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Mechanics of Joints

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Joints have to combine two functions which are interwoven in a complex way. Firstly, they have to ensure mobility of the skeletal system and secondly they must transmit forces between the participating bones. The loads of joints do not only stem from gravity but also from the motion-generating forces themselves.

Mechanics of joints comprises therefore two aspects: kinematic aspects (description of movements and motion guiding apart from the forces which have generated these motions) and dynamic aspects (load analysis in static and dynamic equilibrium and an analysis of the motion-generating forces).

Joints do not only have complex functions, they also have a complex structure. Since long morphologists have been interested in the relationship between structure and function. Where physiologists analyse function as the unknown variable, morphologists consider function as given and study structure as the unknown variable in relation to the given function. Thus they have tried to explain a given function by the analysed characteristics of the structure (Dullemeijer, 1974). One of the ways they followed was an experimental or theoretical variation of these structural characteristics and analysis of the changed function. In fact, such studies were based on parameter variation. Experiments in which ligaments are cut successively are well-known examples, but also theoretical models provide excellent tools for such analyses. The structural elements of the joint relevant mechanically are:

- surface elements: the articular surfaces which are covered with cartilage and have a certain geometry, together with additional intraarticular structures like discs or pads and including the synovial fluid for lubricating purposes;
- passive and active connecting elements: the capsule with its ligamentous reinforcements, other ligaments, the reinforced parts of the surrounding connective tissue and the muscles.

A short review of the functional characteristics of these structural elements in the light of the two complex functions of the joints – mobility and force transmission – will be given in the following sections.

The Surface Elements and Force Transmission

The geometry of the articular surfaces plays an important role in the determination of the path of motion followed by the bone that moves in the observed joint. However, it is not the only factor, as is often suggested by the traditional classifications of joints based on the articular geometry. A conspicuous feature of biological joints, which is often neglected in classical arthrology, is their often striking incongruity. This feature will be discussed in a later section. It is given some attention though with respect to the force-transmitting function of the joints, because incongruity of the articular surfaces, especially if it is rather outspoken, reduces the contact area necessary for force transmission considerably, thus leading to increased stresses. There are several corrective mechanisms which bring about a more favourable constellation.

The first factor is the cartilaginous covering of the bony articular surfaces. This layer of articular cartilage smoothes the small protrusions and other irregularities of the subchondral bone surface. By virtue of its elasticity stresses are spread more evenly and also a small incongruity of the joint is compensated for by its deformability. This may lead to a substantial decrease of stresses caused by the transmitted loads. Weightman & Kempson (1979) pointed out that articular cartilage should have a minimum thickness which should be considerably more than the peak-to-valley heights of the bone irregularities since especially foci of high stresses tend to appear in and around these asperities. Apparently there is no upper limit to the value of thickness of the cartilaginous layer with respect to this stress-lowering effect. On the other hand deformation of articular cartilage during motion gives dissipation of kinetic energy which is perceived as an internal resistance of the motion-performing system. This effect can be compared to the rolling resistance of a soft tire of a motor car. For this reason the thickness of the deformable layer should be restricted to an optimal minimum. An optimal thickness will keep the energy losses also at a minimum in the case of a fairly great incongruity. But then its capacity for spreading the concentrated stresses will become insufficient for obvious geometrical reasons and an additional mechanism becomes necessary.

This second mechanism is provided by intra-articular discs or menisci, which fill the free space in joints with such a large incongruity as the temporomandibular joint and the knee joint have. It is very important to realize that the main structural component of the menisci is formed by circumferentially orientated collagen bundles which are tensed as soon as the axially loaded femur expands the meniscal ring. Thus the meniscal surfaces are brought in close contact with the articular surfaces of the femur and tibia. This force-transmitting function of the meniscus has been experimentally illustrated by Seedhom (1974) whereas predictions from a simple theoretical model point at the same (Sauren et al., 1983). Another supposed mechanical function of the menisci and of articular cartilage in general is shock absorption. However, Radin et al. (1973) produced experimental evidence which suggested that attenuation of peak dynamic forces was not so much a function of synovial fluid and articular cartilage as far more a function of the underlying bone. Kempson (1979) demonstrated mathematically that a relevant damping effect of the cartilage layer could only be expected if the cartilage was noticeably less stiff and more elastic compared with the constitutive features of the underlying bone. Besides, the layer should have a substantial thickness. As said before, this demand may be in conflict with a low articular resistance to motion.

