SUMMARY

In Chapter 1, the purpose of the study is defined: to give an optimally exact description of the movements of the tarsal bones that take place during certain, optimally defined movements of the foot, the description to be of a qualitative as well as of a quantitative nature.

The investigation consisted of two main parts. First, an X-ray photogrammetric determination of the positions of the marked tarsal bones of 10 foot-lower leg preparations during movement in a number of steps, and second, a computation of the helical axes of the tarsal movements. A brief discussion is offered of general kinematic principles such as the conceptions of instantaneous and discrete helical axes, the Reuleaux analysis and the mobile rotation axis.
A survey of definitions of motions as found in the main anatomical textbooks shows that authors have defined identical kinematic conceptions in different ways.
In addition it emerges that a term such as Fick's Kompromiss Achse with the passage of years has been applied by different authors in different ways and that its meaning has changed.

In Chapter 2, the literature is discussed.
Reference is made to classical, more or less emperical methods of determination for axes of revolution that were subsequently interpreted as axes of rotation. Bidimensional analyses (determination of instant centres), such as have been performed for numerous articulations (Groh, 1953; Frankl, 1970; Menschik, 1974; Nietert, 1977; Soudain, 1979 and Panjabi, 1979), even when suitable at all for an exact analysis of the joint, can certainly not be performed to any good purpose for the movements of the tarsal joints.
No mention is made in the literature of any earlier applications of a threedimensional computation method to the tarsal movement.

Chapter 3 describes the principle of X-ray photogrammetry and the method of investigation. In our experimental set-up, X-ray photogrammetry was used to compute the spatial positions, in a number of successive phases of movement of

the lower leg and of four tarsal bones (talus, calcaneus, navicular and cuboid), all of them marked by means of marking balls. The foot-lower leg preparation was placed in a special experimental cage. The preparation was then made to perform a movement subdivided into steps; after every step, X-ray films were made in two projections. With the aid of a comparator, the various projections of the marking balls in the X-ray films were measured. The methods of computing the helical movement from the spatial coordinates of the tarsal balls is based on the method described by Spoor and Veldpaus (1977). From rotation matrices we computed the direction of the rotation axis, the rotation angle and the direction of rotation, and from the translation vectors, the position of the rotation axes and the translations along these axes.

Chapter 4 describes the study material used, the 10 foot-lower leg preparations with marking balls and the experimental set-up. A special test cage was designed in which rotations were transferred to the tibia without opting for one fixed, immobile rotation axis.

In Chapter 5, the various experimental procedures are discussed. They are successively: 1) the computation of the position of the X-ray sources; 2) the marking of the bones; 3) the performance of the experiment with the foot-lower leg preparation in the test cage; 4) measuring of distances in the X-ray films with the comparator. An essential element of an investigation of this nature is a thorough analysis of errors. This subject is dealt with in two chapters, 6 and 7.

In Chapter 6, a detailed X-ray photogrammetric error analysis is presented. The various sources of errors are listed one by one. The third part of this chapter deals with the analysis of errors that has been carried out with the aid of two specially developed calibration objects, viz. the HMTA and the measuring plate.
Critaria of the accuracy of the method were established. It was concluded from the HMTA computations that the distance of the measuring balls from the origin did not affect the accuracy of the computed Z coordinates of the balls. It exerted only a very slight influence on the accuracy of the determination of the position of the balls and a slight influence on the fixed distances of the measuring balls of the HMTA from each other.
Mean error in the computed distance HMTA balls ranged from 0.6‰ to 2.2‰ (average 1 to 1.5‰).

Chapter 7 contains a detailed analysis of errors in the computation of the helical movement. The effect of the errors of the X-ray photogrammetric data, and the influence of the magnitude of the rotation on the computed helical movement have been studied in two ways: first, by means of the HMTA (Chapter 7.1) and second, with the aid of a computation model into which a known error was introduced (Chapter 7.2). The HMTA analysis showed that with 5° of rotation, the error of the direction of the rotation axis φ amounted to less than 1°. The error of the rotation angle α was of the order of magnitude of 0.1° and the error of the translation t on the average less than 0.05 mm. It was found that by increasing the

rotation to 10°, no greater accuracy was achieved in the determination of the direction φ, the angle α and the translation t.
With the aid of the scattered error analysis, using a computation model, the maximal and the main error of the rotation axis were determined for the various nominal rotation angles. Application to the HMTA showed that a variation of the accuracy of the computation of the position of the balls had to be expected that ranged from a minimum of 0.01 mm to a maximum of 0.015 mm. In regard to application to foot-lower leg preparations, the maximal and the mean axial deviations were computed for rotations of 1.5°, 3°, 4°, 5°, 7.5°, 10° and 15°. For a rotation of 5°, the maximal axial deviation ranged from 1.8° to 2.6° with an average of 1.0 to 1.5°.
These computations proved that for a step size of 10°, with omission of phase 1, a rotation exceeding 5° with a mean axial deviation ranging from 1.0° to 1.5° was found in 81.4%, while only the remaining 18.6° showed a rotation between 3° and 5° with a mean axial deviation of approx 2°.

