Quebec Cooperative Study
of Friedreich's Ataxia

Kinematics of the Foot

P. ALLARD, P.S. THIRY, M. DUHAIME, G. GEOFFROY

SUMMARY: *Orthogonal stereoradiographs are frequently utilized in determining three-dimensional geometrical parameters of human body segments. They have been applied here in the estimation of the length and elongation of the ligaments of the normal foot. Three small spherical metallic markers were respectively encrusted into the tibia and fibula, the seven bones of the tarsus and into the five metatarsals of an amputed lower limb to identify uniquely their spatial location. The foot was then positioned on a rotating platform. Standardized antero-posterior and lateral radiographs were taken. Afterwards the foot was dissected and the proximal and distal insertions of most of its ligaments were located by means of spherical markers. A second series of orthogonal radiographs were taken of each of the fourteen bones. The radiographs were digitized. The length of each ligament and elongation for a simple and complex movements were calculated by means of a computer program. The results of a simple movement of rotation representing a normal 20⁰ dorsiflexion at the talocrural joint and of complex movements of rotation simulating an abnormal high arch such as encountered in Friedreich's ataxia are presented and discussed.*

RÉSUMÉ: *Des techniques de stéréoradiographies orthogonales sont souvent utilisées pour déterminer les paramètres géométriques tridimensionnels des segments du corps. Dans cette étude une telle technique a été appliquée pour estimer la longueur et l'allongement des ligaments de pieds normaux. Trois repères métalliques ont été incrustés respectivement dans le tibia et le péroné, dans les sept os du tarse et dans les cinq metatarsiens d'une jambe amputée pour identifier de manière univoque leurs positions. Le pied a été situé sur une plateforme tournante afin d'effectuer des prises de radiographies normalisées en position antéro-postérieure et latérale. La dissection du pied a été complétée et les insertions proximales et distales de ses ligaments ont été identifiées à l'aide de repères métalliques. Pour chacun des quatorze os, une seconde série de radiographies orthogonales a été effectuée. Les radiographies ont été digitalisées. La longueur des ligaments ainsi que leur allongement respectif associé a des mouvements de rotation simples et composés ont été calculés à l'aide d'un programme d'ordinateur. Les résultats de mouvements simples représentant une dorsiflexion normale de 20⁰ à la cheville et de mouvements composés simulant une hausse exagérée de la voûte plantaire telle qu'observée dans l'ataxie de Friedreich sont présentés et discutés.*

From the Pediatric Research Center, Sainte-Justine Hospital and the Department of Mechanical Engineering, Ecole Polytechnique de Montréal.

Reprint Requests for the complete supplement (Phase Three, Part Two) to: Prof. André Barbeau, Clinical Research Institute of Montreal, 110 Pine Avenue West, Montréal, Quebec, Canada, H2W 1R7.

INTRODUCTION

The human foot is a complex functional unit consisting of over a hundred ligaments and thirty muscles attached to twenty-six irregular shaped bones. This arrangement of bones, muscles and ligaments maintains the stability of the foot. During gait, the foot provides the required propulsion (Napier, 1957; Wells and Luttgens, 1978), limits the vertical oscillation of the center of mass (Morris, 1977), absorbs the impact loads during heel-strike and adapts itself to compensate for the various types of ground surface. The ease with which the foot can adapt itself to different situations is well illustrated by its flexibility during heel-strike and its rigidity during heel-off (Sethi, 1977). Between these two extremes, the foot compels itself to various loading conditions according to the ground surface. Furthermore, sprains, foot ailments and neuromuscular disorders drastically interfere with the normal existing interaction between muscles and ligaments.

In North America, the use of different types of shoes may be associated with various foot problems. According to Sammarco (1980) a greater understanding of the biomechanical interaction between the foot and shoe will permit a better management of foot ailments such as bunions.

