle, which is 17.3° smaller in the same subjects, indicate pronation of the forefoot, again as suggested by Turek (1977). Regarding supination of the rearfoot, the representative angles, such as the pronation angle, did not appear in the analysis as being significantly different between the two groups. According to Turek (1977), idiopathic pes cavus would have a heel in varus. Note also that studies by McPoil *et al.* (1988) on healthy subjects showed the presence of varus of the rearfoot in 84% of cases in a population of women aged 18-30. Therefore, the absence of significant differences between the two groups for this angle could be explained by the fact that subjects with pes cavus have associated pathologies that mask the differences or that the pathology is not advanced enough, even though it has been diagnosed.

Although there are no statistically significant differences, other angles can be used to distinguish pes cavus from a healthy foot. According to our data, this is the case with the angles of the medial and lateral bases with respect to the horizontal plane, the lateral Meary-Tomeno angle and the angle of the medial heel with respect to the vertical plane in plantar flexion, which are all 5-46% smaller in pes cavus, and the MTP 2 and 5 angles with respect to the horizontal plane in flexion, which are 1% greater.

4.3 Classification and prediction models

The second objective consisted in developing a model to classify subjects into their reference group to determine whether the variables selected could be used to distinguish subjects with pes cavus from control subjects. The third objective consisted in testing the subject classification prediction model to determine its performance in distinguishing pes cavus from feet with no pathology. Because they present with obvious similarities in the methodology and referrals to the same references in the literature, these two objectives will be discussed together in terms of results obtained.

Using principal component analysis, our subjects were classified into two groups and a prediction model was developed. A result of 97% was obtained for the classification of control subjects and 81% for subjects with pes cavus. For the prediction, 96% of control subjects and 79% of subjects with pes cavus were correctly classified. The results obtained in both cases exceed 87% on average.

First, we will compare these results with those from the discriminant analysis done by Bermejo-Barrera *et al.* (2002) and Peach and McGill (1998). These studies obtained higher results, but with a smaller number of subjects, i.e., 53 for the first and 39 for the second. A perfect prediction was achieved during the first study, but with a test group of only 12 subjects. For the Peach and McGill study (1998), five out of six subjects in their test group were correctly classified. In this study, 72 feet were selected to develop the model and 48 other feet to apply it during the prediction. The number of test subjects (feet) is 4-8 times higher in this study than in the others.

Using the *soft independent modelling of class and analogy* method, Bermejo-Barrera *et al.* (2000) obtained results higher than ours for the classification, with 94%, but not as good for the prediction, with 84%. Using neuronal modeling, Bishop *et al.* obtained results lower than ours (1997) for the classification and prediction, with 86% and 72%, respectively. For the logistical regression, the results of the classification for Bezold *et al.* (1998) and Peach and McGill (1998) were a little better, with 94% and 92%, but the prediction by Peach and McGill (1998) was lower than ours, with 75%. Lastly, Bermejo-Barrera *et al.* (2002) also used PCA. Their classification was higher than ours, with 94% of drug-free subjects and 100% of drug abusers correctly classified, although they had only 53 subjects with which to compare healthy subjects and problem subjects. For their classification into two groups of drug users, an average of 70% of subjects were correctly assigned. Our results are therefore better, even though there was a greater chance of making a classification error with more subjects.

Therefore, several methods can be used to classify subjects into two groups and to test the model by predicting the classification. Our method based on PCA yielded results comparable to those in the literature. The studies that used more subjects than ours did not obtain much better results. Another strong point in our methodology compared with those used in the literature is the fact of having used different subjects to test the model, i.e., 40% of available subjects. Few studies used a test group for their prediction. Based on these results, the limitations of the classification and the prediction probably stem from the subjects and not the type of analysis used.

This study showed that a quantitative evaluation done with the Bioviozion® system can distinguish pes cavus from a healthy foot in 79% of cases without the need for input from a specialist. The model developed in this study could prove to be a complementary tool for foot specialists in the diagnosis and clinical follow-up of this foot pathology.

4.4 Limitations of the study

The principal component analysis was used to successfully distinguish healthy feet from pes cavus. Nevertheless, there were some problems in the study with the quality of the pictures, associated pathologies, interpretation of the variables of the PCA, and the comparison of angle values obtained with those in the literature.

First, the quality of the pictures available was not always ideal for measuring all the angles of the feet, specifically the pictures of pathological subjects. These were not standardized, i.e., lighting and distance standards were not used, thereby leading to variations in picture quality. Moreover, the subject did not have to hold a specific position while the pictures were being taken, which also caused some variations in picture quality, since the camera framing had to be adjusted to each person's position. Also, a picture taken from too far or poorly focused could not be used to distinguish the anatomical elements of the feet needed to measure the angles. Nonetheless, we were able to measure almost all the angles on all the feet, except for a few subjects with pes cavus, for whom several angles are missing in certain views. One of these subjects had to be withdrawn during the principal component analysis. Moreover, the pictures of the feet in the control group were taken under stricter and more standardized conditions. All the angles could be easily measured.

Second, 90% of the feet with pes cavus in the study had an associated pathology. There were many associated pathologies, some of which were related to pes cavus, such as supination, pronation and plantar flexion of the forefoot, whereas others were unrelated, such as heel spur, and still others were complications of pes cavus, such as hallux valgus, sub-metatarsal hyperkeratosis and metatarsal pain. Half of the population of feet with pes cavus had supination or pronation of the rearfoot, 17% plantar flexion, 10% hallux valgus and 7% heel spur or hyperkeratosis. Even though they may have had other associated pathologies, 81% of subjects with pes cavus were classified, and despite these operational limitations, results greater than 87% were obtained for the classification and prediction of all subjects.

