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Editor of series: Nenad Radojković, e-mail: radojkovic@ni.ac.yu
Address: Univerzitetski trg 2, 18000 Niš, YU
Tel: +381 18 547-095, Fax: +381 18 547-950
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ON TECHNOMORPHIC MODELLING OF BIOLOGICAL JOINTS

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Gerhard Bögelsack, Cornelius Schilling

Institut für Mikrosystemtechnik, Mechatronik und Mechanik
Fakultät Maschinenbau,Technische Universität Ilmenau
D-98684 Ilmenau, PF 0565, Deutschland
e-mail: gerhard.boegelsack@maschinenbau.tu-ilmenau.de

Abstract. *This paper deals with the problem of classification of joints. As comparable elements biological and technical joints have not yet classified in such a way that could enable us a satisfactory comparison. Here, the proposals for such classification are given.*

Key words: *biological and technical joints, classification*

1. INTRODUCTION

In design bionics [1] great efforts are made to derive from biological models appropriate ideas for new technical systems. Engineers in robotics, prosthetics, micromechanics are particularly interested in motion systems. In general, biological motion systems are characterized by a high degree of mobility, lithe movement and minimal deployment of material. Comparable elements of biological and technical systems are the joints, but up to now there is no classification that satisfactorily allows to compare both of them. The following paper deals with this problem, analyses the features and prepares proposals for classification of joints.

2. STRUCTURE OF MOTION SYSTEMS

The basic model of a motion system [2] contains actuators A, mechanisms Ü, effectors W and controllers S, related to a reference system B (Fig. 1). In biological systems the reference system is the trunk, effectors are for example legs, hands, fingers. Actuators are

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the muscles which transform chemical energy into mechanical work. The mechanisms are formed by limbs, joints, tendons and ligaments. Neural control is not considered in this paper.

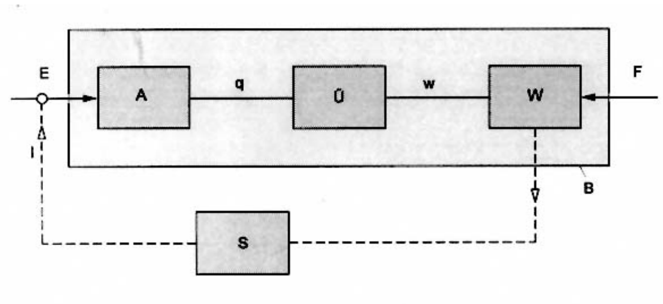

Fig. 1. Basic structure of a motion system; B reference system, A actuator, Ü transmission mechanism, W effector, S control element, E input energy, F external force, I control information, q and w generalized coordinates.

The structure of support in vertebrates is the bony endoskeleton, in arthropods the chitin exoskeleton. Joints connect the limbs in mostly open kinematic chains. Muscles can only work during contraction. They generate only tensile forces which are to be transmitted to the limbs by length-constant but flexible tendons. To turn back the movement needs (at least) one other muscle which acts in the opposite direction. This antagonistic function of flexors and extensors is a principal feature of biological motion systems. It allows also to lock a limb by means of isometric contraction of simultaneously activated antagonists.

Joints in skeletons generally permit only rotatory relative movements. The muscle-generated translatory input motion with coordinate s is to be transformed into rotatory output motion with coordinate φ (Fig. 2). Reference limb, muscle, tendon, joint and driven limb form a closed kinematic chain with the transfer function $\varphi = f(s)$. Only two mechanism elements can be considered as rigid (bone or chitin, resp.). Others are compliant, the system is a compliant mechanism.

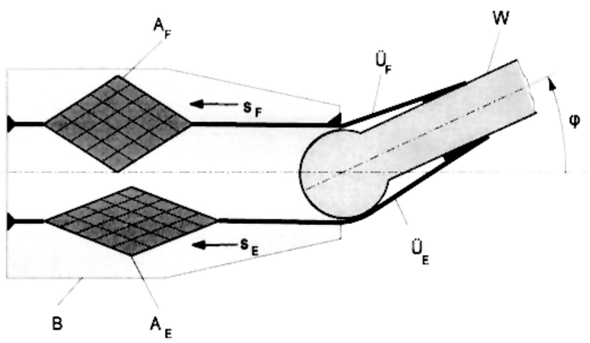

Fig. 2. Antagonistic muscle drive; indices E and F stand for extension and flexion, resp.

