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The morphology of the articular surfaces of biological knee joints provides essential guidance for the construction of functional knee endoprostheses

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Purpose: In comparative examinations of kinematics of the knees of humans and pigs in flexional/extensional motion under compressive loads, the significant differential geometric essentials of articular guidance are elaborated to criticise the shaping of the articular surfaces of conventional knee-endoprostheses and to suggest constructional outlines that allow the endoprosthesis to adopt natural knee kinematics. Implantation is discussed with regard to the remaining ligamentous apparatus.

Methods: Twelve fresh pig knee joints and 19 preserved human knee joints were moved into several flexional/extensional positions. In each joint, the tibia and femur were repeatably caught by metal plates. After removing all ligaments, the tibia and femur were again caught in these positions, and their points of contact were marked on both articular surfaces. Along the marker points, a thin lead wire was glued onto each surface. The positions and shapes of the four contact lines were mapped by teleradiography.

Results: All contact lines were found to be plane curves. The medial and lateral planes were parallel, thus defining the joint's sagittal plane. In the human knee, as compared to the lateral, the medial femoral contact line was always shifted anteriorly by several millimetres. The tibial contact curve was laterally convex and medially concave. In the pig knees, the lateral and medial contact lines were asymmetrically placed. Both tibial curves were convex.

Conclusions: Both knees represent cam mechanisms (with one degree of freedom) that produce rolling of the articular surfaces during the stance phase. Implantation requires preservation of the anterior cruciate ligament, and ligamentous balancing is disadvantageous

Key words: *knee arthroplasty, kinematics, biomechanics, knee, endoprosthesis, pig*

1. Introduction

Conventional knee endoprostheses (total knee replacements, TKRs) are technically not able to imitate the initial rollback of the femur [17], [22], [23]. TKRs consist of a femoral and a tibial device. The artificial femoral articular surface is usually dumb-bell shaped. Laterally and medially, the TKR features a common symmetry axis of rotation (A_F). The lateral and medial artificial articular surfaces of the "tibial plateau" are sagittally concave. Usually, both "plateau" surfaces have a common axis of rotational symmetry (A_T). The sagittal curvatures of the "tibial plateau" are smaller than those of the femoral articular surface. Therefore, in the extended TKR, axis A_T is located proximal to axis A_F. Similarly, the articular surfaces of mobile-bearing endoprostheses exhibit two axes of rotational symmetry (A_F, A_T) with a proximally located tibial axis A_T.

This geometrical configuration, in which a concavity guides a convexity and vice versa, functionally represents an overlapping dimeric link chain [10]. Dumont et al. [4] have shown that (a) exactly this configuration of the articular surfaces is evident in the proximal interphalangeal joint (PIPJ) of the human finger, (b) in flex-

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ion out of extension, the joint space of the PIPJ opens at the palmar side, (c) the two contact spots in the PIPJ then migrate dorsally, (d) the corresponding instantaneous axis of rotation (IRA) is parallel to the rotational axes of the medial and proximal articular surfaces, and (e) the IRA lies between them. Because of this constructively implemented PIPJ-mechanism, the aforementioned TKR families with or without mobile bearings must structurally demonstrate the features of PIPJ-kinematics. During flexion, the joint space should open at the posterior side, the contact spots or the bearings should migrate to the anterior side, and the IRA should be positioned far from the contact spots. Through *in vivo* [1], [2], [20] and *in vitro* [21] studies, this (paradoxical for the knee) PIPJ-kinematics was demonstrated for these TKR families. As a result, knee endoprostheses, like the PIPJ, constructively exhibiting the same overlapping dimeric link chain at the lateral and medial side, cannot be stimulated to rolling of the articular surfaces by the muscular apparatus. Because the torques around the axes A_F and A_T, produced by the flexing muscles, have the same sign, the IRA is necessarily located between these axes: The IRA is far away. To determine how this medial/lateral symmetry can be modified so that, in flexion, the contact spots migrate posteriorly not only on the femoral but also on the tibial articular surfaces to achieve partial rolling of the articular surfaces, we analyse the kinematical features of biological knee joints (BKJ).