Chapter 8 deals with the testing of the reproducibility of the tarsal helical movements. Good reproducibility of the tarsal helical movement for 10° step size with omission of phase 1 was found.

Chapter 9 is concerned with the computed parameters of the tarsal helical movements. The computed movements are the absolute discrete helical movements; these are the helical movements in relation to the fixed system of coordinates with origin 0 in the cage, for the tibia (TI), the talus (TA), the calcaneus (CA), the navicular (NA) and the cuboid (CU). We also computed the relative tarsal helical movements (i.e. the helical movements of one tarsal bone in relation to another, from which information may be obtained concerning the movements in the joint).
Computed movements are the helical movements of the talus in relation to the calcaneus (subtalar movements) (TACA), of the talus in relation to the navicular (TANA), of the talus in relation to the tibia (TATI), of the navicular in relation to the calcaneus (NACA), of the navicular in relation to the cuboid (NACU) and finally, of the cuboid in relation to the calcaneus (CUCA).
Both the absolute and the relative movements were computed for a step size of 10° and for the total movement.
For each helical axis of a tarsal bone the following parameters were computed: 1) the position of the helical axis (axis of points of intersection with the XY, XZ and YZ planes); 2) the direction of the helical axes (the angle φ of the axis with the XY plane, called the inclination angle and the angle π of the projection of the axis in the plane with the XZ plane, called deviation angle); 3) the rotation angle α and the direction of rotation of the bone around the helical axis; 4) the translation t and the direction of the translation of the bone along the helical axis.
We further computed the paths of the points of intersection of helical axes with planes through the tarsus. Bundles of axes are characterized by the bundle width in which R π and R φ represent the differences between extreme values of π and

φ, respectively, and $\Sigma\gamma$ the sum of the angles between the successive axes. The direction of the bundle is characterized by the mean values of the deviation angle ($\bar{\pi}$) and the inclination angle ($\bar{\varphi}$). The method of conversion of π and φ for the bundle axes is discussed.

Chapter 10 deals with the helical movements for the absolute tarsal bones and tibia as obtained by our own investigations.

1. The directions and postions of the absolute tarsal and tibial axes
For the tarsal bones and tibia, we each time computed different bundles of axes of rotation containing rotation axes with different directions.

The axes for the tibia and the talus are very steeply vertical, largely outside the distal tibia c.q. talus (range $\bar{\varphi}$ TI 10°: 82.9° to 87.6°, range $\bar{\varphi}$ TA 10°: 60.3° to 87.5°). The bundle width R φ for the tibia was noticeably smaller than that for the talus (range R φ TI 10°: 0.8° to 10.1° and range R φ TA: 9.1° to 61.7°).
It was interesting to note the difference in deviation angles between the tibia and the talus, $\bar{\pi}$ TI 10° <45° and $\bar{\pi}$ TA 10° >45°. The bundle width R π was large for tibia and talus both; however, that of the tibia was smaller that that for the talus (range R π TI 10°: 8.4° to 98.4°, range R π TA 10°: 22.6° to 239.6°).
In other words, the tibial axial bundle is narrower and situated more closely to the sagittal plane than the talar bundle which is wider and deviates more from the sagittal plane. The patterns of the points of intersection of the TI and TA helical axes with the basal plane were found to differ.

- The bundle of axes for the calcaneus passes obliquely through the inferoposterior part of the calcaneal tubercle, with a direction from anteroinferior to posterosuperior (range $\bar{\varphi}$ CA 10°: -25.6° to -60°), the deviation angle in all cases exceeded 135° (range $\bar{\pi}$ CA 10°: -22.7° to 5.5°). The calcaneal bundle is fairly narrow (range R π CA 10°: 4.1° to 21.1°, range R φ CA 10°: 8.5° to 40.1°).