Foot deformities associated with neuromuscular disorders may also largely benefit from a better understanding of its biomechanics (Allard et al. 1981; Sibille et al. 1981). The application of a biomechanical model to the normal foot may better explain the specific contribution of the ligaments in the cavus foot deformity. With such a model, the osseous and ligamentous components of the foot can be mathematically moved about to simulate different abnormal foot configurations.

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The effects of such imposed displacements on the foot stability may then be analytically studied. To better understand foot deformities associated with neuromuscular diseases, a biomechanical model of the foot is being developed.

Several foot models exist but too often, they are limited to some specific articulations and seldom include the ligamentous structures. Zitzlsperger (1960) presented a first attempt at a geometrical bony reconstruction model of the foot where the spatial coordinates of the articular surfaces were experimentally determined. Moller (1977) carried out an analytical study to establish the moment arms of the triceps surae and showed that the foot behaves as a two speed construction. Stokes et al. (1979) determined, during gait, the applied forces at the metatarso-phalangial joints by means of a bi-dimensional model of the toes.

Bi-planar radiographic methods have been extensively utilised to obtain quantitative anthropometric data for various anatomical structures. McNeice et al. (1975) computed tri-dimensional geometric parameters of the spine from bi-planar radiographs obtained by rotation of the patient in front of a fixed X-ray source. Youm and Yoon (1979) utilised bi-planar radiography in their analytical development of wrist kinematics. In their case, the X-ray source was rotated around an immobilised wrist.

This paper presents a "ligamentous" biomechanical model of the foot. The objectives of the present study are to determine the relative importance of the ligaments in maintaining foot stability. In particular to:

a) determine the location of the ligaments' insertion in the foot,
b) calculate the length of the ligaments,
c) compute the elongation of the ligaments for a given movement of rotation and
d) carry out, as an initial attempt, a simulation of an abnormal condition such as observed in pes cavus.