Third, contrary to several studies, such as that by Sadeghi *et al.* (2002), who explained how PCA could be used to detect the main structure of the actions of the knee flexors and extensors during walking in healthy subjects, we could not determine what explained each of the principal variables extracted from our data. However, it was not necessary to do this since the principal component analysis was not used here as a variable reduction tool but rather as a classification tool.

Finally, as discussed previously, it was difficult to compare the angle values obtained during this study with those in the literature, since most of the angles in the literature are measured from x-rays, and no other author has yet used the Bioviozion® system to take measurements. This system has already been validated (Sadeghi *et al.*, submitted), and this study showed that the characteristic angles found using Bioviozion® can distinguish between pes cavus and healthy feet.

In conclusion, better pictures and an absence of associated pathologies could have probably allowed us to obtain even more conclusive results.

4.5 Clinical relevance of the Biovizion® system

Our general objective was to determine, using measurements taken with the Bioviozion® system, that a distinction could be made between healthy feet and feet with pes cavus. Our method yielded prediction results 5.5% higher on average than those in the literature.

The Bioviozion® system is fast, easy to use and reliable (Sadeghi *et al.*, submitted). It enables easy recognition of foot morphology and tracking of its progress. Our study showed that a quantitative evaluation using this system can help distinguish a pathological foot from a healthy foot in 79% of cases without the need for input from a specialist. The goal here is not to replace specialists, but rather to help them make a better diagnosis using a computer.

The Bioviozion® system could be a relevant tool in a clinical setting, since it could also be used to build a database on all types of feet, healthy and pathological. Accordingly, these tools could help evaluators in a clinical setting, and also help researchers in the field by providing them with a system of standardized measurements and a growing database on foot pathologies, as suggested by Razeghi and Batt (2002).

4.6 Possible follow-ups to this study

This study could be pursued in different ways, since the use of the Bioviozion® system appears highly promising in the field of podiatry. A first follow-up could consist in adding one or several other pathologies to the model to determine whether it can still distinguish healthy feet and whether it can identify each pathology.

Given the limited comparisons with the literature, another option could be to compare the measurements of angles obtained using the Bioviozion® system with those gathered from x-rays or goniometric measurements. This would enable comparison of the performance of the Bioviozion® system with that of other methods and to fully validate the system, whose reliability has already been shown by Sadeghi *et al.* (submitted).

Another study could propose the development of an additional examination protocol for symptomatic feet not diagnosed as such by the prediction model. Patients complaining of feet symptoms could be classified in the healthy feet group by the prediction model. In order to treat these patients, an additional evaluation would be needed to remedy the situation.

Another project could divide feet with pes cavus into categories according to height of the plantar arch and determine whether the different stages of the pathology could be distinguished. This could be useful for studying the progress of the pathology while enabling better classification of pes cavus. This would also enable better patient follow-up by the clinician.

Another project could add more subjects with pes cavus, then subdivide them according to secondary pathologies and determine whether the model developed (using the results gathered using the Bioviozion® system) is sensitive enough to detect them. Good sensitivity would enable tracking of the progress or severity of the pathology. This could also lead to more effective prescriptions for orthoses.

Lastly, based on the results of all these developments, a diagnostic assistance software could be added to the Bioviozion® system. Using appropriate statistical analyses such as those mentioned previously, or more extensive ones such as fuzzy logic and the relevant characteristic parameters of each pathology, this software could give clinicians an overview of the pathologies present and allow them to improve the quality of their evaluation. Clinicians could also make a diagnosis with more certainty, since the software could help them detect or confirm pathologies in patients' feet.

5. CONCLUSION

This study enabled identification of the angles (measured with the Bioviozion® system) which best characterize pes cavus, and the development of a model for predicting the presence of this pathology. Principal component analysis was used to achieve this objective, and the model developed was validated by Fisher and Kappa tests.

Analyses on all of the right and left feet of the control subjects and the pathological subjects showed that the subjects' feet were symmetrical. However, significant differences were noted for the two groups for the pronation angle and for the angle between MTP 2 and 5 with respect to the horizontal plane in plantar flexion. This was also the case for the angle of the line between the middle of the leg and the middle of the heel for the control group and the medial Meary-Tomeno angle for the group with pes cavus. Since these angles are not part of the clinical criteria for detecting pes cavus, they had no effect on development of the model or the prediction.

Initially, five angles were determined to be characteristic of pes cavus. First, in the anteroposterior plane, the angles between MTP 1 and 2 and between MTP 2 and 5 with respect to the horizontal plane, and the Meschan angle. These three angles describe the spacing between the metatarsals and indicate the enlargement of the forefoot due to an overload caused by a high plantar arch. Then, in the medial plane, the angle between the calcaneus and the foot fold with respect to the horizontal plane, and the Djian-Annonier angle. These two angles indicate the height of the plantar arch.

With these five angles, a principal component analysis was done to build a prediction model. To find the best possible model, the angles whose combinations yielded the best results during the classification of subjects into two groups were selected. Accordingly, four angles were sufficient to distinguish 81% of pathological subjects from control subjects. These angles are the angle of MTP 1 and 2 with respect to the horizontal plane, the angle of MTP 2 and 5 with respect to the horizontal plane, the Meschan angle and the Djian-Annonier angle.

Lastly, the performance of the prediction model was evaluated. It was possible to predict the reference group of over 87% of subjects; the reference group proportions were preserved and the subjects were classified correctly according to their original group.

These results are conclusive. Accordingly, the model developed in this study could become a good diagnostic tool for foot specialists. Using the measurements gathered with the Bioviozion® system, it enabled detection of the presence or absence of a foot pathology.

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