For the cuboid and the navicular we always computed approximately horizontal bundles of axes, situated largely outside the bones (range $\bar{\varphi}$ CU 10°: -0.9° to - 15.2°, range $\bar{\varphi}$ NA 10°: -17.9° to 16.2°).
The bundle widths R φ for the cuboid and the navicular were approximately equal (range R φ CU 10°: 1.9° to 25.8°, range R φ NA 10°: 4.7° to 34.1°). The deviation angles of the axes for the two bones were smaller than 45° (range $\bar{\pi}$ NA 10°: -23.9° to -2.2°, range $\bar{\pi}$ CU 10°: -0.9° to 15.2°). The bundles for both the cuboid and the navicular were narrow (range R π CU 10°: 1.6° to 8.8°, range R π NA 10°: 2.8° to 15.3°).

For the total range data, TI 30°/35°, TA 30°/35°, CA 30°/35°, CU 30°/35° and NA 30°/35°, the five respective total range axes of the tarsal bones and the tibia were in agree with the stepsize data.

2. Rotation angles α and directions of rotations for the helical movements of the tibia and tarsal bones.

Because the absolute rotation axes of the linked parts of the chain may differ in position from each other, rotations and translations of linked parts of the chain may differ in extent.

- The tibial rotation ranged from 8.5° to 10.5°, the talar rotation from 6.0° to 9.4°. Interestingly, in 27 of the 47 phases, the rotation computed for the talus exceeded that computed for the tibia. This talotibial rotation surplus ranged from 0.3° to 3.9°; mean 1.4°.
For the first phase transition 0-10° exorotation, talar rotation was always found to lag behind tibial rotation (talotibial rotation deficit).
The tibial movement is almost exclusively one of exorotation, the talar movement is a *combined* abduction-eversion-extension movement, in which the abduction is largest and the extension, smallest.

- Calcaneal rotation ranged from 3.3° to 11.5°. The movement is a combined one of inversion, abduction and extension; in a few specimens (nrs 2, 4 and 7) there was a combined inversion-abduction-flexion movement. Here, the extension or flexion component is smallest.

- The cuboid rotation ranged from 4.3° to 16.5°, the navicular rotation from 5.4° to 18.6°. The movements of both bones are combinations of inversion, abduction and extension, the inversion component being the largest.

- It appears from the mean rotations ($\overline{\alpha}$) for the *first* phase for all 10 specimens, that the sequence of magnitude has always been: TI, TA, NA, CU, CA.
From the mean rotation ($\overline{\alpha}$) per phase for all 10 specimens (without phase 1) there also emerges a sequence of magnitude: the absolute tibial rotation $\overline{\alpha}$ TI 10° in all phases is found to be approx one and a half times as large as the absolute calcaneal rotation $\overline{\alpha}$ CA 10°; the absolute cuboid rotation $\overline{\alpha}$ CU 10° occupies an intermediate position between TI and CA. The mean talar rotations $\overline{\alpha}$ TA 10° slightly exceeds the mean tibial rotation $\overline{\alpha}$ TI 10°.
Deserving of notice were the high mean values of the absolute navicular rotation $\overline{\alpha}$ NA 10° from phase 3, higher than any other tarsal and tibial rotations. There are distinct interindividual differences. The rotations for stepsize 30°/35°, total range data,exhibited a similar sequence of magnitude as the step size data.

3. The translations and directions of translation of the tibia ranged from -0.7 mm (in the downward direction) to 1.6 mm (in the upward direction); for the talus, the translation ranged from 0.5 mm towards the origin to 1.0 mm away the origin; in most cases, 39 out of 47 phases, the talus moved in the posterior direction.

- The calcaneal translations ranged from 0.2 mm towards the origin to 0.5 mm away from the origin. In nearly all phases, the calcaneus translated in the anterior direction. The navicular translations ranged from 1.6 mm towards the origin to 0.07 mm away from the origin. In nearly all phases, the navicular translated in the posterior direction. The cuboid translations ranged from 1.1 mm towards the

origin to 0.6 mm away from the origin. The cuboid, also, in nearly all phases translated in the posterior direction.
During the supination movement, started by tibial laterorotation, the tibia in most specimens moved in an upward direction, the talus, navicular and cuboid translated in a posterior direction and the calcaneus translated in the anterior direction. Accordingly, this is not a 'close packed position', because we prefer to reserve that term for the situation in which the articulations are in maximal contact, whereas with increasing supination this contact is steadily decreasing. The translation data for the 30°/35° stepsize were in agreement with the step size data.

