Kinematic models and the human pelvis

17. KINEMATIC MODELS AND THE HUMAN PELVIS
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This contribution deals with kinematic models in relation to the human pelvis. It is mainly based on the ideas concerning modelling of the human locomotor apparatus which we developed in our research group[1,4,6-10,13-15]. Most of our work focused on the lower extremity and it is only honest to say that the SI-joint was not one of the topics of our main line of research. Yet, there is a clear link with the approach and ideas of Snijders' and Vleeming's work[11,12], so I am sure that the line of thought unfolded in this paper has an obvious relevance for the theme of this conference.
In biomechanics the human musculoskeletal system is often represented by a so-called multibody system comprising a number of rigid bodies (bones) which are connected to each other by movable linkages (joints) and force generators (muscles). This is of course an abstraction, a reduction of the complex reality, and as such afflicted with all the restrictions inherent to 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-bracing* effect in the construction of the pelvis[11]. Their model gives us an idea about the roles played by friction 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 to this solution by treating one pelvic bone as a so-called free body, isolated from its real context: the pelvic ring, while a number of forces act under certain conditions on this bone. 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 sacroiliac joints and the symphysis form a so-called closed kinematic chain. This chain contains three links connected by three linkages. If these linkages had been simple hinges the chain would have been a rigid structure. Due to the nature of its linkages this is not the case, and the ring has some mobility or deformability instead. Not only the pelvic ring, but as has been said before, many, if not all of the parts of the musculoskeletal system can 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 by will. The general effect of such a closure is a reduction of the chain's kinematic degrees of freedom, or an increase of its kinematic constraints. Or, said in more general terms, closure leads to a reduction of the chain's mobility, or a gain in stability. Let us look for a while into this effect more in particular.

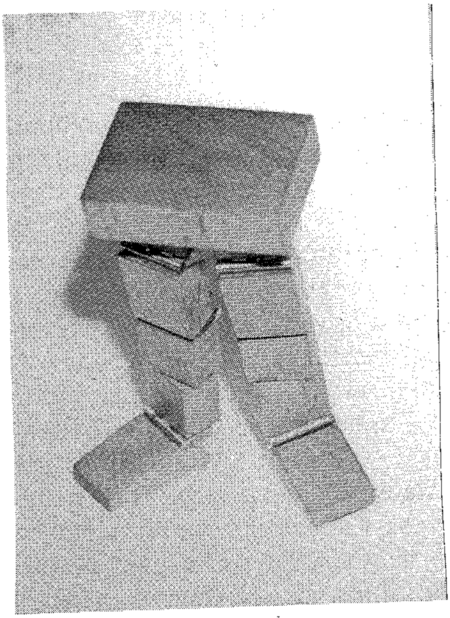


Figure 1. A simple model of the lower part of the human body comprising the pelvis (the upper block), the two upper and lower legs and both feet. See the text for a further explanation.

Figure 1 shows a very simple model of the lower part of the human body, comprising the lower extremities connected by the pelvis and standing on a supporting base. In this case the pelvis is conceived as a single rigid piece. The pelvis, the thighs, the legs, and both feet which are supposed to be firmly connected by friction to the supporting floor form together a closed kinematic chain, built up by six links. Also the linkages or joints have been simplified considerably for modelling purposes. All the joints are reduced to simple hinge joints. For the time being we suppose that the muscles running in different directions around these joints are capable to impose this reduction on the joints. Furthermore, in this model the feet are slightly abducted by exorotation of both legs in the hip joints.
Notice that in this position the model keeps itself upright, while the hips and

ankles are in a mid-position between full extension and flexion. To stabilize these joints apparently no other muscles are needed than those restricting the hips and knees kinematically to hinges. It seems that we are confronted with another example of a *self-bracing effect*. We called this self-bracing effect a muscle saving principle because kinematically the chain can be stabilized with less muscular effort than would be expected from the total number of joints involved. In this case the self-bracing 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.