When loaded by a compressing force, a lateral and a medial contact spot are formed between the incongruous articular surfaces of the tibial and femoral condyles. Under this force closure, the contacting articular surfaces guide the motions of the knee [3], [14]. This articular guidance is automatically given when skeletal muscles act over a BKJ, for physical reasons. Two contact points means that articular guidance at most allows four kinematical degrees of freedom (DOF) for the relative motions between the femur and the tibia. When stimulated by the skeletal muscles, the BKJs of domestic pigs (BKJP) or of humans (BKJM) exhibit almost planar motion during flexion/extension [16], [19]. The muscular apparatus cannot actively produce abduction/adduction; in the BKJM, active stimulation of small axial rotations is only possible in deep flexion [8].

Two basic questions arise:

A. Which mechanisms come into operation when the articular surfaces of the BKJ guide flexion/extension?
B. Which biomechanical roles do the ligamentous apparatus play in the BKJ?

To answer the first question, in Section 2 we relate the curvature morphology of the articular surfaces to the main function of flexion/extension. For this purpose, we (a) experimentally determined *in vitro* the lines along which, in flexion/extension, the contact points migrated on each individual articular surface in each compartment, (b) determined the spatial curvatures of the contact lines, (c) compared the spatial positions of the medial and lateral contact lines, and (d) thus evaluated the cam mechanisms of flexion/extension.

To answer the second question, in Section 3 we discuss the mechanical roles and sensory aspects of the ligamentous and meniscal apparatus both in the literature and from our own data.

2. Material and methods

2.1. Morphological demonstrations of flexion/extension

Fresh or preserved BKJ (with almost natural mobility), possessing the entire ligament apparatus and the menisci, were moved under force closure into several positions of flexion/extension. In each position, the tibia and femur were caught by metal plates, which were fixed to the bones with screws (Fig. 1). By using these plates, the tibia and femur could be repeatedly returned to each of the chosen positions, as described in Fig. 1. These repositionings were also performed after removing all ligaments, the menisci, and the capsule. The contacts between the femoral and tibial condyles were therefore visible and could be marked on each articulating surface. By connecting these marks with lines, contact curves in flexion/extension were uncovered on the tibial and femoral articular surfaces. We thoroughly examined each contact curve visually and using circle templates. All contact curves were found to be planar and not spatially bent. Additionally, the planes in which the lateral and medial contact curves ran were found to be parallel in almost all BKJ. For these cases, the normal vector of the sagittal planes was thereby functionally defined. To compare the sagittal positions of the lateral and medial contact curves, thin lead wires were glued along the marked lines. For each BKJ, the femur and the tibia were again repositioned in their mounts and the relative sagittal positions of the respective contact curves were determined by lateral teleradiography.

A total of 19 (10 left and 9 right) BKJM were investigated. The BKJM were preserved using a solution that did only marginally alter the stiffness and

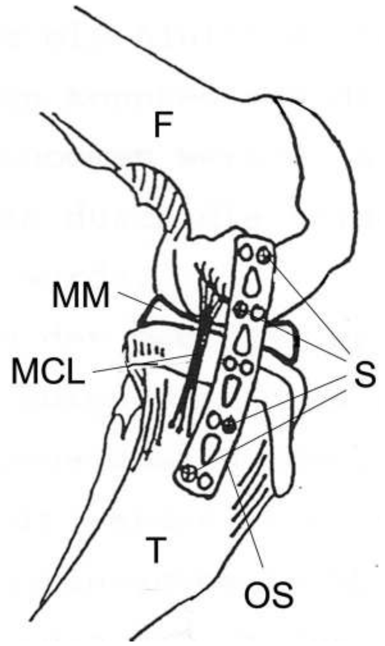

Fig. 1. Evaluation of the contact lines: *F* – femur, *T* – tibia, *MM* – medial meniscus, *LCM* – medial collateral ligament, OS – ostheosynthesis plate, S – screw
The knee, still possessing the entire ligament apparatus, was brought into the natural home position (flexional angle: ≈100°). Femur and tibia were fixed in a frame. Each bone was rigidly connected to an osteosynthesis plate at the medial and lateral side with two screws in each bone. After releasing the fixation of the femur, the bone was brought in a flexed (or extended) position and again fixed to the frame. In this new position the femur was again screwed to the plates. New screw holes defined the new femoral position. The same procedure was applied to further femoral positions, which could be then repeatedly located. After removing the entire ligamentous apparatus of the joints, the femur was successively brought into the flexional/extensional positions, which were defined by the screw holes afore. In each joint position the appearing joint space between the articular surfaces was moulded by using precision techniques well established in dentistry. After removing the osteosynthesis plates and the fixations in the frame the contact points on the tibial and femoral articular surfaces were found by the casts of the joint spaces putting them in accurately fitting position onto the respective tibial or femoral articular surfaces

