CHAPTER I

INTRODUCTION

1.1 GENERAL INTRODUCTION

Even in recent literature, Morris (1977), Inman (1977) there are still controversial opinions to be found concerning the movements that take place in the subtalar joint and in Chopart's articulation. Typical of the current, still widely quoted view of articular movements is that expressed by Morris (1977), "from the viewpoint of descriptive anatomy the subtalar joint appears to be quite complicated, from the functional standpoint, however, the subtalar joint is a simple single axis joint which behaves like an oblique hinge". This view, which regards articular movements as simple rotations around a (fixed) rotation axis, is shared by Manter (1941), Hicks (1953), Elftman (1960), Wright et al (1964), Inman (1966 and 1977), Close (1967) and Lanz-Wachsmuth (1972).
Another view was held by Fick (1904), Virchow (1899) and Huson (1961). Huson in 1961 made an accurate qualitative analysis of the movements of the tarsal bones. He enlarged in detail on the difference between axes of motion and socalled axes of revolution; the existence of 'mobile axes of rotation' was already postulated by Huson on the basis of his analysis of the relationship between the geometry of the articular surfaces and the configuration of the ligaments. The question whether tarsal movements are actually pure hinge motions or not, can only be resolved by a very accurate determination of the axes of motion.

The starting point for this study is a description, as exact as possible, of the motions of the tarsal bones such as they take place during certain movements of the foot, described as accurately as possible. This description should be a qualitative as well as a quantitative one. Proceeding from Huson's study, we have formulated the following questions:

a) What positions in space do the tarsal bones successively occupy during a supinatory movement induced in a particular manner? What axes of motion may then be calculated for these absolute tarsal motions?
b) What positions in relation to each other do the tarsal bones successively occupy during supination? What axes of motion may subsequently be calculated for these relative tarsal movements, in particular for the

movements in the subtalar, the calcaneocuboid and the talonavicular articulation?

Regarding these absolute (see a) and relative (see b) helical axes, we then have to establish their position and direction: what are the directions of rotation and translation of the movements around and along these helical axes and what is the range of these rotations and translations?
It will be clear that in order to find answers to these questions, we had to develop a very accurate measuring apparatus and very exact measuring and computation methods.

For this investigation, an X-ray photogrammetric study was made of a series of 10 foot-lower leg preparations. An X-ray photogrammetric calculation method rendered it possible accurately to calculate the three-dimensional positions of the tarsal bones in eight or seven intermediate positions of the total movement. Huson (1961, 1973 and 1982) described the tarsus (talus, calcaneus, cuboid and navicular bones) as a spatial closed kinematic chain 'with constrained motion'. Exorotation of the tibia produces supination of the tarsus. In this supinatory movement, the calcaneus, cuboid and navicular bone simultaneously move in relation to the talus that is carried along by the tibia. Because in everyday life this movement takes place under weightbearing conditions, we have opted for a testing apparatus in which the movements of the preparation could be recorded while vertical pressure was being exerted on the leg.

In this testing apparatus, the tibia of the foot-lower leg preparation was rotated step by step around its 'longitudinal axis' in a cage specially designed for the purpose. After every step, X-ray photographs of the four above-named marked tarsal bones were made in two projections. Subsequently, from the data supplied by these X-ray photographs using an X-ray photogrammetric procedure, the spatial positions which these tarsal bones had reached at the end of every step were calculated. These spatial positions now being known, the steps between them could be described as helical movements with the aid of a calculation programme.

Accordingly, there are two main parts to the investigation conducted. Firstly, determination of the positions of the marked tarsal bones and secondly, a calculation of the helical axes for the tarsal movements.

