Kinematic models and the human pelvis

8. Kinematic models and the human pelvis

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INTRODUCTION

This chapter deals with kinematic models in relation to the human pelvis. It is mainly based on the ideas concerning modeling of the human locomotor apparatus that we have developed in our research group (Benink 1985, Huson et al 1989, Morrenhof 1989, Ottevanger et al 1989, Schreppers et al 1990, Spoor et al 1989, 1990, Van Langelaan 1983, Van Leeuwen et al 1990, Wismans et al 1980). Although most of our work focused on the lower extremity and did not pay particular attention to the sacroiliac joint (SIJ), there is still a clear link with the approach and ideas of Snijders' and Vleeming's work (e.g. Snijders et al 1993a, Vleeming et al 1995b). Therefore the line of thought unfolded in this chapter has an obvious relevance for the theme of this book.

In biomechanics, the human musculoskeletal system is often represented by a so-called multi-body system comprising (1) a number of rigid bodies (bones), which are connected to each other by (2) movable linkages (joints) and (3) force generators (muscles). This is of course an abstraction, a reduction of the complex reality, and as such is subject to all the restrictions inherent in abstractions. However, such an approach may enable us to unravel the complexity of particular mechanical relationships. An elegant example is Snijders' and Vleeming's explanation of the self-locking effect in the construction of the pelvis (Vleeming et al 1995b). Their model gives us an idea of the roles played by friction, the position of contact surfaces between the bones, and certain pelvic dimensions as parameters of pelvic shape in the functional task to keep the pelvic assembly together under a vertical static load. Snijders and Vleeming arrived at this solution by treating the pelvic bones as so-called free bodies, virtually isolated from their real context (the pelvic ring), while a number of forces act under certain conditions on these bones. In this way, descriptive anatomy acquires in their hands a quantitative and measurable aspect and at once the description becomes explanatory.

The sacrum and the pelvic bones, connected to each other by the SIJ and the pubic symphysis, form what is described as a closed kinematic chain. This chain contains only three links connected by three linkages. Had these linkages been simple hinges, the chain would have been in kinematic terms a rigid structure. However, due to the nature of the pelvis and its linkages, this is in kinematic as well as in static terms not the case, and the ring has instead a certain mobility or deformability. Not only the pelvic ring, but, as has been said before, many if not all of the sub-systems of the musculoskeletal system can also be described as kinematic chains, either closed or open. While the pelvis is a structurally closed chain, many of the other chains are open and can be closed voluntarily. The general effect of such a closure leads to an increase of its kinematic constraints, in other words it is a reduction of the chain's kinematic degrees of freedom of motion (DFOM). Said in more general terms, closure leads to a reduction of the chain's mobility, or a gain in stability. Let us consider this effect in more detail.

CLOSED KINEMATIC CHAINS

Figure 8.1 shows a very simple model of the lower part of the human body, consisting of only

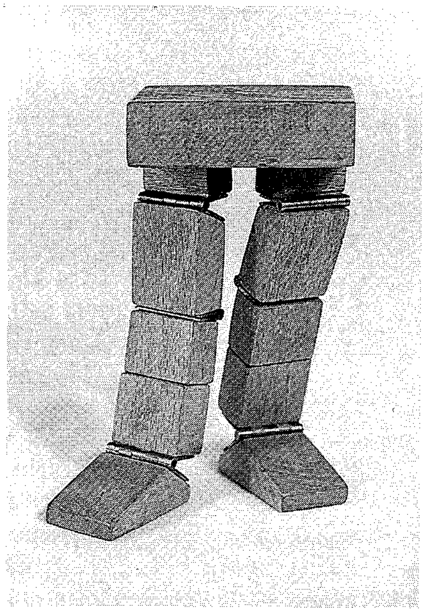


Fig. 8.1 A simple model of the lower part of the human body comprising the pelvis (the upper block as one of its six links), the thighs (two other links), the legs (again two links), and both feet (the feet, together with the floor, representing the sixth link). The purpose of the horizontal cleft dividing the legs into two parts will be clarified by Fig. 8.9 below. See text for further explanation.