The configuration of the free natural surface of articular cartilage is still disputed. Observation of specimens, either frozen or fresh, followed by various histotechnical procedures and the use of LM, TEM, SEM or studies of the tracings of cast replicas have led to rather conflicting opinions with respect to the question whether or not there are several categories of undulations, shallow pits, humps or pores at the free surface (Bloebaum & Wilson, 1980; Gardner et al., 1981; Hesse 1981; Ghadially et al. 1982; Boyde & Jones, 1983).

To-day even authors, who held opposite views regarding the surface configuration, agree that the different preparative techniques which were in current use have a profound effect on the condition of the cartilage specimen under study and thus on its eventual geometric appearance. Meanwhile there is now a growing amount of evidence that fresh and unloaded articular cartilage has a smooth surface. There are also indications that apart from the question regarding its geometry the free surface is covered by an aggregate which may consist of lipids, a specific proteoglycan and perhaps hyaluron-bound components adhering to the superficially running collagen bundles and contributing to lubrication (Swann, 1978; Swanson, 1979; Hesse, 1981, McCutchen, 1983). Besides, Hesse showed that immobilization of joints and prevention of their normal weight bearing function may lead to an eventual though reversible disappearance of this surface-bound aggregate.

It must be noted, however, that even the most subtle technique may produce at best reliable pictures of the cartilage in its very condition only, just before processing. Not without reason Ghadially and other authors stressed time and again that their pictures do not provide immediate and conclusive evidence regarding the condition of articular cartilage in vivo. Meanwhile the question is not of academic interest only because several theoretical models, developed in order to explain the lubrication of joints, presuppose the existence of a surface roughness. In the light of what has been said before any valid theory on lubrication must take into account that the actual configuration of the cartilage structure may change under the varying loading conditions. Cartilage is a composite structure which is subjected to interlocked stresses, governed by the continuous interaction of the tension-resisting collagen fibres as well as the swelling pressure of the interfibrillary matrix with its capacity of binding water. It is therefore doubtful whether a pure morphological study of the cartilage surface only will contribute to a solution of the problems regarding the interaction of cartilage and synovial fluid in lubrication. On the other hand a thorough analysis of the physico-chemical factors governing the configuration of the cartilage structure and thus its surface in various histotechnical procedures may be very conclusive. The development of suitable models simulating the mechanical behaviour of cartilage under varying loading conditions during physiological motions, might also be an attractive and ultimately rewarding strategy. A large obstacle to such an endeavour is the lack of valid data concerning the mechanical properties of living material so badly needed for these models.

Kinematic Aspects of the Surface Elements

Since long the kinematic significance of the articular geometry has been judged against the construction of technical connections with their congruous surface contact, such as ball-head joints, hinges or screws. According to this view all geometrical shapes of joint surfaces are essentially parts of any axisymmetric surface. Even the geometry of saddle joints and ellipsoid joints was idealized as a compromise between two different, though somewhat comparable, axisymmetric surfaces (ring and spindle shape). One assumed that, apart from the knee joint with its kinematically inevitable incongruity, the incongruence of other joints was compensated for by the elasticity of the cartilage layer, or that only parts of the joint surface had an axisymmetric shape with a corresponding kinematic function (A. Fick, 1854; Dönitz, 1903; Fischer, 107; R Fick, 1911); Bausenhardt, 1949). This concept was very attractive because the axis of motion was completely defined by the axis of symmetry of the generic surface.

Another concept however started from the assumption that incongruity was a principal feature of living joints and it accentuated, in contrast with the former views, the restrictions of surface contact (Goodsir, 1868; Walmsley, 1928; MacConnail, 1969). MacConnail distinguishes only two principal geometric types of the joint surfaces: an ovoid and a saddle type, with all modifications conceivable. Meanwhile neither of the two former concepts give an answer to the question why a noticeable incongruity is found so frequently and in so many different types of joints. Although it is clear that the articular geometry plays an important role in the guidance of joint motion, by accepting incongruity as a typical feature of living joints, the problem arises how the guiding contact areas are selected during motion. To solve this problem one should pay attention to the kinematical significance of the connecting elements, especially the passive elements or ligaments. Yet a second approach proved to be very attractive: the use of models which are based on the principle of a closed kinematic chain. As even ligaments as construction elements can be incorporated in these models; their kinematic aspects will be considered with respect to such models.