1.2 GENERAL KINEMATIC PRINCIPLES

Since a number of terms will be used regularly in the following paragraphs, a concise explanation of these terms follows here.
All movements of rigid bodies can be described as successive helical movements. The helical movement we define as a particular combination of rotation and translation, in such a manner that the movement can be broken

down into a rotation around a screw axis and a translation along this screw axis. Parameters of this helical movement are then the direction and position of the screw axis and the rotation and direction of rotation around, and the translation and direction of translation along the screw axis. We distinguish instantaneous and discrete motions.
Instantaneous means: the infinitely small partial movement taking place at a particular moment of a continuous movement. Since a continuous movement consists of an infinite number of instantaneous partial movements, there are also an infinite number of instantaneous screw axes which together constitute a curved surface (the axode). It might also be defined as a mobile axis moving smoothly in the axode.
Discrete here means: corresponding to a finite (and measurable) rotation between two given moments of the continuous movement. A discrete helical movement describes the transition from the position of the first moment into that of the second moment. As the time required for the transition from one position to the other approaches zero, this discrete helical movement will approach the instantaneous movement.
For any given movement, these discrete helical axes will have different directions and positions; we may then speak of a number of discrete axes which together constitute a broken surface or that lie in a (discrete) bundle of axes. We might also speak of a mobile screw axis (rotation axis) which during the movement changes position according to a particular pattern. The concept of the mobile rotation axis may be elucidated by starting from a bi-dimensional situation with the aid of the socalled Reuleaux analysis. In Figure 1-1 we see a rectangle that has been moved over the flat surface from A to E and which has successively occupied the discrete positions A, B, C, D and E. Since in this example we are concerned with a movement in one plane, we speak of a rotation centre instead of a rotation axis.
For the transition from A to B, a discrete rotation centre may be determined as follows:
On the rectangle in position A, two random points P and Q are chosen, which are found back in position B as P' and Q'. Between P and P' and between Q and Q', connecting lines are drawn after which perpendicular bisectors are drawn through PP' and QQ', respectively.
The point of intersection AB of these two bisectors is called the discrete rotation centre or the discrete polar centre. Points P and P' and Q and Q', respectively, are situated on two concentric circles (O_{AB}, AB-P) and (O_{AB}, AB-Q), so that position A by simple rotation around AB can change to position B. For the transitions from B to C, C to D and D to E, we may also construct discrete rotation centres (polar centres). In Figure 1-1, these are respectively the discrete rotation centres BC, CD and DE. These discrete rotation centres AB, BC, CD and DE may be connected with each other by a broken line.