the pelvis with the lower extremities and standing on a supporting base. In this case, the pelvis is conceived of as a single rigid piece. The pelvis, the thighs, the legs, and both feet, which are supposed to be firmly connected to the supporting floor by the combined effects of gravity and friction, together form a closed kinematic chain, containing six links. The linkages or joints in this model have been considerably simplified for modeling purposes. In this model, all the joints are reduced to simple hinge joints. For the time being, we are assuming that the muscles running in different directions around these joints are capable of imposing this reduction on the joints. Furthermore, in this model the feet are slightly abducted by exorotation of both legs at the hip joints. Notice that, in this position, the model can keep itself in an upright position while standing on a flat supporting surface without any external support, keeping its hips and ankles still in a mid-position between full extension and flexion. Only the knees are locked in full extension. Apparently, no muscles are needed to stabilize these joints other than those supposed to change the hips and knees kinematically into hinges. It seems that we are confronted with another example of a self-locking effect. We have called this self-locking effect a muscle-saving principle because the chain can kinematically be stabilized with less muscular effort than would be expected from the total number of joints involved (Huson 1983). In this case, the self-locking effect is a consequence of the particular combination of joints in this closed kinematic chain. The next figures will explain this typical effect in more detail.

TWO-DIMENSIONAL SIMPLE CHAINS

Figure 8.2 shows an open kinematic chain comprising four links. It has one fixed or base link, indicated by the number 1 and recognizable by its hatching, and two arms, one of them containing two links (the right arm with the numbers 3 and 4) and the other one having only one link (number 2 at the left-hand side). All of the linkages – A (between links 4 and 1), B (between links 2 and 1), and D (between links 3 and 4) – are simple hinges. Because the hinge axes are parallel to each other and perpendicular to the plane of the drawing, this is called a two-dimensional or planar chain.

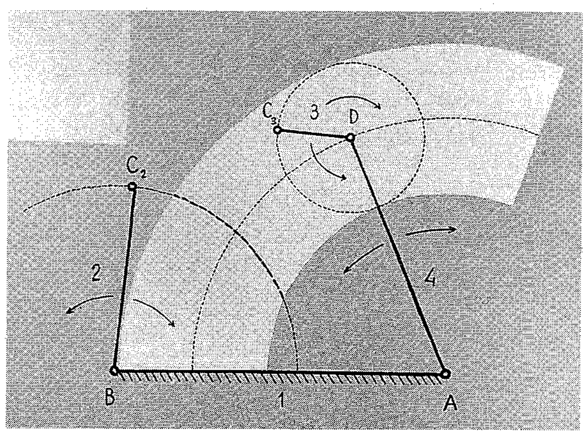


Fig. 8.2 A two-dimensional or planar four-bar chain. The chain has been opened at its linkage C. Now both arms can be moved independently with respect to the hatched reference link (1). In the depicted position of the arms, points C_2, C_3, and D can move along the circular paths depicted by the broken lines. The segment in bold of the circular path about rotation center B defines the only path along which C can move after closure of the chain.

Its motions occur in a single plane or in a set of parallel planes, in which case the motions can be projected on a single plane. Point C_2 of the one-link arm can move along the circular path about B; likewise point D can move along a circular path with A as its center of rotation, whereas in the position of link 4 depicted, point C_3 can move along the circular path with D as its rotation center. However, as soon as link 4 is set free to rotate about A, point C_3 can move freely within the boundaries of the curved lightly shaded area. Consequently, links 2 and 4 have only one DFOM each, whereas link 3 has two.

After assembling the two arms by joining the points C_3 and C_2 into a new hinge, i.e. after closure of the chain, the kinematic conditions within the chain have changed dramatically: the newly formed hinge C can move only along the common circular path of both formerly open arms. Thus link 3 also now has a limited freedom of one DFOM. It must be noted that in its closed configuration, the chain is provided with four hinges, one more than in its open condition. Together they are good for four DFOM. Yet the actual kinematic freedom of all its links allows only one DFOM because after closure both points C and D can move only along the circular paths about A and B in a particular combination, prescribed by the length of the connecting link 3. Apparently, three DFOM have disappeared after closure of the chain (see also the upper part of Fig. 8.4 below). Let us see what happens if we add one more link to the chain.