hardness of the bony structures or the elastic properties of the ligaments. Thus, comparable to fresh specimens, the articular surfaces could maintain their dominance in guiding movement when the joints were moved under force closure. The 12 (7 left and 5 right) BKJP used were fresh.

3. Results

BKJP: We found that, for flexion/extensional motions under force closure in all 12 specimens, (a) the lateral and medial contact curves formed by these motions were planar, (b) the respective contact curve planes were parallel, (c) the two femoral plane contact lines were guided by the two tibial plane contact lines, and vice versa, and (d) neither the femoral nor the tibial contact lines exhibited any symmetrical relations. The BKJP were found to be kinematically constrained cam mechanisms possessing only one kinematical DOF. Further, the four contact lines of the cam mechanism were found to be approximately circular (Fig. 2a). Hence, two femoral (M_{FM}, M_{Fl}) and two tibial (M_{TM}, M_{Tl}) axes could be empirically defined in the BKJP. The four observed contact circles were defined in the natural position of standing (Fig. 2b). In this home position of the knee, the angle between femur and tibia was approximately 110°. The cam mechanism could be approximated by the equivalent four-bar-chain of the four parallel axes (M_{FM}, M_{Fl}, M_{TM}, M_{Tl}). We then determined the lengths of the bars and the radii of the four contact circles (Table 1).

BKJM: In 17 of 19 BKJM studied, the lateral and medial planes in which the pairs of femoral and tibial contact curves were located were found to be parallel. The respective femoral contact curves (c_{Fm}; c_{Fl}) were almost circular, though their anterior/posterior positioning revealed a distinct asymmetry between the lateral and medial sides (Fig. 3a). The curves were staggered in the anterior/posterior direction: the centre (M_{Fm}) of the medial femoral contact curve was found to be shifted by a small distance F to the anterior compared to the lateral centre M_{Fl}. These centres (M_{Fm}; M_{Fl}) necessarily represented the lateral projections of the two femoral rotational axes, which were perpendicular to the sagittal planes. The approximately circular tibial contact curves were laterally convex and medially concave. Centres M_{Tm} and M_{Tl} represented the lateral projections of the two tibial rotational axes with distance T (Fig. 3b). Analogous to the BKJP, the cam mechanism of the human knee can be approximated by an equivalent four-bar-chain of four parallel axes (M_{FM}, M_{Fl}, M_{TM}, M_{Tl}). In Table 2, the lengths of the bars and the radii of the four contact circles are summarised. A spatial illustration (Fig. 4) shows qualitatively (a) the four axes (M_{FM}, M_{Fl}, M_{TM}, M_{Tl}) of the equivalent four-bar-chain in the extended (home) position of the BKJM, (b) the transverse section lines of plane (M_{Fl}, M_{Tl}) through the lateral condyles, (c) the transverse section lines of plane (M_{Fm}, M_{Tm}) through the medial condyles, (d) the contact spots K_l and K_m at the median slopes of the articular surfaces, and (e) the IRA as the intersection line of plane (M_{Fl}, M_{Tl}) with plane (M_{Fm}, M_{Tm}).

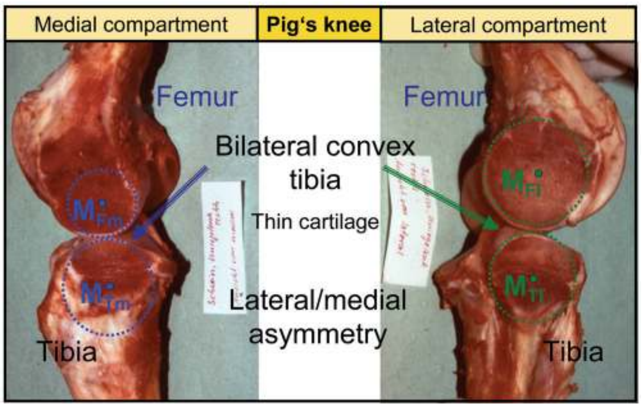

Fig. 2a. The circular contact curves shown above ensure that neither the femoral axes M_{Fm} and M_{Fl} nor the tibial axes M_{Tm} and M_{Tl} coincide