The Ligaments and their Functional Aspects

Many attempts have been made to analyse the force transmission by ligaments. Its clinical relevance is beyond any doubt. Unfortunately, such studies meet with great problems. Firstly, ligaments are often badly defined anatomical entities. Indeed, continuity of its connective tissue is such a striking feature of the organization of living organisms that it should not be neglected, although this continuous

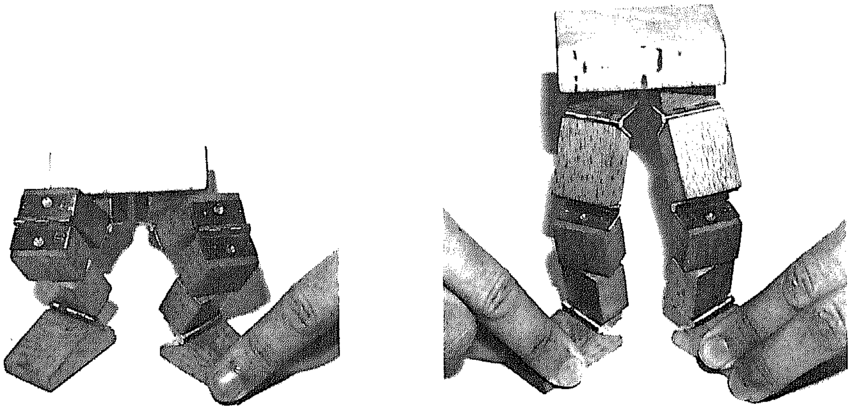

Fig. 1 Model of the human lower limbs based on a closed kinematic chain (explanation in text)

system admittedly has its local reinforcements, which can be more or less artificially isolated and identified as ligaments. Furthermore, the knowledge of the complex mechanical properties of biological materials is very incomplete. This hampers the development of the otherwise so attractive mathematical models. The same can be said of the kinematic aspects, though it may be worthwhile to dwell some more upon this side of the problem.

With respect to their kinematical function ligaments received much less attention, in contrast with the geometry of articular surfaces. Perhaps the first theoretical approach is Petersens' "Bänderkinematik" (kinematics of ligaments) from 1918. Many investigators have tried to test experimentally which fibres tightened or slackened during which movements and which abnormal movability resulted after cutting various ligaments. However, relatively few attemps have been made to analyse the relationship between the articular geometry and the arrangement of fibres as closely co-operating functional determinants. The only exception might be the knee joint with its cruciate ligaments (Strasser, 1917; Schwarz, 1944; Knese, 1950; Barnett, 1953; Huson, 1974, 1983; Wismans, 1980; Van Dijk, 1983) and more recent studies on carpal and tarsal kinematics (Huson, 1965, 1982; Kauer, 1974). In these studies the attention is focussed on the typical motion-guiding arrangement of ligament fibres of differential length. The predicted characteristics of the motions occurring in several tarsal joints (Huson, 1961, 1982) could be confirmed in an extensive roentgenphotogrammetric analysis (Van Langelaan, 1982, 1983). As has been said before, the closed kinematic chain proves to be a good model for the analysis of the mechanics of joints, joint complexes or even larger parts of the locomotor apparatus. A closed kinematic chain comprises a certain number of rigid bodies which are connected to each other in a movable way, each having at least two connections, It may move in one plane only or in space. Not only bones can be conceived as parts of a kinematic chain, but this applies to ligaments as well as long as their fibres are kept taut. The latter condition may be one of the functional effects of the presence of (incompressible) bones as elements of the chain. Muscles may be seen as links with a variable length. Models based on a closed kinematic chain have been used not only in the study of a single, though complex joint like the knee, but also for poly-articular systems such as the carpus and the tarsus or larger subsystems like the pelvis with the lower extremitites. A closed chain has a specific (constrained) motion pattern when its configuration meets certain conditions. Closure of an open chain with a specific number of links and types of joints reduces the freedom of motion predictably. The reduction is, of course, not only quantitative but qualitative as well in the sense that the initial free and variable mobility of the system is reduced to a more limited and mathematically predictable motion. This effect may be considered as *stabilizing* or *muscle saving* and its specifications depend, as we have seen, on certain characteristics of form and dimensions of the chain. The muscle-saving effect is illustrated by the depicted model in which pelvis, legs and bottom are conceived as a closed spatial kinematic chain. If the muscles restrict the hip, knee and ankle motions to simple but non-coaxial hinge motions, the model can keep its upright position, although none of its joints has reached a stable end position. To maintain this position only the feet must be kept firmly to the ground as friction is too low to achieve this. As soon as one of the feet is allowed to slip away the model tumbles down. Torsion in the shaft of the bones of the lower leg, together with exorotation of the legs which prevent coaxiality of the joints, is one of the critical conditions to be met in order to reach such a muscle-saving stability. It is these conditions that illustrate the kinematical relationship between form and function of the assembled joints.