The upper part of Fig. 8.3 shows again an open chain, but now consisting of five links. This chain too has one fixed, or base link, number 1 (again recognizable by its hatching). Now, however, the two arms have two links each: numbers 2 and 3 at the left, and numbers 4 and 5 at the right. In this chain, both end links – 3 and 4 – can move with two DFOM within the boundaries of the two curved hatched and lightly shaded areas.

As soon as the two arms are connected with each other, by assembling D_3 and D_4 into a new hinge, the mobility of D in the now-closed chain is limited to the overlapping area only: the lightly shaded area without hatching. Yet it means that links 3 and 4 still have two DFOM each. However, in its closed configuration (the lower part of Fig. 8.3), the chain is provided with five hinges, representing in total five DFOM. Apparently again, *three* DFOM have disappeared after closure of the chain. A similar reduction of three DFOM would occur if we added another link to the chain, resulting in a six-bar chain that has one link having three DFOM with respect to its reference link.

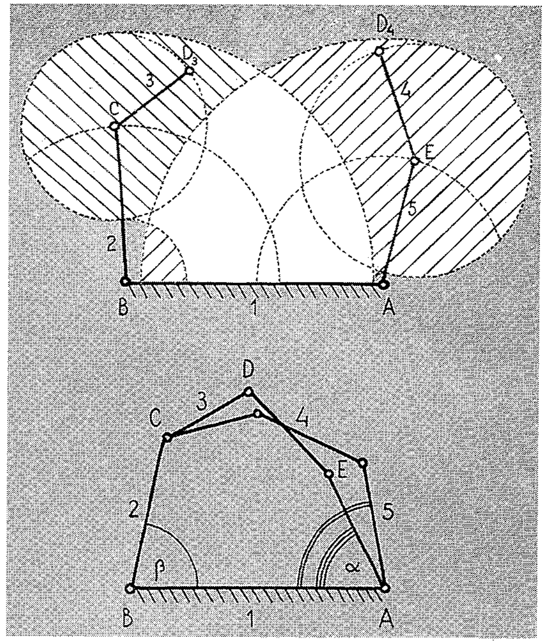


Fig. 8.3 The upper part shows a two-dimensional, five-bar chain in an open condition similar to the chain in Fig. 8.2. The lower part depicts a closed five-bar chain with two DFOM for point D. The position of the chain can be defined unequivocally by defining two variables, the angles α and β.

COMPOUND CLOSED CHAINS

It is important to note that the four-bar chain, having only one DFOM, can be stabilized (immobilized) by stabilizing just one of its four hinges. Thus stabilizing one of the four joints has an immobilizing effect on all the other joints too. On the other hand, if we add one more link to the chain, turning it into a five-bar chain, two joints have to be stabilized in order also to immobilize all the other joints. However, as soon as we loosen one of these two stabilized joints, the chain has regained one DFOM, which means that, apart from the other as yet still immobilized joint, the other three joints can immediately move freely again. This transition can be described in another way by saying that stabilizing one joint of the five-bar chain changes this chain into a four-bar chain (see the lower part of Fig. 8.3).

Such an effect will also be seen under similar conditions if similar but longer chains are considered. The longer such a chain, the more joints will be included in the sudden increase of instability when one of its joints becomes disconnected or one of its links is broken. In other words, the muscle-saving principle suddenly loses its effect if the chain changes from the kinematic condition of zero DFOM to one or more DFOM.

If we consider the chain comprising the pelvis and both legs under the conditions of human walking, such sudden changes in its state of kinematic constraints occur physiologically at heel strike and toe-off. During each step cycle, the chain is alternately closed and opened twice, and it is exactly at these critical events that the main bursts of muscle activity occur (Morrenhof 1989).

Figure 8.4 shows two examples of a closed kinematic chain, the upper having only four links, the lower having six links, but now in two different configurations. The upper one is a simple-closed chain, like our four- and five-bar chains depicted in Figs 8.2 and 8.3 above. The lower chain, however, is a so-called compound-closed chain, having one link (number 6) as a cross-link between the two opposite triangular links 2 and 5. The simple chain has four hinges and its resulting kinematic freedom is one DFOM, a reduction, as we have seen, of three DFOM as a consequence of closure in a planar system. The compound chain, however, has seven hinges, yet a mobility of only one DFOM. It will move only according to a single prescribed and reproducible motion mode. Thus, reduction after closure in a *compound* configuration goes much further, since in this example apparently *six* DFOM have disappeared. Very long chains constructed as coupled compound configurations can effect even greater reductions. The example shown in Fig. 8.5 will result in a reduction of as many as 33 DFOM.