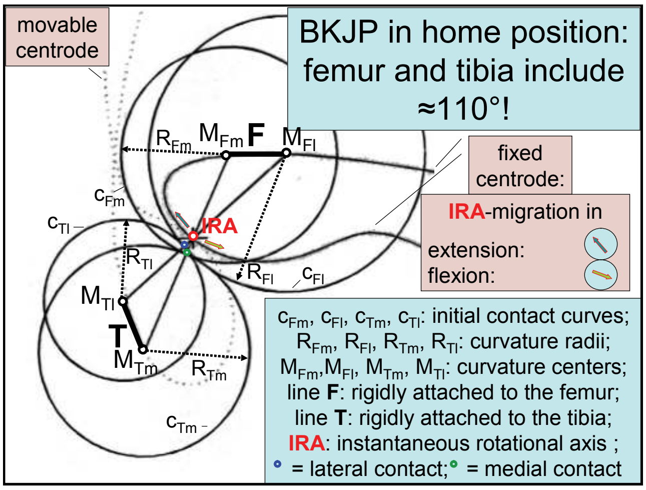

Fig. 2b. The two femoral axes M_{Fm} and M_{Fl} and the two tibial axes M_{Tm} and M_{Tl} are linked to a constrained link quadrangle. In home position, the instantaneous rotational axis (IRA) is located close to the lateral and medial contacts. The articular surfaces predominantly roll out in flexion as well as in extension from this resting position in flexion as well as in extension

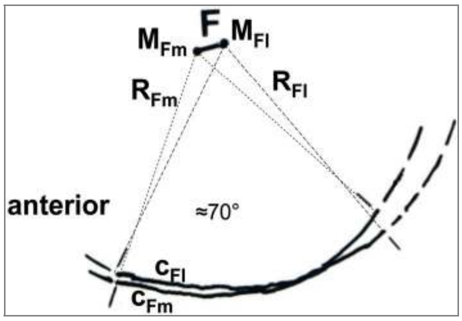

Fig. 3a. Teleradiography of a femur in lateral projection yields sagittal tracings of the femoral contact curves made visible by lead wires glued along them (medial: c_{Fm}; lateral: c_{Fl}). The curves exist in parallel planes. c_{Fm} and c_{Fl} were approximated by circles (medial centre: M_{Fm}, medial radius: R_{Fm}; lateral centre: M_{Fl}, lateral Radius: R_{Fl}). F – distance between the two femoral axes defined by the centres of the contact curves

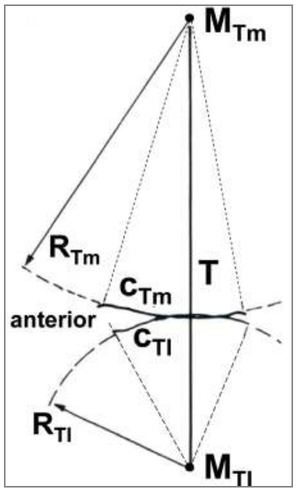

Fig. 3b. Teleradiography of a tibia in lateral projection yields the sagittal tracings of the tibial contact curves, made visible by lead wires glued along them (medial: c_{Tm}; lateral: c_{Tl}). The curves exist in parallel planes. The concave c_{Tm} and the convex c_{Tl} were approximated by circles (medial centre: M_{Tm}, medial radius: R_{Tm}; lateral centre: M_{Tl}, lateral Radius: R_{Tl}). T – distance between the two tibial axes defined by the centres of the contact curves

Table 1. BKJP, mean values and standard deviations of the radii of the contact curves and the distances between adjoining axes: femur: $F = (M_{Fm}, M_{Fl})$; tibia: $T = (M_{Tm}, M_{Tl})$; lateral compartment: $R_l = (M_{Tl}, M_{Fl})$; medial compartment: $R_m = (M_{Tm}, M_{Fm})$