Now when the time required for the transition from one position to the other

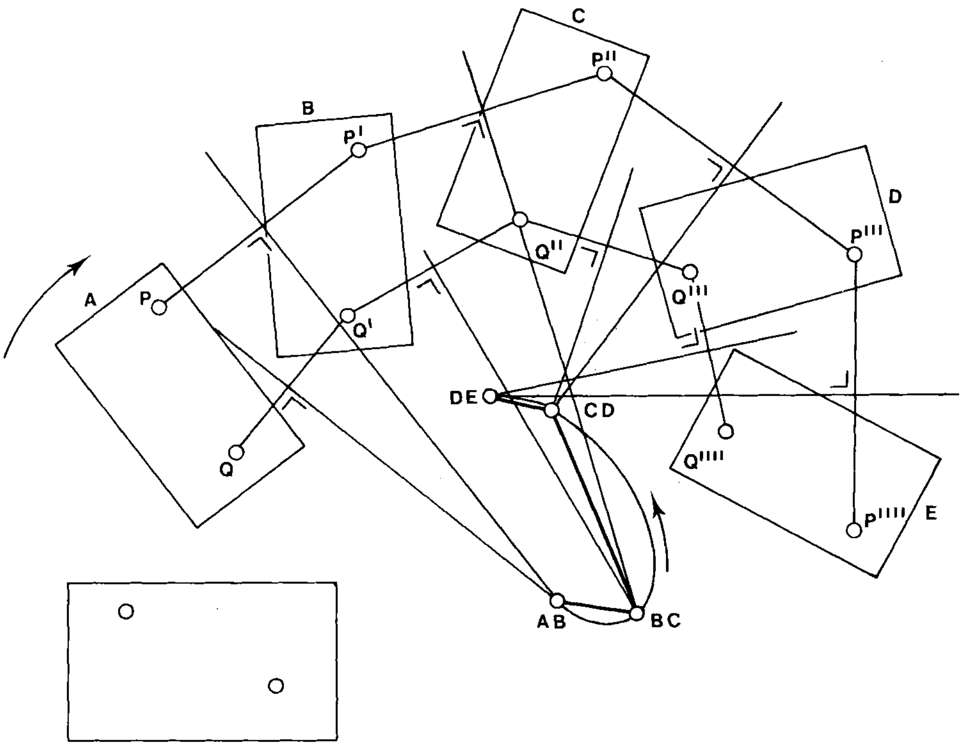

Figure 1-1. Determination of discrete centres of rotation by means of a Reuleaux analysis.

approaches zero, the discrete rotation centres will approach the instantaneous rotation centres. An instantaneous rotation centre, also called pole or velocity centre is a point around which it is always possible, at a given moment, to describe a rotation with the point at that moment having a velocity of zero. Strictly speaking, that rotation also is then infinitely small.

Since an infinite number of instantaneous rotation centres are conceivable, the connecting line between instantaneous rotation centres is a curved line for the continuous shifts from position A through B, C, D and E. This curved line is called the polar path, or polode or centrode. This polar path is the (geometrical)locus of instantaneous rotation centres of a moving figure in a plane. In Figure 1-1, a polar path has been drawn as a smoothly curving line from AB to BC, CD and terminating in DE. In this drawing, the polar path passes through the discrete rotation centres; this is not generally the case. That it is not the case may be explained again with the aid of another planar motion. In this way, the difference between an instantaneous and a discrete rotation centre will also be elucidated once more.

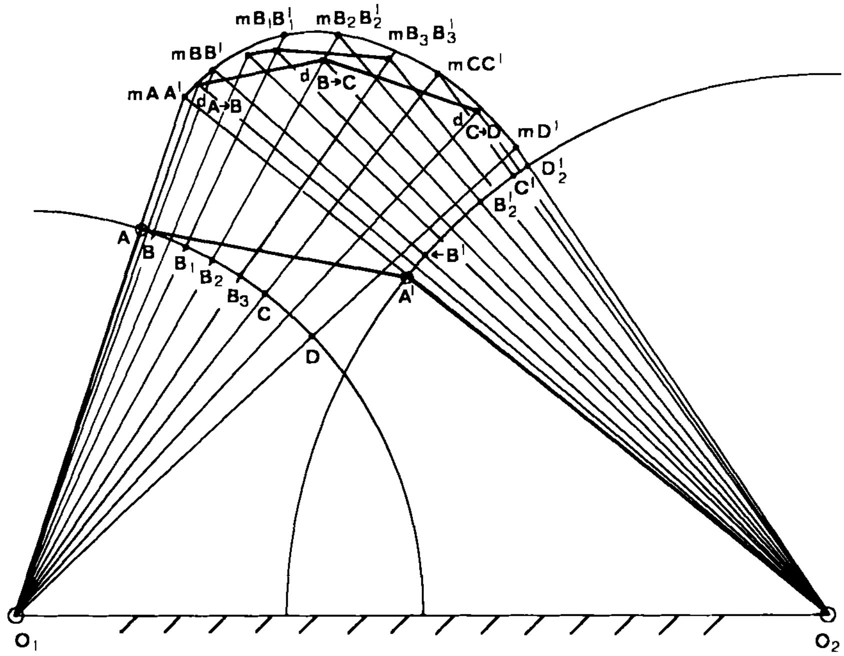

Figure 1-2. Discrete and instanteous rotation centres.

Figure 1-2 shows a four-bar system, $O_1AA'O_2$, with the fixed pivots O_1 and O_2. One of its four links, link AA' will move according to a prescribed pattern, point A following the left circular pathway (circle O_1, O_1 A) and point A' following the right circular pathway (circle O_2, O_2A). Thus, A successively passes through B, B_1, B_2, B_3, C and D, while A' at the same time passes through the corresponding points on the right-hand circle.