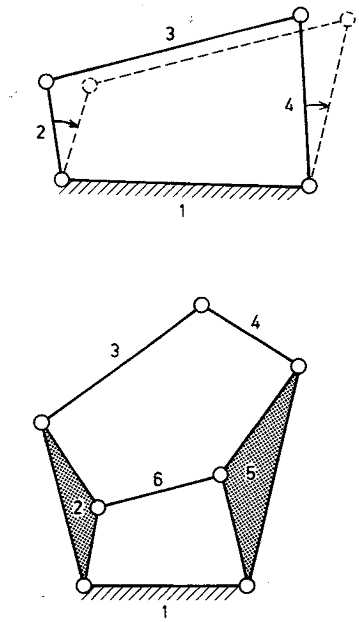
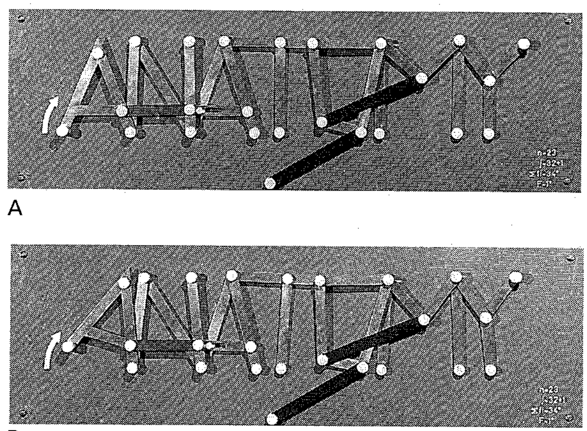


Fig. 8.4 Two different configurations of a closed, two-dimensional chain. The upper one has four links yielding one DFOM and is a simple chain. The lower one is a compound-closed chain and also has only one DFOM, even though it has seven linkages.



A

B

Fig. 8.5 A very long planar, compound-closed kinematic chain photographed in two positions. Despite its great number of linkages, it has only one DFOM. Note that the chain is essentially an assemblage of many coupled four-bar chains.

THREE-DIMENSIONAL CLOSED KINEMATIC CHAINS

Apart from a configuration characteristic such as compound closure, there can be still another

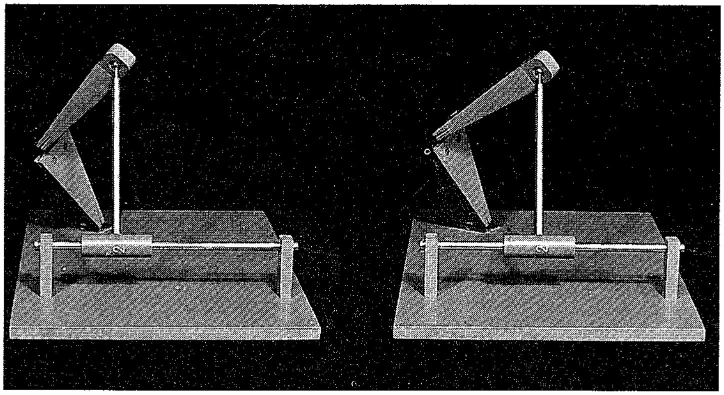


Fig. 8.6 Two different positions of a three-dimensional or spatial four-bar chain. The chain has only one DFOM, although its joints together represent seven DFOM: $(2 \times 1) + 3 + 2 = 7$. The four joints comprise two hinges (the two lower joints of the long arm, visible in the background, each having one DFOM), one ball and socket joint (the upper joint of the long arm having three DFOM: three rotational modes), and one cylindrical joint (the joint in the foreground having two DFOM: one rotational and one translational mode).

boundary condition that determines the extent to which the mobility of a particular kinematic chain will be reduced. If a simple closed chain is not a two-dimensional or planar chain but a three-dimensional or spatial chain instead, closure of the chain in a simple configuration will produce a reduction of *six* DFOM, twice the reduction occurring after closure of a planar chain. In a spatial chain, hinge-like linkages have no parallel axes and these chains may even have ball and socket joints; in more general terms, they may have joints with more DFOM than simple hinges have. Their motions do not occur in single plane only but in space, which is three-dimensional. Therefore they have to be described with respect to three orthogonal references axes. Figure 8.6 shows such a three-dimensional chain in two different positions.