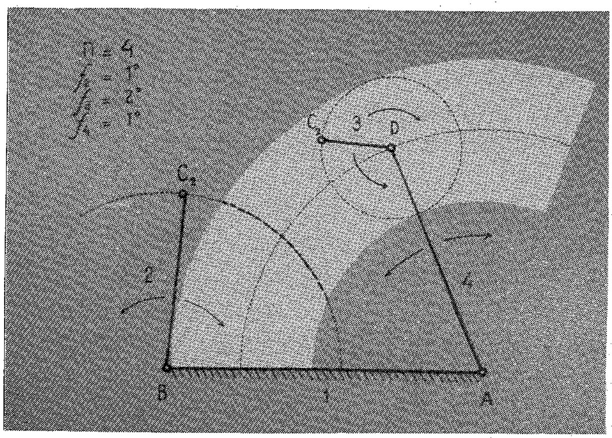


Figure 2. A two-dimensional or planar four-bar chain. The chain has been opened at its linkage C. Now both arms can be moved independently with respect to the reference link (1).

Figure 2 shows an open kinematic chain comprising of four links. It has one fixed, or base link, indicated as number 1 and recognizable by its hatching, and two arms, one of them counting two links (the numbers 3 and 4) and the other counting only one link (number 2). All of its linkages, A, B and D are simple hinges. Because the hinge axes are parallel to each other, and perpendicular to the plane of the drawing this chain is called a two-dimensional or planar one. Point C^2 of the one-link-arm can move along the circular path about B, whereas point C^3 can move freely within the boundaries of the white area. Consequently,
link 2 and 4 have only one degree FOM, each whereas link 3 has two degrees FOM. After assembling the two arms by joining the points C^3 and C^2 into a new hinge, this hinge can move only along the common circular path of both formerly open arms. Now also link 3 has a limited freedom of one degree FOM. It must be noted that in its closed configuration the chain is provided with four hinges. These are together good for four degrees

freedom of motion (degrees FOM). Yet the actual kinematic freedom of all its links counts only one degree FOM 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 degrees FOM have disappeared after closure of the chain. Let us see what happens if we add one more link to the chain.

The upper part of Figure 3 shows again an open chain, but now comprising of five links. This chain too has one fixed, or base link, number 1 recognizable by its hatching, but the two arms consist each of two links, the numbers 2 and 3 at the left, and 4 and 5 at the right side. Now both end links 3 and 4 can move with two degrees FOM within the boundaries of the hatched 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. Now the links 3 and 4 have still two degrees FOM.

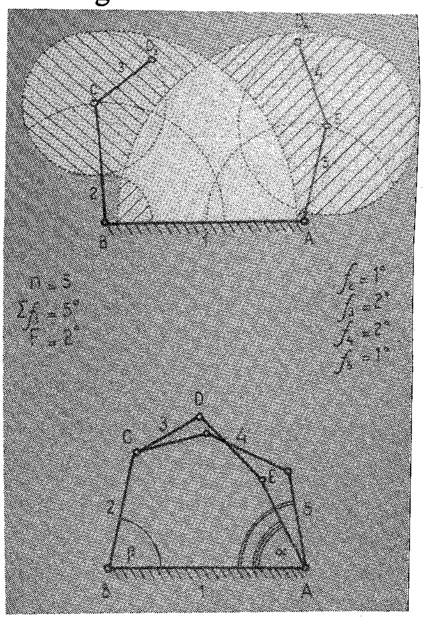


Figure 3. Upper part: A two-dimensional five-bar chain in a similar condition as the chain in Figure 2. Lower part: A closed five-bar chain with 2 degrees FOM. The position of the chain can be defined unequivocally by defining the angles α and β.

However, in its closed configuration (lower part of Figure 3) the chain is provided with five hinges representing in total five degrees FOM. Apparently three degrees FOM have disappeared again after closure of the chain. A similar reduction will happen if we add another link to the chain. It is important to note that the four bar chain having only one degree FOM can be stabilized (immobilized) by stabilizing just one of its four hinges. Stabilizing one of the four joints has an immobilizing effect on all the other joints too! At 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 to immobilize all the other joints too. But as soon as we will loosen one of these two stabilized joints, the chain has gained one degree FOM again and this means that apart of the other as yet still immobilized joint all at a sudden the other three joints can move freely again. Such an effect will be repeatedly seen under similar conditions in similar, but longer chains. And the longer such a chain is, the more joints will be included in this sudden increase of instability as soon as one of its joints becomes loosened. In other words all at a sudden the muscle saving principle has become without effect if the chain changes from the kinematic condition of zero degrees FOM to one or more degrees FOM. Such sudden changes in its state of kinematic constraints occur physiologically in the chain of pelvis and both legs at heel strike and toe off during walking. 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[8].