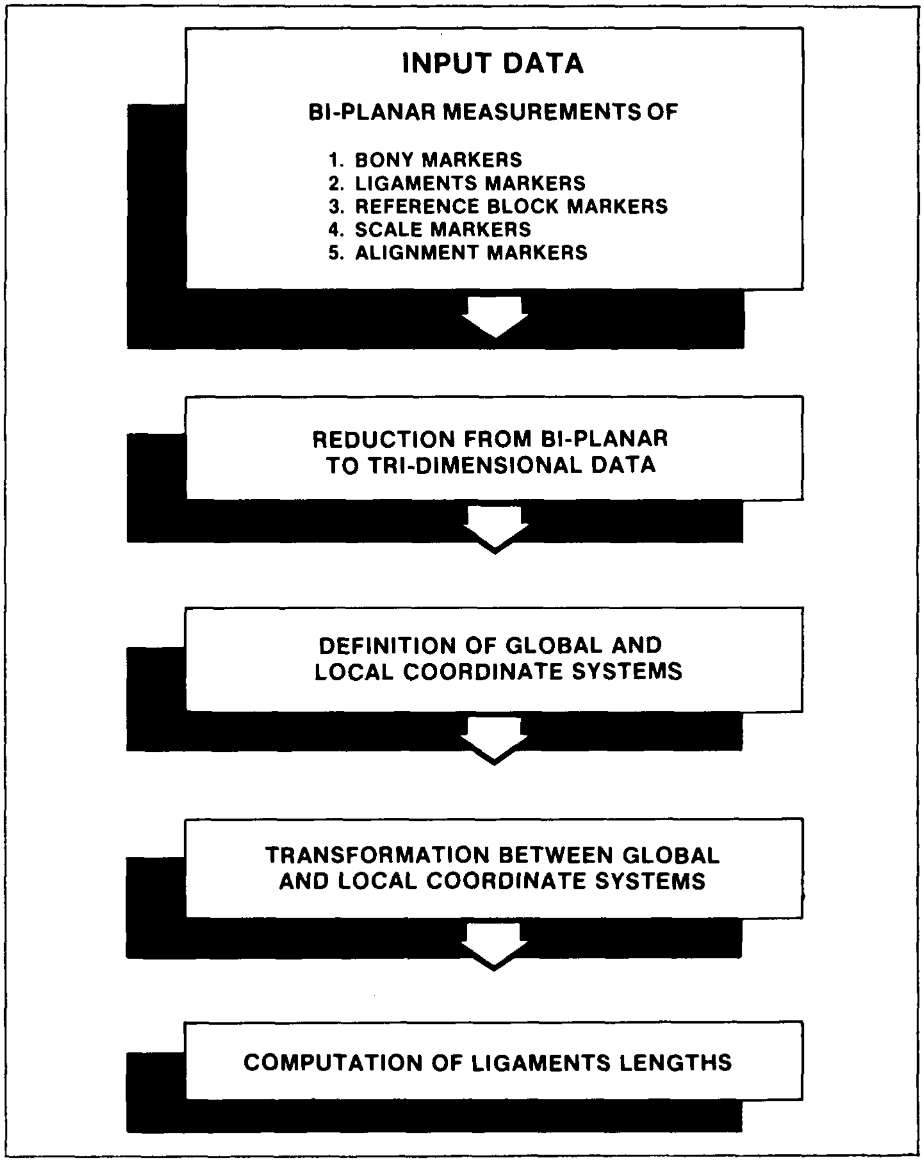

Figure 1 — Schematic outline illustrating the various experimental and analytical steps involved in the development of the biomechanical model of the foot.

ELEMENTS OF THE MODEL

The proposed mathematical model has to be flexible enough to conform itself with the available and newly acquired data on the biomechanics of the foot. In its current state, the model consists of seventy-five osseous and ligamentous elements. The four articular capsules respectively surrounding the talocrural, subtalar, talocalcaneonavicular and the calcaneocuboid articulations have not been included in the present model. The fourteen osseous elements consist of the tibia and the fibula as well as all of the bony structures of the foot excluding those of the toes. For the time being, the phalanges are not considered since they have already been exhaustively studied by Stokes et al. (1978, 1979).

Sixty ligaments are attached to the bony structure. Four of which namely, the deltoid, the long plantar ligament, the bifurcated ligament and the transverse metatarsal ligament have several distal fibers. The plantar fascia which is also included in the ligamentous structure has five distal fibers. In all, the ligamentous elements consisted of sixty-one proximal fibers and seventy-four distal fibers.

METHODOLOGY

Figure 1 schematically illustrates the interaction between the input data, the

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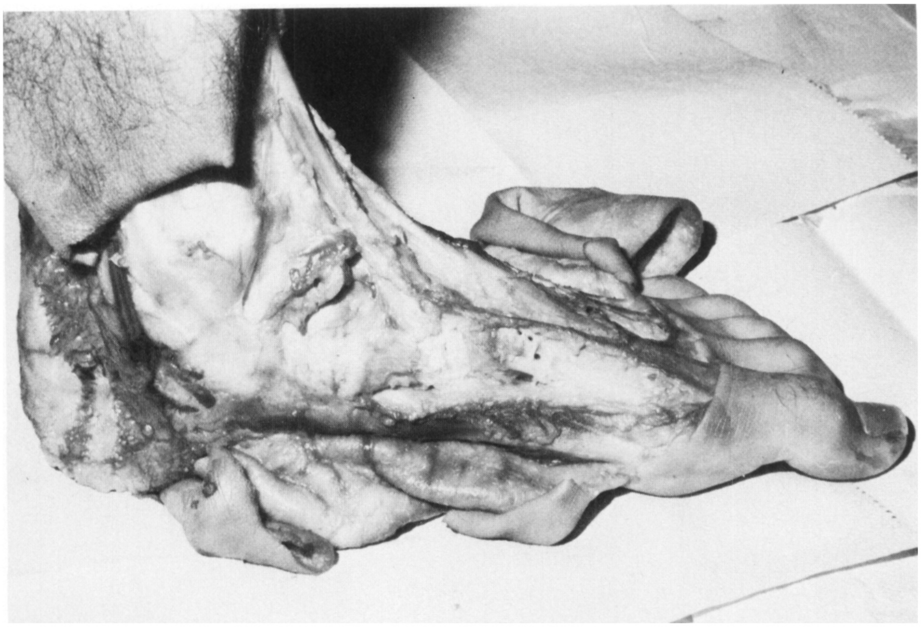