In spatial configurations of closed kinematic chains, the reduction of its DFOM will also increase considerably when the chain has a compound configuration. Such three-dimensional, compound-closed kinematic chains occur in the complex skeletoligamentous system of the human body. A typical example of such a three-dimensional, compound-closed kinematic chain is the carpal complex of the human wrist. Figure 8.7 shows a schematic representation of this complex. An estimation of the kinematic reduction incorporated in this system yields 20–30 DFOM, depending on certain assumptions concerning its kinematic features. This may illustrate why rupture of a single small ligament

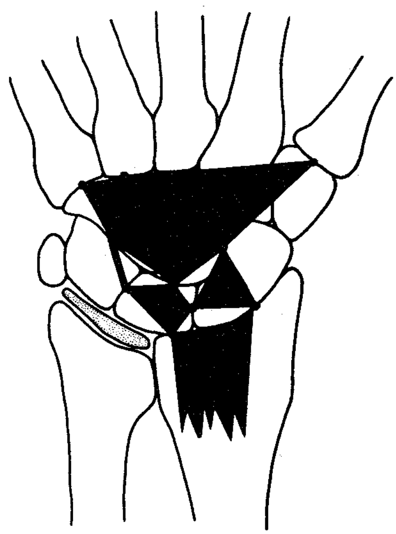


Fig. 8.7 Schematic representation of the carpus as a spatial, compound-closed kinematic chain. This example comprises only the following linkages: the radio-scaphoid joint, the radio-lunatum joint, the lunato-scaphoid joint, the lunato-triquetrum joint, the hamato-scaphoid joint, the hamato-lunatum joint, and the hamato-triquetrum joint.

(e.g. an injury of the fibrous connection between lunatum and scaphoid, which is so hard to detect on a standard X-ray), or fracture of only one bone (e.g. the notorious scaphoid fracture), is such a fatal occurrence for the normal function of the carpal mechanism.

TIBIAL TORSION: A KINEMATIC CONSTRAINT?

We will now return to our model consisting of pelvis, lower extremities, and floor because it demonstrates so well another interesting kinematic feature. Figure 8.8 shows a schematic representation of the model. The left-hand part of this figure illustrates that the model can be seen as an open box with six sides. These sides are connected to each other by a set of six hinges comprising two subsets of three parallel hinges. It is obvious that the upper side can move vertically up and down, stretching or folding the sides of the box. Thus the upper lid of the box has one DFOM.

In the central figure, the box has been translated into our pelvis-with-lower-limbs model, showing similar kinematic features. According to our foregoing reasoning, this is a spatial, simple-closed kinematic chain with six hinges, and for this reason it should be subject to a reduction of six DFOM. This actually means that its kinematic condition should have yielded a mobility of zero DFOM: it should have been immobile! However, its actual kinematic condition produces, as we have seen from the example of the six-sided box, one DFOM. This is due to its particular kinematic feature of having two sets of three parallel hinge axes.

The figure at the right shows our pelvis-legs-and-feet model again, but in contrast to the central model this one is not able to move up and down: it does indeed have zero DFOM. The difference has to be sought in the torsion of the two bars that represent the lower legs. This torsion disturbs the parallel position of the hinge axes of knee and ankle. The chain has apparently acquired the kinematic features of a spatial chain, and this is sufficient to give a further reduction of the mobility of the closed chain. It is a well-established fact that tibial (external) torsion is a real anatomical characteristic of the human lower limb that develops during the first 10 years after birth (Lang & Wachsmuth 1972).