3. STRUCTURE OF JOINTS

A joint in a motion system is the connection of adjacent parts which allows their relative mobility in a certain *degree of freedom*, abbr. d.o.f. This definition emphasizes two characteristics: connection and mobility. Principally there are three different possibilities to make a movable connection: i) one joint element encloses the other (form closure), ii) both of the joint elements are kept in contact by a compressive force (force closure), iii) the joint is formed by an anisotropic compliant segment of a limb (material coherence).

Each biological joint is more or less materially coherent, purely in synarthroses. In diarthroses coherence embodied by ligaments, tendons, capsules is coupled with force closure and partial form closure. To prevent disarticulations, sometimes besides the tensile effects of ligaments and tendons also load-depending compressive effects of pericapsule muscle bodies are used (e.g. hypomochlia, rotator cuff).

The certain degree of freedom is necessary in open kinematic chains to guide a link relative to the adjacent one in a determined way and in closed kinematic chains with respect to the guidance function of adjacent joints to secure the mobility of the whole system. Guidance of a driven link is influenced by the shape and arrangement of corresponding joint surfaces (form guidance) as well as by external forces applied on the link (force guidance). Only in a few kinds of joints the axis of relative motion is defined only by form (cylindrical joint, prismatic, joint, screw joint). In most of the biological joints form and force are acting simultaneously. In anatomy the terms "muscle guidance", "ligament guidance" and "soft tissue guidance" are known.

Some examples are shown in Fig. 3. The human shoulder joint in a) has a partial form closure which allows spherical movement. The desired path of the elbow, however, will be determined by force guidance. Another example more is the human eye in b) eyeball and eye cave are in a kind of spherical form closure, the eyeball is force guided about two axes. A dysfunctional rotation about the third, the optical, axis is prevented by means of the outer eye muscles. Finally in c) is shown a finger joint in the plane of flexion and extension. The outlines of basis and caput are approximated by incongruent circles. They need to have force closure and - beside form guidance - also force guidance.

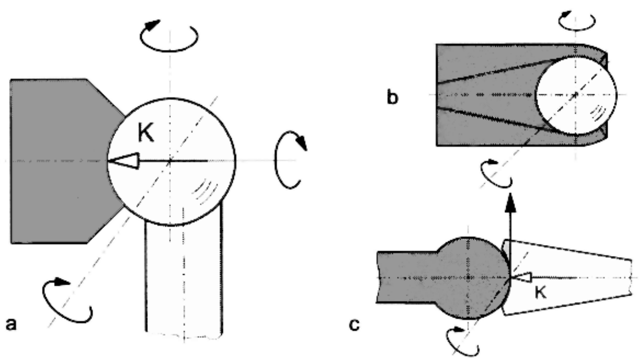

Fig. 3. Form and force guidance; a shoulder joint, b eye "joint", c finger joint, K contact force.

In the extreme case only force closure and force guidance are to be found, for example in the movable connection of shoulder-blade and trunk of certain mammals [3], in zoology known as *synsarcotic connection* [4]: The shoulder-blade moves between muscles layers approximately in a plane (Fig. 4) and has the possibilities to translate in two axes and to rotate about the axis orthogonally to both of the others. A generalized model of this joint is to be seen in Fig. 5.

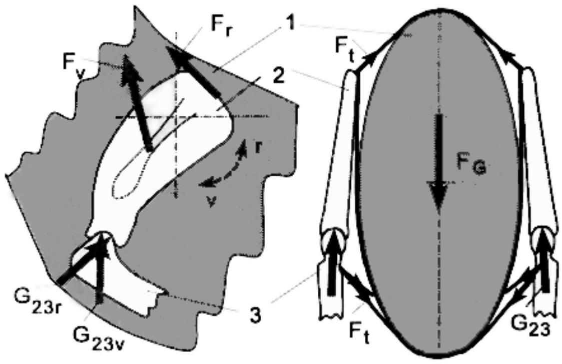

Fig. 4. Force closure and force guidance; *synsarcotic connection* of trunk 1 and shoulder-blade 2 in dogs; upper arm 3, joint force G_{23}, force of gravity F_G; forward-pulling forces F_v, G_{23v}; backward-pulling forces F_r, G_{23v}; supporting forces F (Index 23 means: force on link 2 from link 3).

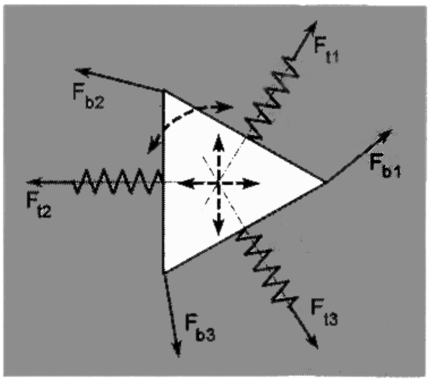

Fig. 5. General model of a force-guided planar joint d.o.f. $f = 3$; driving forces F_b; supporting forces F_t.