In Chapter 11, the findings for the relative tarsal movements are discussed, while for each individual joint, reference is also made to data from the literature.

1. The directions of the relative tarsal rotation axes
For the relative tarsal movements we constantly computed different bundles of rotation axes, containing axes with different direction. There was definitely no question of a 'functional hinge joint'.

- The relative talotibial axes in the bundle (TATI) cross in the region of the talar neck and have a noticeably transverse orientation (range $\overline{\pi}$ TATI 10°: -102.0° to 107.5; irrespective of the sign, the lowest value of π TATI 10° was 56.7°).
In 8 specimens, the direction of the axis was horizontal while in 2 specimens (nrs 7 and 9) it was not (range $\overline{\varphi}$ TATI 10°: -4.6° to 66.4°).
The width of the TATI bundle varied considerably (range R π TATI 10°: 2.7° to 142.0°, range R φ TATI 10°: 9.7° to 152.5°). The rotation axis found in phase 1 (transition 0-10°) was markedly steeper than that found in the other phases (range φ 34.5° to 86.5°; mean 65.5°), consistent with a lagging behind of the talus during tibial rotation.

- The relative talocalcaneal axes in the bundle (TACA) cross in the region of the tarsal sinus and canal, run an oblique course and have a direction from antero-mediosuperior to posterolateroinferior. The deviation angle is always smaller than 45° (range $\overline{\pi}$ TACA 10°: 0.9° to 32.3°; range $\overline{\varphi}$ TACA 10°: 23.2° to 54.4°). The bundle of TACA axes is fairly narrow (range R π TACA 10°: 4.4° to 24.8°, range R φ TACA 10°: 2.8° to 26.3°).

The role of the various talocalcaneal ligaments is then considered. Earlier, Huson (1961) postulated a position of the TACA axes at the site of the short fibres of the interosseous talocalcaneal ligament. This study confirmed this assumption.
Computation of the path of points of intersection of the TACA axode with a horizontal plane through the tarsal canal revealed a characteristic pattern of displacement of the TACA axes from anterolateral at the site of the anterior oblique fibrous bundle of the interosseous talocalcaneal ligament to postero-medial at the site of the medial oblique fibrous bundle. In the dorsoplantar and sagittal projections, the TACA axes stand at approximately right angles to the

fibres of the interosseous talocalcaneal ligament, while in the frontal projection the direction of the axes is virtually identical to that of the fibres.

- The relative cuboid calcaneal axes in the bundle (CUCA) pass through the anteromedial and anteroproximal part of the cuboidcalcaneal articular surface where they cross at a short distance from each other. The directions of the axes are from anteromedio(latero)superior to posterolatero(medio)inferior. The CUCA axes make a small angle with the sagittal plane and are inclined at a markedly steep angle, unlike the axis described for the cuboidcalcaneal joint in the literature (range $\overline{\pi}$ CUCA 10°: -19.9° to 33.6°; range $\overline{\varphi}$ CUCA 10°: 43.2° to 72.1°). The bundle widths for the CUCA axes varied greatly (range R π CUCA 10°: 5.9° to 65.6°; range R φ CUCA 10°: 8.6° to 39.8°).

The role of the various cuboidcalcaneal ligaments is discussed. Huson (1961) presumed that the rotation axes were situated in the region of the short fibres of the plantar calcaneocuboid ligament and the calcaneocuboid slip of the bifurcate ligament. Computations of paths of intersection points for the CUCA axode with a vertical plane through the anterior calcaneal process reveal a characteristically narrow vertical strip with a pattern of displacement mostly in the Z direction. The displacement of the intersection points cannot simply be equated with an increase or decrease of φ only, because the axes may undergo displacement in the anteroposterior direction too.

- The relative naviculocalcaneal axes in the bundle (NACA) just as the CUCA axes pass through the anteromedial part of the cuboidcalcaneal articular surface, the axes having directions from anteriomedio(latero)superior to posterolatero(medio)inferior; the NACA bundle lies farther anterolaterally than the TACA bundle. The NACA axes, also, make a small angle with the sagittal plane and are inclined at a steep angle (range $\overline{\pi}$ NACA 10°: -16.0° to 22.6°, range $\overline{\varphi}$ NACA 10°: 17.9° to 59.7°). The bundle width varied greatly (range R π NACA 10°: 3° to 45.5°, range R φ NACA 10°: 16.4° to 50.0°).