Figure 2 — Partially dissected foot illustrating the three spherical markers encrusted into the first metatarsal.

model and the anticipated results from the mathematical simulation. The methodology used in the development of the biomechanical model of the foot can be divided into two parts. The first part consists of the experimental input data quantitatively describing the spatial location of the bones, ligamentous insertion sites and the fixed axes of rotation. The second part consists of the analytical elaboration of the model which can simulate the kinematics of the normal human foot.

1. *Data Collection*

The methodology used in the anthropometric data collection was inspired in part by that of Youm and Yoon (1979). Their technique consists of arbitrarily encrusting three metallic markers into each bones of the hand to uniquely identify its spatial location. These markers were also utilised to define for each bone, its coordinate reference system. This technique eliminates the errors associated with the coordinate reference systems defined by means of anatomical landmarks such as those presented for the hand by Chao et al. (1976) and Toft and Berme (1980).

A radiographic technique was utilised to determine the spatial location of the ligamentous insertion sites, of the bones and those of the fixed axes of rotation defined after Hicks (1952). In particular, the standardized orthogonal stereographic technique described by McNeice et al. (1975) was selected. Such a method has been in use for over four years at Sainte-Justine Hospital in a tri-dimensional geometric study of spinal deformities (Allard et al. 1980). Furthermore, various experimental and analytical studies on the validation of this technique have been carried out by our group (Dansereau et al., 1982).

The methodology used by Youm and Yoon (1979) has been modified and adapted in an original and innovative manner in order to obtain the location of the interosseous ligaments insertion sites without disturbing the geometrical spatial relationship of the bones. This analytical technique of reconstruction is herewith described.

Three lower limbs amputated at mid-shank were utilised in this study. The specimens were frozen for conservation purpose. After thawing at room temperature for twelve hours, each foot was superficially dissected to expose the lower third of the tibia and the fibula, the seven bones composing the tarsus and the five metatarsals. Three 0,79 mm diameter spherical markers were encrusted into each bony structure, as illustrated in Fig. 2 for the first metatarsal, to uniquely identify its spatial location. Antero-posterior and lateral radiographs were taken utilising a method similar to that of McNeice et al. (1975). Afterwards the foot was methodically and systematically dissected to locate the insertion sites of most of its ligaments. The procedure consisted for each ligament, in locating its insertion by encrusting in the site a spherical marker identified by a color-coded pin. The fourteen detached bones were again put on the rotating platform as illustrated in Fig. 4, for another set of orthogonal radiographs. Finally the precise loca-