One of the most important features of joints is the degree of freedom *f*. It is defined as the number of independent coordinates needed to describe the relative positions of pairing (corresponding) elements [5]. Usually the d.o.f. of technical rigid body joints is derived from geometrical properties.

Taken into account the possibilities of translation and rotation and the relative arrangements of their axes there are 11 different basic variants of joints. Where the form is not closed, force closure is needed to keep the elements in contact. Biological rigid-body joints (*diarthroses*), if classified with respect to the form of their rigid elements, show some similarities with technical joints. The examples d, e, f in Fig. 6, however, are of the same kinematic value due to their one-point contact. The form-determined d.o.f. $f = 5$ has no practical significance, it is reduced to an *effective d.o.f* by means of ligaments and tendons which take up tension forces only, whereas in the points of contact of the rigid elements only compression forces can be transmitted. In contrast to most of the technical joints, in biological joints the reaction to external forces and moments are one-axial states of stress. This design principle of differentiation between functions offers certain prospects of finding new kinds of technical joints. One example is the "*constrained double-joint*", designed for application in industrial robots [7]. It is using the human knee as a model. Fig. 7 shows the double-joint in which rigid bodies are provided to take up compression forces and ligaments are loaded by tension forces. The angle of rotation is realized by a kind of planetary wheel set (Fig 8).

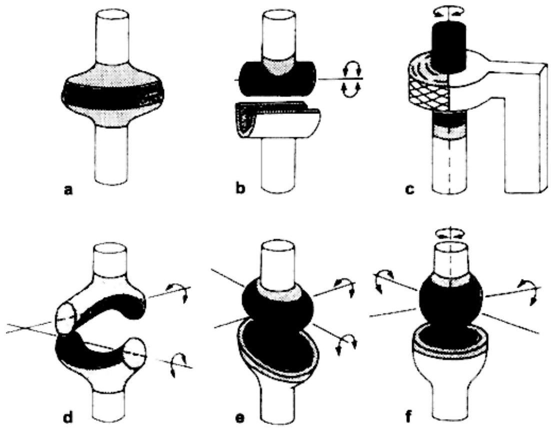

Fig. 6. Types of biological joints (adapted from [6]); a Articulatio plana, b Ginglymus, c Art. trochoidea, d Art. sellaris, e Art. ellipsoidea, f Art. spheroidea.

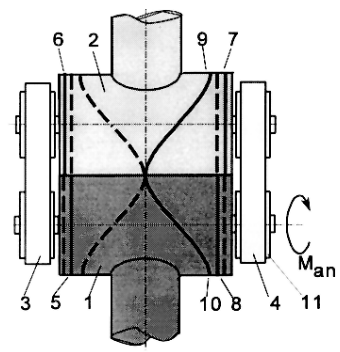

Fig. 7. Double-joint (adapted from [8]); 1 fixed wheel, 2 circulating wheel, 3,4 cord, 5,6,7,8 lateral cord, 9,10 crucial cord, 11 driving wheel.

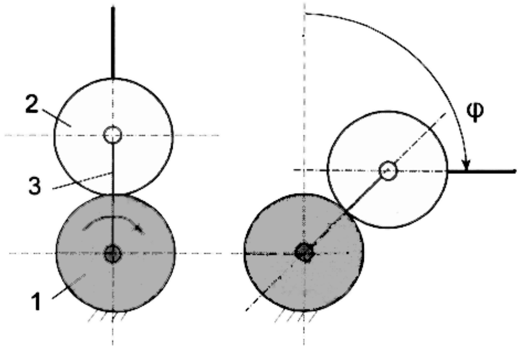

Fig. 8. Principle of planetary wheel in doublejoints [8]; 1 fixed wheel, 2 circulating wheel, 3 circulating link.

4 KINETOSTATIC ANALYSIS

In general the curvatures of corresponding surfaces in biological joints are not constant and the circles of curvature of related convex and concave surfaces are not congruent [9]. That means the geometric d.o.f. can be changing within the range of relative motion of a joint. During the transition from $f = 1$ to $f = 2$ (see Fig. 9) and the motion with $f = 2$ the relative instanteous axis of rotation will be displaced. (A similar effect caused by wedge-shaped guidance happens in the human ankle joint at the *trochlea tali*).