A physical representation of the model (Fig. 8.9) demonstrates this special kinematic effect. The model can stand upright as did the model in Fig. 8.1 above, but now it is even able to do so with flexed knees while the hips and ankles are still in the midpositions of their motion ranges. Owing to the external torsion of the lower links (the tibial parts) of the legs, these joints apparently need no external stabilizing support to maintain their positions, like the situation demonstrated in Fig. 8.1 above.

However, this configuration of the limbs and joints leads to another complication. In order to obtain full flat contact between the supporting surface and the feet, the model has to lean backwards. To prevent it falling down backwards, the feet have to be fixed by external forces to the floor, as can be seen in the photograph. As soon

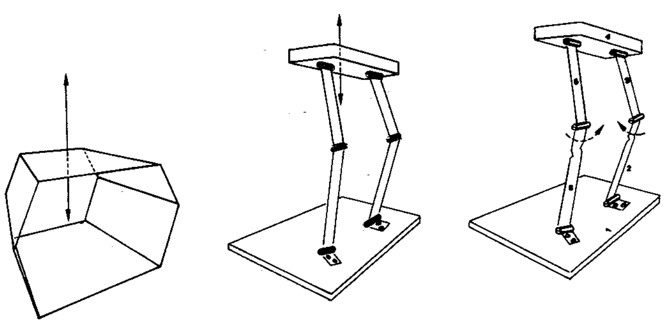


Fig. 8.8 Drawings of two different configurations of the model shown in Fig. 8.1 above (central and right figure), together with their basic kinematic model (left figure).

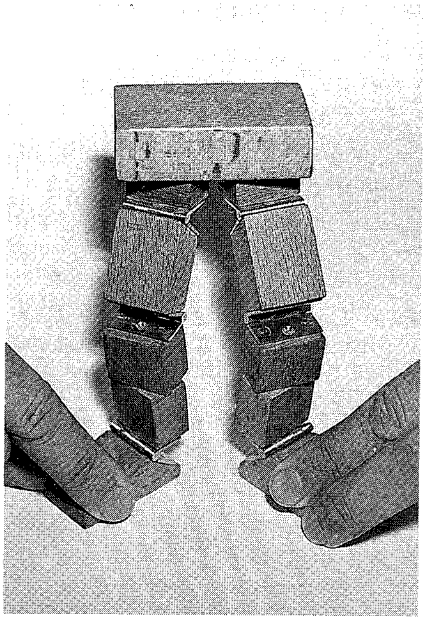


Fig. 8.9 The model from Fig. 8.8 in a physical representation.

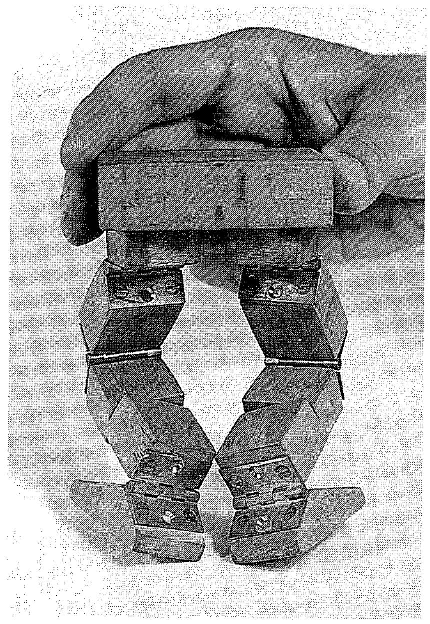


Fig. 8.10 The same model as in Fig. 8.9, but in this position the feet are everted. See text for further explanation.

as one hand is removed, the model collapses. After undoing the tibial torsion the demonstrator not only has to keep the feet in contact with the floor, but also has to stabilize one of the joints. Again, removing this external stabilization leads to a collapse of the model in spite of its feet being kept fixed to the floor. Thus under certain kinematic conditions, a particular *anatomic* feature such as a tibial torsion produces a kinematic boundary condition with a functional effect that concerns all the joints within the closed kinematic chain of pelvis and legs.