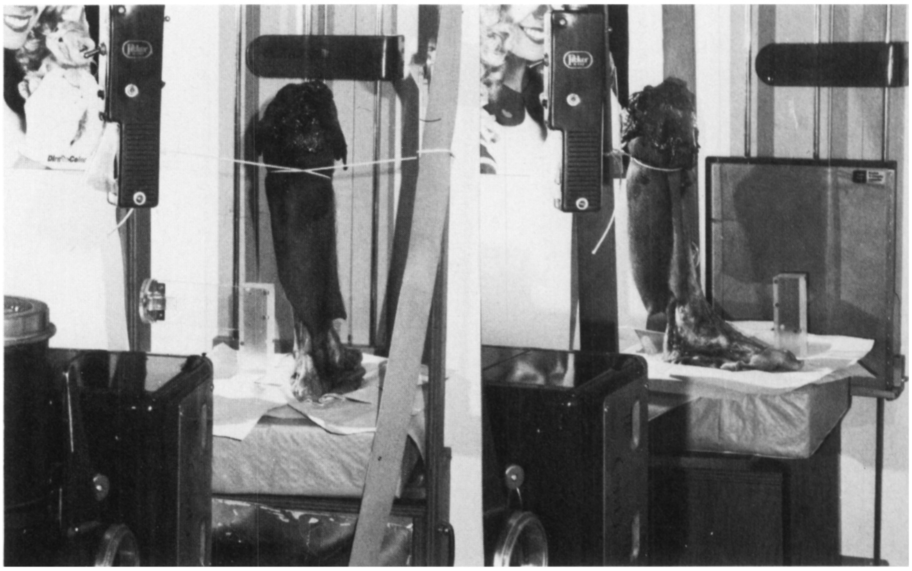

Figure 3 — Lower limb on the rotating platform for (A) antero-posterior and (B) lateral normalized radiographs.

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tion of the markers on both sets of the radiographs were carefully recorded with an X-Y digitizer. On the foot radiographs, seven fixed axes of rotation defined after Hicks (1952) were located. These axes are the:

a) ankle dorsiflexion,
b) ankle plantar flexion,
c) talonavicular-cuboid,
d) oblique metatarsal,
e) first ray and
f) fifth ray.

2. *Mathematical Model*

The mathematical manipulations, shown in Fig. 1, required for the reduction of the experimental anthropometric data into absolute tri-dimensional data consist of two steps: reduction from bi-planar to tri-dimensional data and transformation between the local and global coordinate reference systems.

In the first step, for each pair of radiographs, the image of several markers (ligaments, bones, scales etc.) are reduced from bi-planar to tri-dimensional data by means of equations relevant to plane geometry. The coordinates determined by this method are in the global reference systems of the *detached* bones and of the whole foot (*attached* bones).

In the second step, the coordinate reference systems associated to the attached and detached bone radiographs are first defined. Figure 5 illustrates for the cuboid, the spatial position of the bony markers, A, B and C. The attached global coordinate system (AGCS) of the foot X-ray is arbitrarily defined and located on the bi-planar radiographs. The attached local coordinate system (ALCS) is located at the centroid, G, of the triangle ABC. The axes of the ALCS have been defined after Youm and Yoon (1979) and where the Z axis is defined by the unit vector, $\vec{k}$, normal to the triangle ABC. The X axis is defined by the unit vector, $\vec{i}$,

$$\vec{i} = (\vec{BC} - \vec{AB} + \vec{D}) / [\vec{BC} - \vec{AB} + \vec{D}],$$

where $\vec{D}$ is defined as a vector lying on triangle ABC perpendicular to $\vec{AC}$ and of the same magnitude as $\vec{AC}$. The Y axis is the result from the vector product of $\vec{k} \times \vec{i}$.