To begin with, for the passage A-B and A'-B', with the aid of a Reuleaux analysis, the discrete rotation centre d_{AB} was determined. Analogously, the discrete rotation centre d_{BC} found for the passages B-C and B'-C', and the discrete rotation centre d_{CD} for the passages C-D and C'-D'. The respective perpendicular bisectors are shown in the drawing. The three discrete rotation centres are interconnected in Figure 1-2 by a broken heavy line. In Figure 1-2, instantaneous rotation centres can also be shown: when a point moves along a circle, namely, the velocity component in the direction of the origin is zero! This means that at the moment when link AA' is in position AA', all points that have a zero velocity in the direction of O_1 or O_2 lie in the lines O_1A or O_2A.

The point of intersection of O_1A and O_2A' then gives us a point which has a zero velocity in two different directions, which means that the point is fixed. This gives us the instantaneous rotation centre for link AA': in the figure, m AA'. Analogously, we find the instantaneous rotation centres m BB', m CC' and m DD' for the moments when the link passes positions BB', CC' and DD'. If a very large

number of instantaneous rotation centres are determined in this manner, a smoothly curved line appears: the centrode.
When we compare the instantaneous rotation centres with the discrete rotation centres, we find that the discrete rotation centres are not lying in the polar path. Here, the polar path, as it were, surrounds the discrete rotation centres.
This figure also shows that if the Reuleaux analysis is applied to changes of position over shorter distances, the discrete rotation centres found will also approach the polar path. To illustrate this, we have chosen three more points on the circle (O_1, O_1A), viz B_1, B_2 and B_3, with corresponding points B_1', B_2' and B_3' on the circle (O_2, O_2A'). In this manner, the distance B-C travelled by end A of link AA' is divided into four equal stages. For the shifts of position A, BB_1, BB_2 and B_2C we now determined the discrete rotation centres d BB_1, d BB_2 and d B_2C. The travelled distance BB_1 is one-half as long as the travelled distance BB_2 or B_2C and the latter in their turn are one-half of BC; accordingly, we find that d BB_1 lies closer to the polar path than d BB_2 and d B_2C, and these in their turn are closer to the polar path than d BC.

For a three-dimensional motion analysis, a Reuleaux analysis should be carried out only under certain conditions, viz:

> the central direction of projection or radius vector always has to coincide with the axis of rotation, in other words, the X-ray source should move along with the axis of rotation so that the latter is always shown as a point; the axis of rotation, therefore, should always be perpendicular to the projection plane. A consequence of the above is that with changing direction of the axis of rotation, the roentgen tube and the projection plane should also change direction. Since the position of the axis (axes) of rotation of the tarsus is not known, such an analysis cannot be carried out.

1.3 REVIEW OF TARSAL MOTION DEFINITIONS IN THE LITERATURE

While studying the literature on articular mechanics, we regularly encountered certain terms which in the light of the above merit a more detailed discussion. These terms are:

a. Joint centre, functional joint centre (Dempster, 1955), instant centre of rotation (Williams and Lissner, 1967, Frankl and Burnstein, 1970); Momentandrehpunkt (Fick, 1904).
b. Kompromis-Achse, resultierende Achse, Konstruktions-Achse (Fick, 1904), resultant axis (Elftman, 1954).
c. Instanteous axis of rotation, instant axis of rotation, instantaneous axis of rotation (Elftman, 1954 and 1960; Mann, 1964); instantaner Achse, Augenblick-Achse (Fick, 1904).

sub a)
The context in which the terms listed under a are used shows that these authors

in every case have desired to convey that the axis of rotation in a particular joint did not have a fixed position.
Fick mentions the Momentandrehpunkt in a theoretical discussion of the movement of a body in a plane to which he applies a Reuleaux analysis. Actually, therefore, he determines a discrete centre of rotation in the plane, valid for the shift between two positions on the pathway of movement not occurring at the same time. Using the terms 'momentan' or 'instantan' in this case is not very apt.