Apart from this contribution to 'self-locking', the tibial torsion has yet another functional effect. This effect became already apparent by the backward leaning posture that the model assumed when both feet were placed in flat contact with the floor (Fig. 8.9). If we want to avoid this backward leaning posture by holding the pelvic piece of the model vertically in line with its feet, the model assumes a posture as shown in Fig. 8.10. In this photograph, the model is brought into a vertical alignment of the pelvis and feet while its knees are slightly abducted and flexed. As can now be seen, the tibial torsion forces both feet into an everted, or pronated, position with respect to the floor. An additional abduction of the flexed knees to improve bilateral stabilization will further increase this effect. In order to bring the feet into firm contact with the ground, both feet must invert. Thus inversion seems to be an indispensable mechanism in the normal functional range of the lower extremities and not only a useful capability of the foot to adapt its position to an uneven underground.

A KINEMATIC MODEL FOR THE TARSAL MOTIONS

Inversion is effected by the tarsal mechanism of the foot, which again has the configuration of a spatial, closed kinematic chain with only one DFOM. As will be apparent from Fig. 8.11, showing a kinematic model of the foot in two positions, inversion of the tarsus is a complex combination of different motions of the bones involved in the tarsal mechanism. When the foot is inverted by tilting over its lateral border, the accompanying adduction of the foot is blocked and has to be compensated for by an external rotation of the leg. The ankle mortice compels the talus into a similar and concurrent abduction,

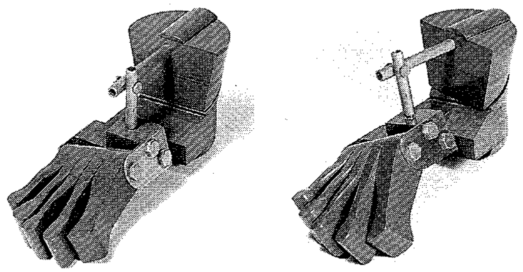


Fig. 8.11 A physical model of the foot comprising the tarsus and metatarsus. The tarsal part is represented as a spatial, closed kinematic, four-bar chain. At the left is the neutral position, at the right, the inversion position.

and the calcaneus follows this motion with a less extensive abduction and a slight inversion tilt. The abducting talar head forces the navicular together with the cuboid into an inversion added to the calcaneal inversion. Thus the forefoot supinates with respect to the hindfoot. This becomes visible as a heightening of the medial foot arch. In certain postures, as we have seen in Fig. 8.9, inversion is an indispensable mechanism. Thus if the legs are used with flexed knees, the knee joints must provide for the possibility of meeting this requirement by allowing external and internal rotation in their flexed position in order to make the feet free for a compensating inversion (Huson 1991).

FINAL REMARKS AND DISCUSSION

All the examples shown point to the fact that the human body comprises a great number of kinematic chains. Therefore mobility and stability of the human body in terms of their kinematic DFOM is determined by the kinematic constraints of these chains. Such constraints can be imposed by muscles (active elements) and ligaments (passive elements). However, apart from these easily recognizable elements, there are, as we have seen, other determinants that are less self-evident. Such structural and/or configuration-dependent determinants are:

- the actual state of the chain – closed versus open
- the composition of the chain – compound versus simple
- the dimensionality of the chain – two- versus three-dimensional
- the axial angularity, i.e. this special relationship between the axes of motion of the joints in the chain, such as parallelism or co-axiality.

So far we have dealt only with the kinematic approach to modeling, forces have not been taken into consideration. It is obvious that a more complete picture of the conditions that determine mobility and stability requires a more comprehensive model, including the acting forces (Vleeming et al 1995b). However, in such a more comprehensive approach we can also observe within the locomotor system mechanical effects acting at a distance in a musculoskeletal system, such as we have seen in our kinematic models (Bobbert & Van Ingen Schenau 1988). The ideas presented by Snijders, Stoeckart and Vleeming concerning the force streams and their anatomical findings give clear support to this point (e.g. Vleeming et al 1995a, 1995b).

CONCLUSIONS

1. Changes in the kinematic condition of a particular closed articular chain in the human body has immediate effects on the kinematics of other joints.
2. These effects can be observed even at a great distance, thus affecting the kinematic behaviour of the whole chain.
3. The model predicts that reduction of the stability of the SIJ (loosening of the joint) must lead to instability of other joints.
4. This is especially relevant since it is difficult to stabilize the loosened SIJ effectively and directly with the help of local muscles.

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