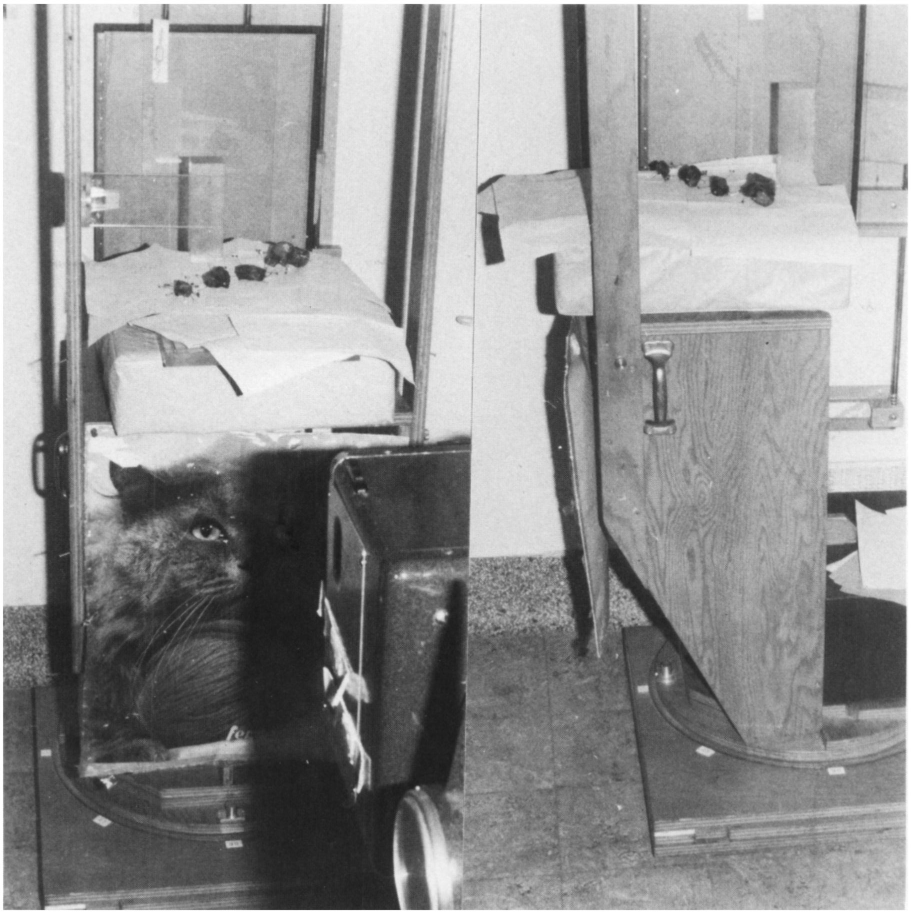

Figure 4 — Detached bones on the rotating platform for orthogonal radiographs.

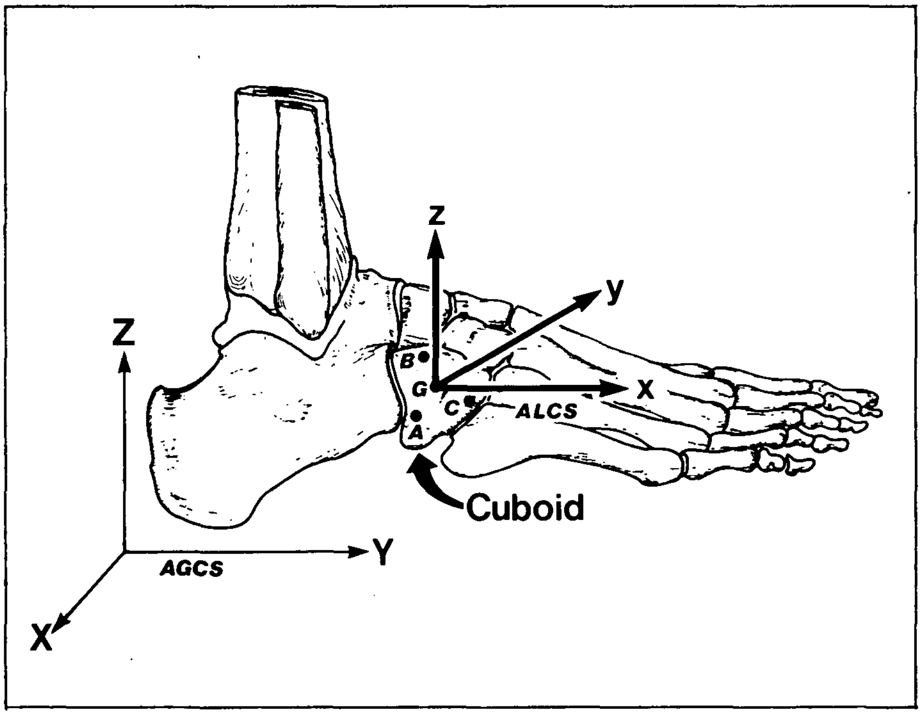

Figure 5 — Schematic representation of the foot illustrating for the cuboid the global and the local attached coordinate systems.