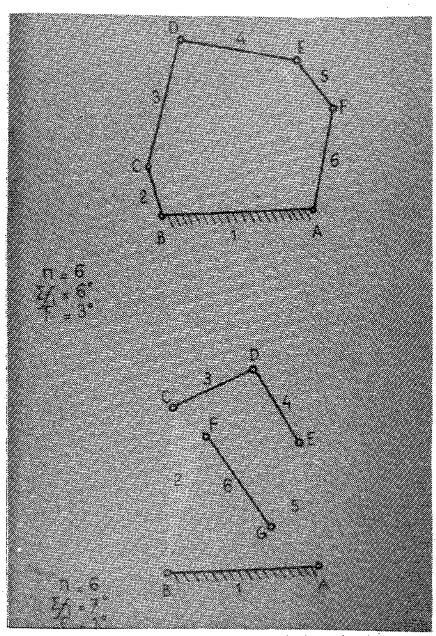


Figure 4. Two different configurations of a closed two-dimensional six-bar chain. The upper one has 3 degrees FOM and is a simple one, whereas the compound lower one has only 1 degree FOM, although it has one linkage more than the upper one.

Figure 4 shows two examples of a closed kinematic chain both having six links, but now in two different configurations. The upper one is a simple closed chain, like our four and five bar chains. The lower one, however is a 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 six hinges and its resulting kinematic freedom is three degrees FOM, again a

reduction of three degrees FOM as a consequence of closure. The compound chain, however, has even seven hinges, yet a mobility of only one degree FOM. It will move only according to a single prescribed and reproducible motion mode.
Thus, reduction after closure in a *compound* configuration goes much further as apparently in this example *six degrees* FOM have disappeared. Very long chains composed as compound configurations can effectuate even much greater reductions.
The example shown in Figure 5 is good for a reduction of as much as thirty three degrees FOM.

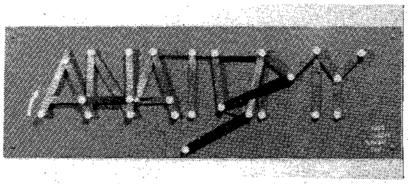


Figure 5. A very long compound planar closed kinematic chain. Despite its great number of linkages it has only one degree FOM. Note that essentially the chain is an assemblage of many coupled four-bar chains.

Apart from compound closure there is still another boundary condition which determines the extent to which the mobility of a particular kinematic chain will be reduced. If the chain is not a two-dimensional, or planar chain, but a three-dimensional, or spatial chain, closure of the chain in a simple configuration will produce a reduction of *six degrees* FOM, thus twice the reduction occurring after closure of a planar chain. In a spatial chain linkages have no parallel axes and may have ball-and-socket joints, or in more general terms: they may have joints with more degrees FOM than simple hinges have.
Figure 6 shows such a 3-D chain in two different positions. Also in spatial closed kinematic chains the reduction of its degrees FOM will increase considerably when the chain has a compound configuration. A typical example of a three-dimensional compound closed kinematic chain is the carpal complex of the human wrist.
Figure 7 shows a schematic representation of this complex. An estimation of the kinematic reduction incorporated in this system yields *twenty to thirty degrees* FOM depending on certain assumptions concerning its kinematic features. This may illustrate why rupture of a single small ligament, or fracture of only one bone is such a fatal occurrence for the function of the carpal mechanism.

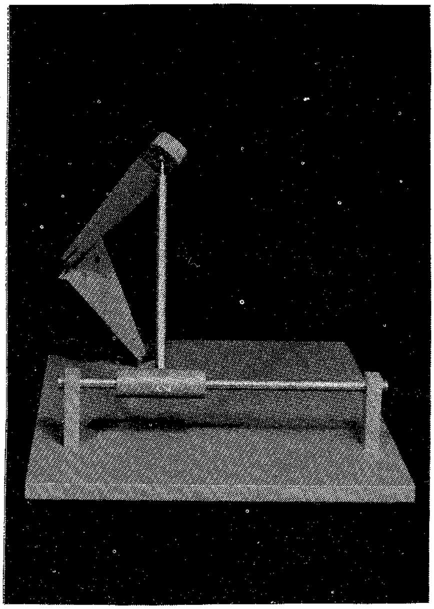
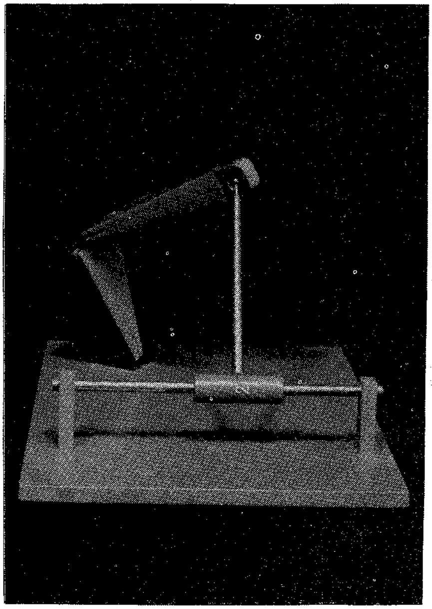