The tarsal mechanism has also been simulated by a closed spatial kinematic chain. In this case the chain had a constraint motion: it moved in a completely specified way and had one degree of freedom only. Most investigators have neglected this typical feature of the tarsal movements. Starting from this kinematical condition and the given number of participating bones and articulations it proved to be very unlikely that the intertarsal joints could perform

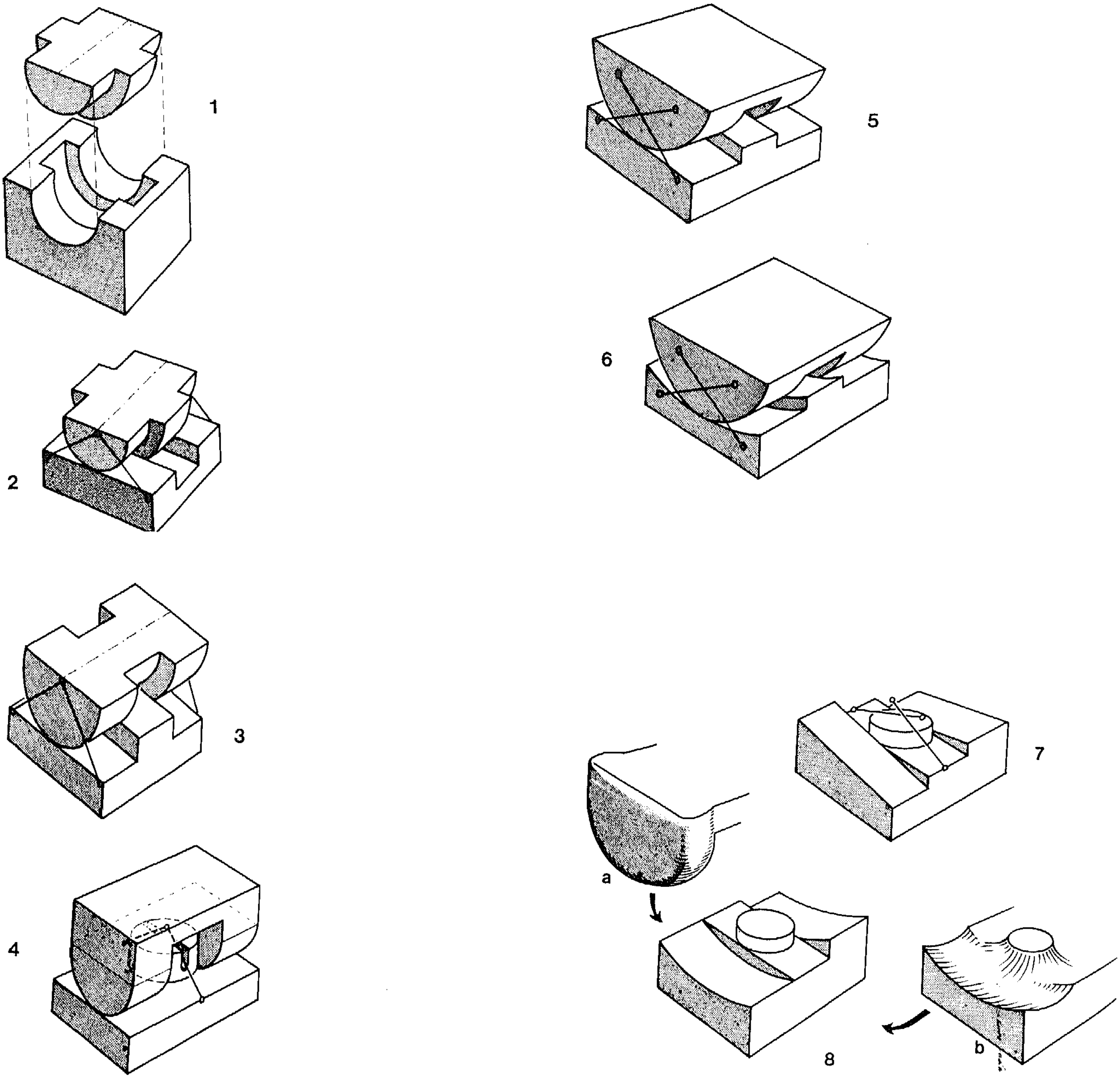

Fig. 2 Schematic drawing of a hinge joint like the humeroulnar joint. It has congruent articular surfaces with a ridge-and-groove arrangement to prevent sideward translation

2. In this drawing the facets are highly incongruent and therefore mooring ligaments must locate the hinge axis.

3. Now the ridge-and-groove arrangement has been inverted, which introduces a bicondylar male surface.

4. The ridge has been reshaped into a disc and the mooring ligaments have been given a central position, which opens the possibility of an additional rotation.

5. and 6. The mooring ligaments are cross-wise inserted. This results in a shifting axis of rotation running through both points of intersection of the bilateral cross-wise running ligaments.

7. In this drawing reshaping of the ridge into a disc has been repeated, while the cross-wise running ligaments occupy a central position. As they will wind up or unwind during rotation around a vertical axis, one of the tibial plateau halves has been given an appropriate slant with respect to the other one.

8. In the last figures the facets have been given a more rounded shape. (Reproduced from Acta Morphol. Neerl.-Scand. 1983 by courtesy of the publisher)

their function as simple hinge joints. Theoretically there are several combinations possible, but in each of them at least two joints should have two degrees of freedom or more. Besides, two adjacent joints should not have a common axis, because if so the intercalated bone can rotate around this axis independently and thus without any consequence with respect to the integrated motion pattern of the entire mechanism. Therefore, neighbouring joints should not be spherical joints, but ply-axial condylar joints instead, which do not meet the principle of axisymmetry. This means at the same time that they will show an inevitable incongruity during their movement. This again leads to the conclusion that ligaments must play an important role in the guidance of motion and select which part of the articular surface will act as motion-guiding contact areas.