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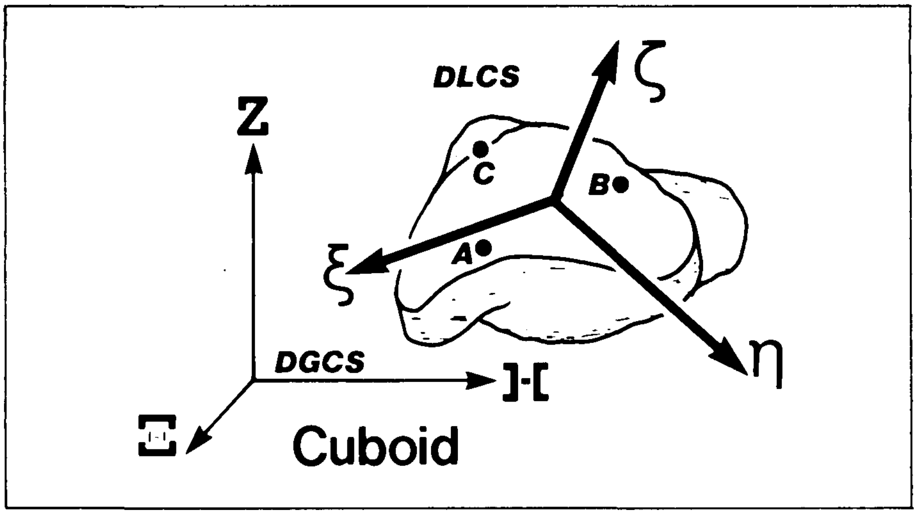

Figure 6 — Schematic representation of the cuboid illustrating the global and the local detached coordinate systems.

Figure 6 illustrates the cuboid once it has been removed from the foot. Again the detached global coordinate system (DGCS) and the detached local coordinate system (DLCS) are defined as in the attached coordinate systems. Transformation matrices between the detached and the attached coordinate systems allow reconstruction of the spatial position of each ligament and bony markers in the attached foot.

A computer program was written to calculate the length of the ligaments of the foot from the digitized radiographs. A simulation program was developed to compute the length variation due to an arbitrary rotation of 0 degrees about a fixed axis of rotation. The coordinates, after rotation, were calculated from three equations related to solid geometry (Allard et al., 1982)m

SIMULATION

The purpose of the simulation program was to determine the influence and importance of the ligaments in maintaining foot stability. The program consisted of imposed movements about one or several fixed axes of rotation. It was of two types.

The first type consisted of simple movements of maximal amplitude, about a fixed axis of rotation, from the foot's neutral position. As an example of a normal condition, a simulation was carried out for a dorsiflexion of 20^0 about the ankle joint.

The second type of simulation represented an attempt to characterize the behaviour of the ligaments for an abnormal condition representing a cavus foot deformity. This condition was achieved by systematically and successively carrying out the following complex movements of rotation about the following five fixed axes:

10^0 of supination about the talonavicular-cuboid axis,
7^0 of supination about the oblique metatarsal axis,
3^0 of supination about the antero-posterior metatarsal axis,
7^0 of extension about the first ray axis and
4^0 of plantar flexion about the fifth ray axis.

For both types of simulation the computer program calculated the length and elongation of the ligaments respectively involved in the solicitated joints.

RESULTS AND DISCUSSION

The analytical results obtained from the tri-dimensional geometric reconstruction and from the simulation of the biomechanical model of the foot are presented and discussed in this section.

From the absolute coordinates obtained from the analytical reconstruction, the length of the ligaments was estimated as the linear distance between their insertion sites. For some ligaments, Table I presents the computed values as well as those measured or reported in the literature for the same ligaments. The computed length values are respectively comparable to those measured experimentally.