Figure 6. Two different positions of a three-dimensional or spatial four- bar chain. The chain has only 1 degree FOM. Its four joints comprise two hinges, one ball-and-socket joint (3 degrees FOM: 3 rotational modes) and one cylindrical joint (2 degrees FOM: 1 rotational and 1 translational mode).



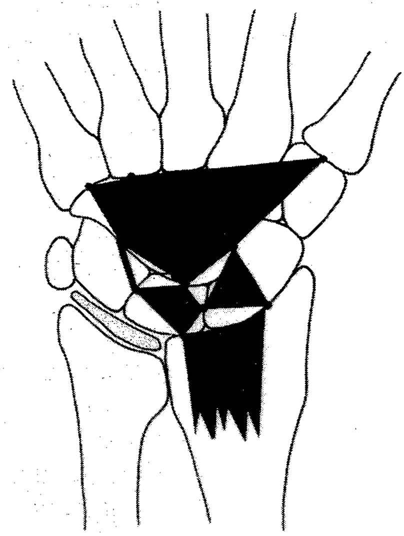


Figure 7. Schematic representation of the carpus as a compound spatial kinematic chain.

Now we will return to our model of pelvis, lower extremities and ground because this model illustrates another interesting kinematic feature.

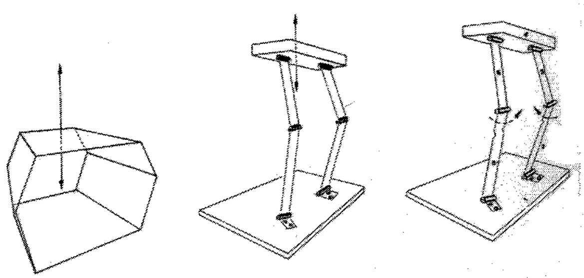


Figure 8. Drawing of similar models as shown in Figure 1 (central and right figure) together with their basic kinematic model (left figure). See text for further explanation.

Figure 8 shows a schematic representation of the model. The left 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 six parallel hinges and it will be obvious that the upper side can move vertically up and down, while stretching or flexing the sides of the box. In the central figure the box has been translated into our pelvis-with-legs-model showing similar kinematic features. According to our foregoing reasoning this is a spatial closed kinematic chain with six hinges and for this reason it should have been subjected to a reduction of six degrees FOM. Thus, it would be expected to be subjected to a kinematic condition of zero degrees FOM: it should have been immobile! However, its actual kinematic condition produces one degree FOM. This is due to its particular feature of having two sets of three parallel hinge-axes. The figure at the right shows our model again, but in contrast to the central model this one is not able to move up and down. The difference should be sought indeed in the torsion of the two bars which represent the lower legs. This torsion disturbs the parallel position of the hinge axes of knee and ankle, and this change is sufficient to increase the reduction of the mobility of the closed chain. It is a well-established fact that tibial torsion is a real anatomical characteristic which develops during the first ten years after birth[5].

The next series of photographs (Figures 9a-d) demonstrates this special effect. At the left (Figure 9a) one can see the model with parallel hinges standing upright. This is possible by stabilizing only one of the six joints. In this case the left ankle is kept in its desired position by the demonstrator.