Finally, the application of the closed kinematic chain to the knee joint disclosed a number of characteristic kinematical features of this joint. The configuration of the simulated ligaments, whether crossed or uncrossed, proved to be very significant mechanically for such parameters as the direction and position of the instantaneous axes and the rolling and gliding behaviour of the condyles with the corresponding translation velocities of their surfaces. These theoretically derived variations of the configuration of the ligaments show the essential significance of the cruciate alignment. On the other hand, although the form of the articular surfaces proved to depend immediately on the arrangement and insertion points of the guiding ligaments, each chosen set of the latter can be combined with an infinite number of pairs of contact surfaces. In such a set the directions and positions of th successive instantaneous axes will remain unchanged, although the translation velocities between the contact surfaces will vary with their varying geometry. If the model is conceived as a three-dimensional one, the typical possibility of external and internal rotation of the flexed knee can be added. This requires further adaptations of the geometry of the articular surfaces whic correspond very well to several morphological features of the knee. By use of this conceptual procedure the knee joint could be developed starting from a simple hinge-joint model. This clarified typcial anatomical and functional features of the knee, which contrast sharply to the simple hinge (Huson, 1983).

In conclusion, models such as those described above offer a more comprehensive approach to the study of mechanics of joints and they open perspectives for further research in the interdisciplinary field between the technical and the morphological sciences. One must realize, however, that their validity is based on the sound application of mechanical laws to the structure and function of living organisms. They illustrate some mechanical aspects of these organisms. Such an application does not imply that organisms are principally complex machines which could be understood completely if analysed by a comprehensive and detailed biophysical theory.

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