Before presenting the results of the simulation, the problem associated to the measurement of the ligament initial length must be discussed. Each ligament has a length corresponding to its initial unstressed state (zero applied force). This length, called the initial length, needs to be known to calculate the elongation of the ligaments. The measurement of the initial length is a most complex problem which can only be resolved by an extensive experimen-

TABLE I

LIGAMENT LENGTH

	Calculated Length (mm)	Measured Length (mm)
Deltoid		
- tibionavicular fibers	28	22
Anterior talofibular	23	21
Posterior talofibular	53	47†
Dorsal calcaneocuboid	24	16
Tarso-metatarsal (cuboid - IV M)	15	14
Plantar fascia	147	150*

† Sosna and Sosna (1977)
* Lapidus (1943)

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tal study on the mechanical behaviour of each ligaments in the foot. A simplifying assumption such as, the initial length is equal to the minimum calculated length that the ligament can assume for a given movement, may be made. A simulation based on this hypothesis has been carried out and excessive elongations of over 200% have been observed. More reasonable values of elongations have been obtained by selecting as the initial length, the length of the ligament corresponding to the foot's neutral position.

The results obtained from the simulation are divided into two groups: simple and complex movements of rotation.

1. *Results of Simple Movements of Rotation*

Table II presents the results obtained after a simulation of a simple movement about the talocrural joint representing a normal 20^0 dorsiflexion of the foot. Only the deep fibers of the deltoid ligament have been solicited. The contribution of the other ligaments, during such a movement, did not seem significant.

For the deltoid ligament, the *anterior talotibial* fibers were slightly stretched (less than 1%) throughout the dorsiflexion. However, the *posterior talotibial* fibers were lengthened by 2,4 mm (3,7%). This lengthening is the greatest observed; therefore, the action of these fibers seems very important in maintaining the stability of the talocrural joint during a movement of dorsiflexion. The *tibionavicular and calcaneotibial* fibers were relatively stable during the imposed movements of simulation. They seem to slightly retract by 0,2 mm and 0,7 mm respectively.

The *anterior talofibular ligament, calcaneofibular ligament* and the *posterior talofibular ligament* do not participate in maintaining the foot's stability during the dorsiflexion.

TABLE II

LIGAMENT LENGTH AND ELONGATION AT THE TALOCRURAL JOINT FOR A 20 DEGREE DORSI-FLEXION

	Minimum Length (mm)	**Maximum Length (mm)**	**Elongation**	
			(mm)	**(%)**
Ligaments				
Anterior talofibular	22.6	23.1	-0.50	-2.2
Calcaneofibular	20.4	21.1	-0.70	-3.3
Posterior talofibular	53.0	56.3	-3.3	-5.9
Deltoid				
posterior talotibial fibers	65.8	66.6	+0.8	+1.2
Anterior talotibial fibers	33.6	33.7	+0.1	+0.3
Tibionavicular fibers	28.2	28.4	-0.2	-0.7
Calcaneotibial fibers	20.4	21.1	-0.7	-3.4

2. *Results of Complex Movements of Rotation*

To illustrate the potential of the model, a complex movement involving five articulations has been carried out. This type of movement approximately corresponds to that of an abnormal high arch often encountered in Friedreich's ataxia. Thirty-three of the sixty-one considered ligaments in the model have been involved to obtain this abnormal configuration of the foot. Twenty ligaments have been slightly solicited (less than 20% elongation). A second group of ten ligaments have been stretched by more than 20%. In particular half of them are intrinsic to the tarsus. Their elongations are a consequence of the assumed position of the bones after rotation. For example, the *medial and posterior talocalcaneal ligaments* have been respectively elongated by 32% and 33%, illustrating a varus attitude. Respective elongations of 28% and 29% of the *dorsal calcaneocuboid ligament* and of the *calcaneonavicular ligament* represent a medial rotation of the cuboid and navicular with respect to the calcaneus.

The results obtained from the simulation of complex movements of rotation only illustrates an abnormal condition of the foot. The amplitude of rotation about each of the fixed axes have been arbitrarily selected. If a better quantitative description of the pathomechanics of cavus foot deformity was available, the computer program could be adapted to include that information. This information combined with the mathematical model of the foot may then provide a more accurate insight on the relative importance of the ligaments in the different evolution stages of pes cavus.

In this initial model, the muscular elements have not been considered. These elements are very complex and important in the overall biomechanics of the foot. They should be included in a future development of this biomechanical model of the foot.

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