sub b)
Fick (1904) wanted to indicate the direction of the axis of rotation of a bone that had changed position in relation to the three socalled body planes. He called the axis determined in this manner the 'Kompromis-Achse', 'resultierende Achse' or 'Konstruktions-Achse'. He did this in reference to a study of the movements of the wrist. To this purpose he described the spatial movements of the hand in relation to the forearm as a combination of rotations around three axes at right angles to each other. Fick then plotted the number of degrees of rotation measured by him around each of these three axes as distances on the axes in question. In this manner, a parallelepiped was obtained. Subsequently, by vectorial addition of these three components, he was able to calculate the length and the direction of the resultant R. In Figure 1-3, this R is shown as the diagonal of that parallelepiped. Around this resultant, the socalled 'resultierende Achse' or 'Kompromis-Achse', a 'resultierende' or 'Kompromis-Bewegung' would supposedly take place. Fick emphasized, however, that strictly speaking it is only permissible to apply this method in composing infinitely small movements.

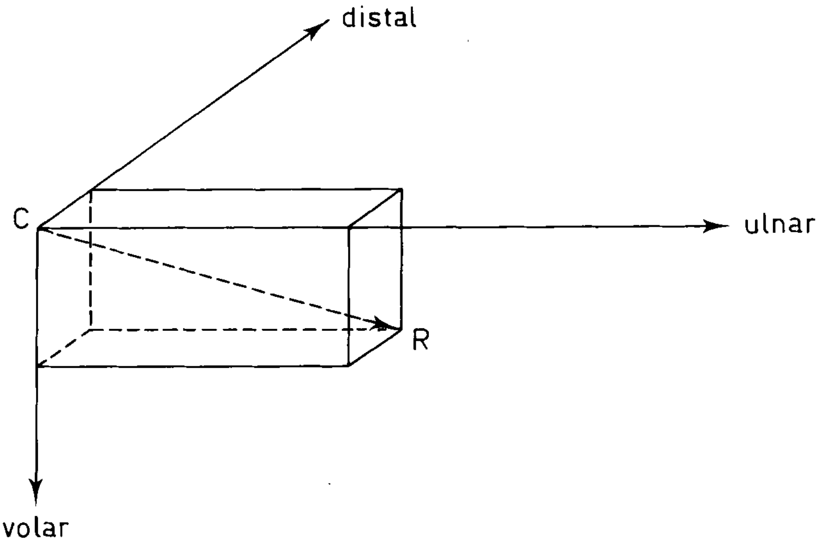

Figure 1-3. Combination of axes for the three components of the movement of radial abduction of the right hand (through capitate bone) according to Fick.

This method as described by Fick inspires the following comment:

1. Fick speaks only of rotations and ignores the possibility of translations.
2. Fick fails to state exactly how the three component rotations have been determined.
3. Fick determined the component rotations by comparing the starting and end points of a moving bone; in this respect, his Kompromis-Achse resembles a discrete axis of rotation.
4. Use of this method is only permissible for infinitely small movements, as Fick himself also states. In this respect, then, his Kompromis-Achse would rather more resemble an instantaneous axis of rotation. This method may be applied to movements that are not infinitely small only if the rotations take place simultaneously and the ratio of the component rotations remains constant.

Although the 'resultant axis' as referred to by Elftman and Mann is a literal translation of 'resultierende Achse', Elftman's descriptions nevertheless show it to have (a) different meaning(s) from Fick's 'resultierende Achse'. In Elftman's work we find two different applications for a 'resultant axis' construction. One case concerns the movements in joints with ellipsoid or saddle-shaped articular surfaces. In that case, he first traces a line perpendicular to the two imaginary axes of curvature of these articular surfaces. The 'resultant axis' is then represented by some line which at a point somewhere intersects the perpendicular. Elftman gives as an example the 'resultant cuboid calcaneal axis'. Although the axes of curvature are actually fixed axes, the 'resultant axis' according to Elftman may have 'instantaneous' positions, depending on the spatial position of the bones.