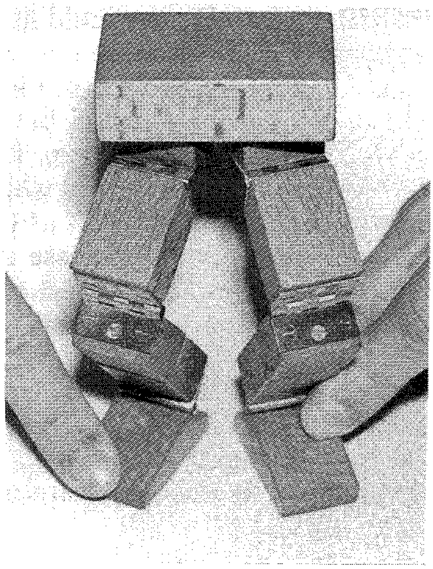


Figure 9a

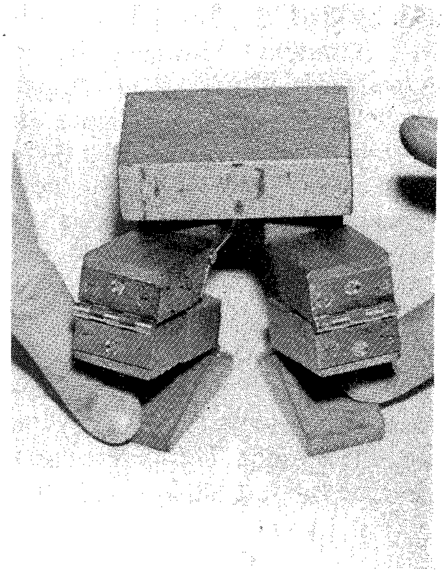


Figure 9b

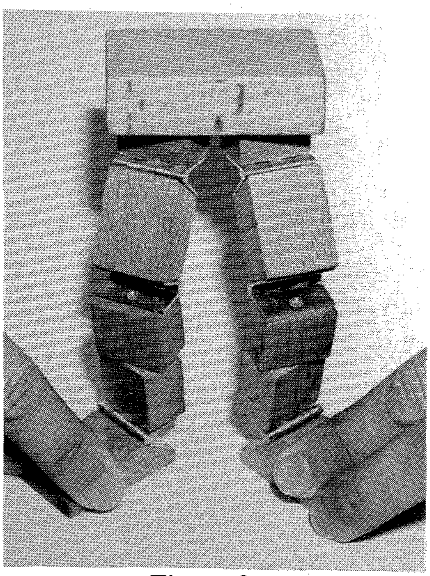


Figure 9c

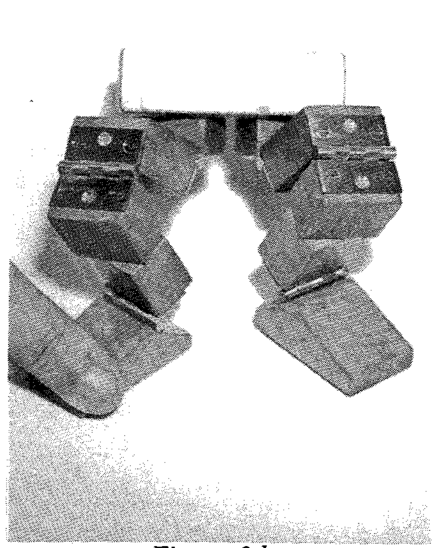


Figure 9d

Figure 9. The models of Figure 8 in a physical representation. See text for a further explanation.

As soon as we remove this fixation the model collapses as can be seen in Figure 9b. In the Figures 9c and 9d we see the same model, but now the hinges of knee and ankle are no longer parallel to each other. As can be seen in Figure 9c the model is able to keep itself in an upright position without any help to stabilize its joints. Only the feet have to be fixed to the ground because friction in such a small model is to low to prevent slipping of the feet. As soon as we allow one foot to slip away the model collapses as is shown in Figure 9d.
Thus, under certain kinematic conditions a particular *anatomic feature* such as a tibial torsion produces a kinematic boundary condition with a functional effect which concerns all the joints within the closed chain.
Apart from this contribution to a "self-bracing effect" the tibial torsion has still another functional effect. This becomes apparent if we look at the Figure 10.

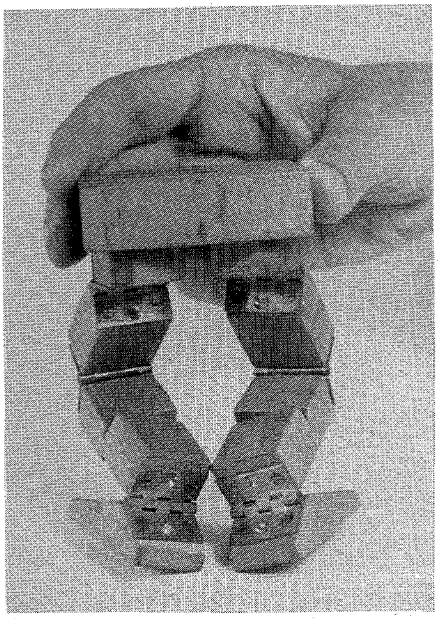


Figure 10. See text for a further explanation.