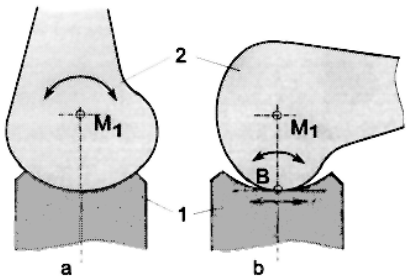

Fig. 9. Transition from $f = 1$ to $f = 2$ [10].

Modelling of joints is impeded by the influences of *cartiilage* and *synovia*. Therefore, in the following analysis of a joint of the human middle finger in the plane of flexion and extension only rigid elements are considered. Since the d.o.f. is $f = 2$ the joint is comparable with a technical *cam pair*. Position and orientation of the moved *phalanx* is determined by the curvature and the applied forces.

Generally the limbs of vertebrates are subjected to external strain by the gravitational force and function-depending resistance (e.g. in processes of locomotion, manipulation, prehension). Additionally the dynamic forces of inertia are acting. These forces have to be kept in equilibrium by the muscle-generated driving forces which cause flexion or extension, adduction or abduction of the respective l-imb. Equilibrium of a driven link is given when the sums of all applied forces and moments are zero. If friction is negligible, contact surfaces in joints take up forces perpendicular to the tangential plane of contact. Therefore the line of action of a joint force G at the point of contact B has to pass both the centres of curvature of the surfaces. In the finger joints (as in other joints of extremities) the lines of action of muscle forces are determined by the shape of bones and joints. That means, force guidance is also influenced by the structure of skeleton: The magnitude of a force vector is *functionally*, its direction *structurally* determined. Fig. 10 describes the forces at the middle phalanx with the index 2. Basic phalanx has index 1, end phalanx index 3. In the indication of forces the first index means the link on which the force is applied, the second index, where the force has its reaction. Inversion of indices means change of sign. Links which are situated more proximal than the reference link 1 are taken as to be part of the reference link. As a result of a functional force at the finger tip link 2 should be loaded by the joint force G_{23}. The flexor force is F_{21} Further forces are joint force G_{21} and ligament force Lg_{21}. The line of action of the extensor is e_{21}. Dividing of force G_{23} into three components of given directions is solvable by means of *Culmann's* force C. The result is a relatively big joint force G_{21}. In the chosen position the ligament force Lg_{21} is not very important.

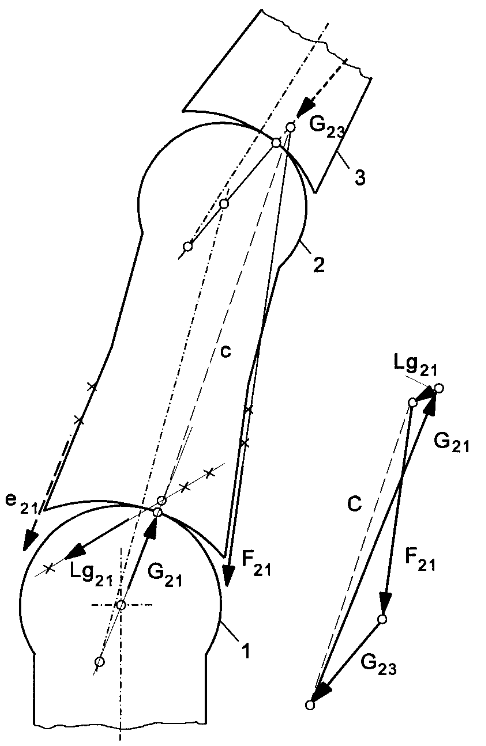

Fig. 10. Forces at a middle phalanx.

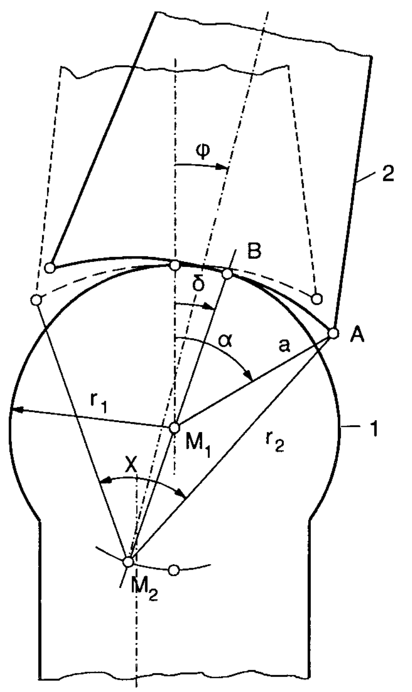

Fig. 11. Geometry of a finger joint.