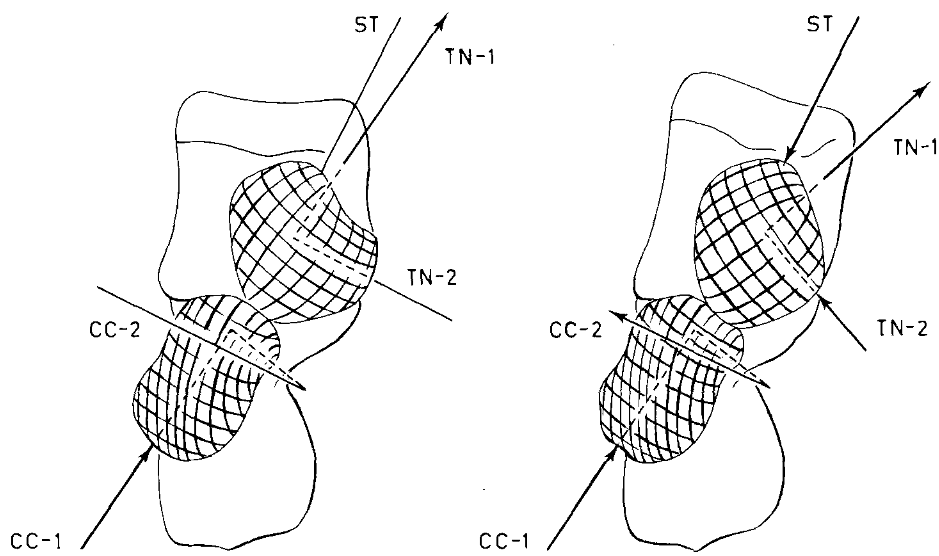

Figure 1-4. Resultant axis according to Elftman.

On this description of Elftman's 'resultant axis', the following comments may be made:

1. Elftman proceeded from axes of curvature. Fick, on the other hand, proceeded from body coordinate axes (component axes).
2. According to Elftman, the position of an axis of curvature is determined by the articular surface; the magnitude of the rotation around that axis then does not affect the position of the 'resultant axis'. Fick, on the other hand, did consider an interdependence of magnitude of rotations around component axes and the position of the 'resultierende Achse'.
3. Elftman does not specify how he determined his two axes of curvature for the calcaneocuboid joint, except to say that he did it 'with the eye of the connoisseur'.
4. Mathematically considered it is correct that on the perpendicular connecting line of two crossing axes of rotation *(axes of curvature)* there lies a point through which the axis of rotation for the combined movement passes (see Figure 1-4). Elftman does not clearly indicate the site of this postulated combined axis of rotation.

In the other case, the 'resultant axis' is found by combining the articular axes of several joints. He then applies the same procedure.

sub c)
As appears from the above, the terms 'instanteous', 'instantaneous', 'instantaner' and 'Augenblick' are being used fairly often when actually, discrete points or axes of rotation are meant. Elftman concluded that in the knee joint, there had to exist a movable axis of rotation, an 'instant axis'. This 'instant axis' then supposedly moved along a centrode (see par. 1.2); this centrode in its turn was formed by the centres of curvature of the femoral condyle. These centres were interpreted by Elftman as 'instant centres' for the axis around which the flexion and extension of the knee supposedly occur. According to Elftman, the use of an 'instant axis' offers the advantage that in the description of articular movements it facilitates the visualization of lever arms of muscles.

Frankl and Burnstein, Williams and Lissner have also indicated an 'instant axis' for the knee joint. They, however, did not use the radii of curvature of the femoral condyle, but applied a Reuleaux analysis; actually, these authors once again determined only the discrete centres of rotation through which the 'instant axis' supposedly passed. Dempster, also, determined what he called 'instant axes' for several joints; in reality, these, also, were 'discrete centres of rotation'.