The computations of the path of points of intersection for the NACA axode with a vertical plane through the anterior calcaneal process just as for CUCA reveal concentrations of axes; here, considerable variation in the Y direction is sometimes encountered.

- The relative talonavicular axes in the bundle (TANA) pass through the region of the talar neck and head, with directions from anteromedio(latero)superior to posterolatero(medio)inferior. The TANA axes make a sharp angle with the sagittal plane and run an oblique course (range $\overline{\pi}$ TANA 10°: 7.5° to 23.7°, range $\overline{\varphi}$ TANA 10°: 24.3° to 49.6°. The bundle of TANA axes is fairly narrow (range R π TANA 10°: 1.8° to 29.4°, range R φ TANA 10°: 6.3 φ to 31.9°).

Computations of the path of points of intersection of the TANA axode with a vertical plane revealed a noticeable concentration of TANA axes which cross at very short distances in the talar head. Interestingly, in view of the above the talonavicular joint may functionally be compared to a ball-and-socket joint, while the talar head, considering the directions of its curvatures, is quite *unlike a ball.*

The 30°/35° step size data were found to agree with the 10° stepsize data.

2. Rotation angles α and directions of rotations for the relative tarsal helical movements

- The talotibial rotations α TATI 10° ranged from 0.7° to 9.4°, in which connection it may be remarked that during supination of the foot, only a small tract of the talotibial rotation is involved. The direction of the rotation of the talus in relation to the tibia is mostly an extension.
In the first phase (see talar delay), on the other hand, an adduction is involved.
- The talocalcaneal (subtalar) rotations α TACA 10° ranged from 3.1° to 15.8°. The movement is one of combined abduction and eversion with a slight extension component.
- The cuboidcalcaneal rotations α CUCA 10° ranged from 3.1° to 8.2°. The movement is a combined one of adduction and inversion with a slight plantar-flexion component.
- The naviculocalcaneal rotations α NACA 10° ranged from 3° to 11.4°. The mean values were systematically higher than those for CUCA. Just as the CUCA rotation, the NACA rotation is a combination of adduction and inversion.
- The talonavicular rotations α TANA 10° ranged from 6.4° to 23.9°. Of all intertarsal rotations computed, the TANA rotations are largest. There is a clear correlation of the intertarsal rotations. The mean value of the TANA rotations very closely approximates the sum of the mean values of the TACA and NACA rotations (difference ranging from 2 to 8%). The TANA rotations consist in an eversion-abduction-extension movement.
- The cuboidnavicular rotations α CUNA 10° ranged from 0.3° to 5.9°. This amphiarthrosis has the smallest of all tarsal rotations computed. The CUNA movement is one of eversion; the transverse arch, as it were, was slightly flattened.

3. The translations t and directions of translation for the relative tarsal helical movements

- The talotibial translations t TATI 10° ranged from 0 mm to 0.2 mm; the talus in relation to the tibia translated in the medial direction. During the first phase (translation 0-10°), the talus translated slightly in the upward direction.
- The talocalcaneal translations t TACA 10° ranged from 0 mm to 2.1 mm; the talus in relation to the calcaneus translated in the posterolateral direction.
- The cuboidcalcaneal translations t CUCA 10° ranged from 0.1 mm to 1.8 mm; the cuboid in relation to the calcaneus translated in the posterior direction.
- The naviculocalcaneal translations t NACA 10° ranged from 0.0 mm to 1.0 mm; just as the cuboid, the navicular bone translated in relation to the calcaneus in the posterior direction.
- The talonavicular translations t TANA 10° ranged from 0 mm to 1.0 mm; the talus in relation to the navicular translated in the anterior direction.

The translations and directions of translations for the 30°/35° step size were in agreement with the 10° step size.

In Chapter 12 conclusions are drawn. Joint motion studies only give relevant information when a precise threedimensional calculating method has been used. For this purpose X-ray photogrammetry is a useful method. Movements take place around a moving rotation axis, of which the position is approximated by a bundle of discrete helical axes. There is no evidence to consider the respective tarsal joints as "complicatedly structured but functionally simple hinge joints." For the tarsal movements we always calculated bundles of helical axes, situated at characteristically places in the tarsus. A survey of all the different bundles of axes has been stated.
The tarsus has to be seen as a closed kinematic chain with rotations and translations around different mobile rotation axes.
From the analysis we learned that the rotations of an individual tarsal chain member as well as the intertarsal rotations can considerably exceed the (input) rotation of the tibia. There is a clear rank in magnitude for the mean intertarsal rotations with a constant relation among them.