	Mean/mm	SD/mm
R_{Fl}	27.0	2.8
R_{Fm}	20.1	2.2
F	10.1	3.7
R_{Tl}	15.0	3.1
R_{Tm}	20.1	2.0
T	8.0	2.8
$R_l = R_{Fl} + R_{Tl}$	42.1	3.7
$R_m = R_{Fm} + R_{Tm}$	40.2	2.7

Table 2. BKJM, mean values and standard deviations of the radii of the contact curves and the distances between adjoining axes: femur: $F = (M_{Fm}, M_{Fl})$; tibia: $T = (M_{Tm}, M_{Tl})$; lateral compartment: $R_l = (M_{Tl}, M_{Fl})$; medial compartment: $R_m = (M_{Tm}, M_{Fm})$

	Mean/mm	SD/mm
R_{Fl}	26.5	5.1
R_{Fm}	28.5	5.3
F	7.8	2.3
R_{Tl}	51.1	7.1
R_{Tm}	76.4	8.7
T	125.2	11.2
$R_l = R_{Fl} + R_{Tl}$	48.5	6.9
$R_m = R_{Fm} + R_{Tm}$	78.2	8.9

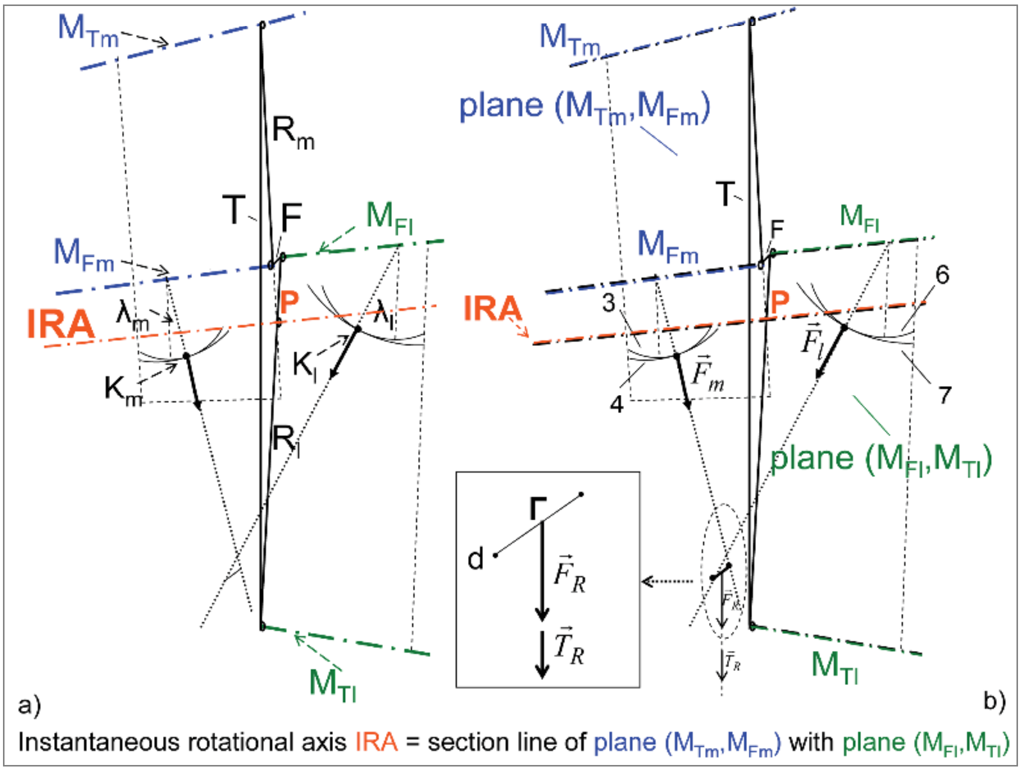

Fig. 4. Initial four-bar-chain of the BKJM in home position formed by the medial axes M_{Tm} and M_{Fm} and the lateral axes M_{Tl} and M_{Fl}. In flexion out of home position, the articular surfaces are predominantly rolling because the IRA is located close to the contact centres K_m and K_l. Intersection lines 3, 4, 6, 7: transversal contours produced by the intersections of the planes (M_{Tm}, M_{Fm}) and (M_{Tl}, M_{Fl}) through the respective condyles of the medial and lateral compartments. The contact centres are located at the median slopes of the tibial and femoral condyles. The two articular forces $\vec{F}_m$ and $\vec{F}_l$ run normal to the articular surfaces at the contact points K_m and K_l. $\vec{F}_m$ and $\vec{F}_l$ form a force wrench with torque $\vec{T}_R$