If the model is placed in any vertical position with both knees in a slight flexion the tibial torsion brings both feet into an everted, or pronated position. An additional abduction of the flexed knees will increase this effect further. In order to keep firm contact with the ground both feet must invert, so inversion seems to be an indispensable mechanism in the functional range of the lower extremities, and not only a useful capability of the foot to adapt its position to an uneven underground. Inversion is effectuated by the tarsal

mechanism of the foot which again is a closed kinematic chain with only one degree of freedom.
As will be apparent from the Figures 11a and 11b showing a kinematic model of the foot, inversion of the tarsus is coupled to abduction of the talus, which in its turn is accompanied by exorotation of the leg. As inversion is an indispensable mechanism if the legs are used with flexed knees, the knee joints must provide for a possibility to meet this requirement by allowing external and internal rotation in their flexed position[3].

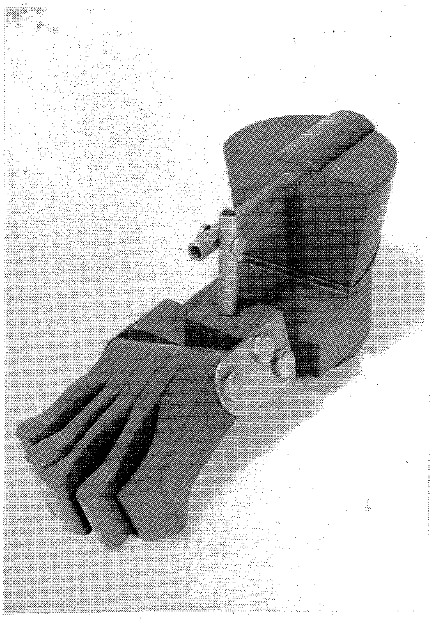


Figure 11a

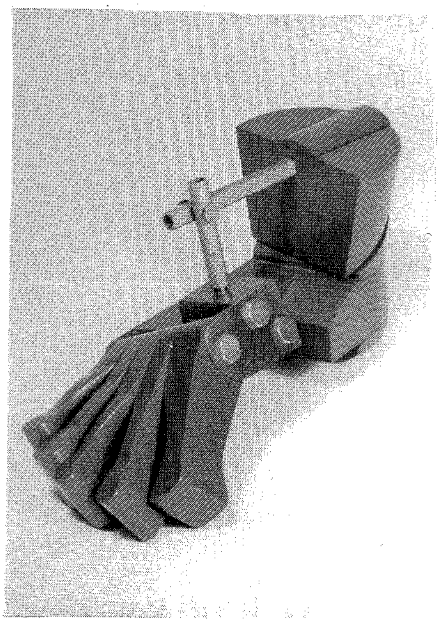


Figure 11b

Figure 11. Photograph of a physical model of the foot comprising the tarsus and the metatarsus. Its tarsal part is represented as a closed spatial kinematic four-bar chain. Figure 11a: neutral position, Figure 11b: inverted position. See the text for further explanation.

All the shown examples 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 degrees of freedom is determined by the kinematic constraints of these chains. Such constraints can be imposed by muscles (active elements) and ligaments (passive elements). But apart from these easily recognizable elements there are other determinants as we have seen which are less self-evident. Such configuration dependent determinants are:

1. actual state of the chain - closed vs open;
2. composition of the chain - compound vs simple;
3. dimensionality of the chain - two- vs three-dimensionality
4. axial angularity, i.e. special relationship between the axes of motion of the joints in the chain: vis. parallelism, co-axiality

Thus far we have only dealt with the kinematic approach of modelling. Forces were not taken into consideration. It is obvious that a more complete picture of the conditions which determine mobility and stability requires a more comprehensive model including the acting forces. However, also in such a more comprehensive approach we will find within the locomotor system similar effects at distance as we have seen in our kinematic models[2]. The ideas presented by Snijders, Stoeckart and Vleeming concerning the force streams and their anatomical findings give clear support to this point. In conclusion, the message of my contribution says that changes in the kinematics of a particular linkage of a closed articular chain in the human body has immediate effects on the kinematics of other joints, even at a greater distance, and thus affects the kinematic behaviour of the whole chain. The model predicts that reduction of the stability of the SI-joints (loosening of these joints) must lead to instability of other joints, especially if it is difficult to stabilize the loosened SI-joints effectively and directly with the help of local muscles.

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