The position of link 2, expressed by the angle of rotation φ and the angle of position δ of point B, is to be described by the given radii of curvature r_1, r_2, sector angle X and the coordinates a and a of an arbitrary point A. According to d.o.f. $f = 2$ the angles φ and δ are independent from one another. Their actual ratio is determined by the position of the instantaneous pole of rotation P_{12}. When P_{12} coincides with the centre of curvature M follows $\delta = \varphi$, point B slides on the contour of link 1. If P_{12} coincides with B, link 2 rolls on link 1 without sliding. In general P_{12} is placed on the straight line normal to the plane of contact in point B. Pole P_{12} is to be found as the point of intersection of the perpendiculars of the path tangents of all points of a moving plane.

With respect to the strain of cartilage and synovia the ratio λ of rolling to sliding seems to be an interesting parameter of biological joints. It is defined as the quotient of the covered section of the moved contour to the covered section of the fixed contour during the relative joint motion [11]. Having the pole, $\lambda = (u_B - v_{B21}) / u_B$ (Fig. 12), where v_{B21} the velocity of B and uB the velocity of the change of B (proportional to the pole velocity u) [12].

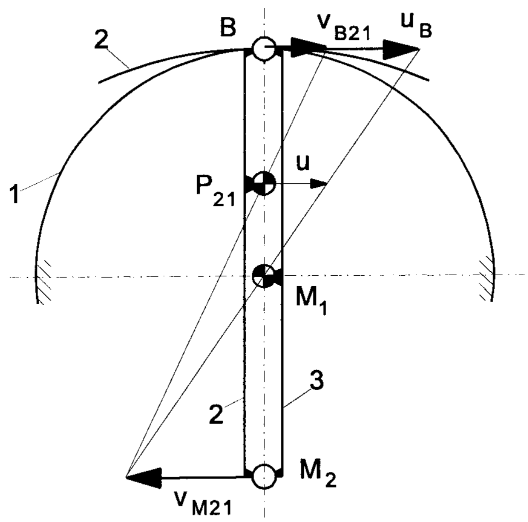

Fig. 12. To ratio of rolling-sliding (see text).

5. Conclusions

1) Aspects that are generally used for classification of rigid-body joints can be applied on biological joints, too. They are, however, to be completed by those aspects coming from materially coherent connections and their combination with the other kinds of closure. Furthermore, the specific kind of guidance by controlled forces and the avoidance of compound stresses are to be taken into account. The following survey shows a summary of all characteristics:

- Degree of freedom ($f = 1...6$) with additional information on the kind of relative motion (rotation, translation) and alignment of axes (orthogonal, parallel);

- Variability of the degree of freedom within the range of relative motion with additional information on the means by which change is caused.
- Restrictions of the range of relative motion (by form, force, material coherence)
- Kind of stress in the motion-locking elements as reaction to external forces and moments (compression, tension);

Joints having surfaces of rigid elements in contact (*Diartihroses* in *exo*- and *endoskeletons*) need some aspects more:

- Maintenance of closure (by form, force, material);
- Guidance of adjacent elements (by form, force, material);
- Geometry of contact (point, line, surface);
- Behaviour in contact (sliding, rolling, drilling).

In the case of joints being in material coherence exclusively (*Synartihroses*) information is needed on deformability i.e. properties of material *(modulus of elasticity, gradient of density, texture*) and geometrical parameters (*shape and area of cross-section*).

2) Examples show that biological joints offer possibilities helping to find new solutions for technical joints in robotics and prosthesis. Particularly for application in micromechanics biological motion systems are very interesting: Micromechanisms need structures which could be made of one piece, as far as possible without any assembling processes. Internal mobility can be achieved by means of compliant joints.

3) Kinetostatic analysis allows to assess the strain of the joint elements and the other elements of the motion system. It serves as completion of experimental biomechanical investigations and is an essential prerequisite for computer simulation of the real motion processes. Each joint has to have its specific model based on geometric, kinematic, dynamic and material parameters of the biological system. Reliable parametrization and successful modelling need close cooperation of biologists and engineers.

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O INŽENJERSKOM MODELISANJU ZGLOBOVA ŽIVOTINJA

Gerhard Bögelsack, Cornelius Schilling

Ovaj rad se bavi problemom klasifikacije zglobnih veza. Kao uporeivi elementi, biološke i tehničke zglobne veze još uvek nisu klasifikovane na takav način koji bi nam omogućio zadovoljavajuće upoređenje. Ovde su dati neki predlozi za jednu takvu klasifikaciju.