4. Discussion

4.1. Kinematical meaning of the joint morphology

By the lateral and medial pairs of the plane tibial/femoral contact curves, articular guidances were described for flexion/extension and traced back to cam mechanisms. The normal of the functional sagittal planes was coherently defined for the cases in which the lateral and medial planes of the tibial/femoral pairs of contact curves were parallel. We could not detect any symmetrical relations between the lateral and medial femoral or between the respective tibial contact curves. Consequently, the cam mechanisms are constrained, possessing only one kinematic degree of freedom. Geometric measures defined the fixed and mobile centrodes whose momentary contact, representing the instantaneous rotational axis (IRA), depended on the angle of flexion/extension. Thus, we disproved the widespread hypothesis that an anatomically determined knee axis would exist in the BKJ, defined by a line connecting the centres of both femoral condyles. As the femoral contact curves approximately represented circles in the angular range from 0° to ≈70°, four axes could be defined by the lateral and the medial pair of contact curves, and the constrained cam mechanisms for flexion/extension were functionally approximated by equivalent four-bar-chains describing flexion/extension up to approximately 70° flexion (or approximately 70° extension in the BKJP). The chains of the BJKM and the BJKP belong to the category of double rockers possessing two dead-centre positions.

In the two BKJM cases observed for which the planes of the lateral and medial contact curves were not parallel, flexion/extension exhibited increasingly complex, constrained spherical (intersection of the four axes in a common intersecting point) or helical (no intersection of the four axes) motions.

The most important functional property of the cam mechanisms was that, in the extended (home) position of each BKJ, the IRA was positioned close to the medial and lateral contact spots (Figs. 2b, 4, 5). This position of the IRA determines that, in both BKJ categories, the articular surfaces are predominantly rolling out of home position.

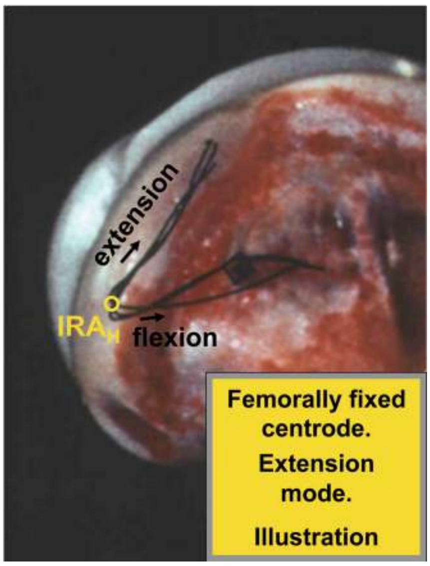

Fig. 5. BJKP: Illustration of the femorally measured fixed centrode of the instantaneous rotational axis (IRA) with home position IRA_H. In extension mode, the IRA migrates along the femoral articular surface: the tibial articular surface predominantly rolls along the femoral surface

BKJP: We found anatomically remarkable peculiarities in the BKJP: The medial tibial condyle was convexly shaped in the sagittal plane. The sum $F + R_m$ was nearly equal to the sum $T + R_l$ (Table 1a), or the mean difference $U = (F + R_m) - (T + R_l) = 0.17$ mm (SD = 1.23 mm) was statistically not differentiated from zero on the basis of the 12 specimens. Thus: (a) in home resting position, the BKJP four-bar-chains were in a double dead-centre position (the two dead-centre positions coincided); (b) out of home position the BKJP could use two modes of IRA-migration; (c) in one mode, the articular surfaces were rolling in extension (Fig. 5); and (d) in the second, the flexional mode, the surfaces were also rolling. The BKJP possesses a type of gearshift containing a reverse and a forward gear to provide rolling in extension *and* in flexion. As we have observed in experiments on enlarged models of the four-bar-chain (constructed by Plexiglas rods), when exclusively in home position, the BKJP can be switched from the flexional to the extensional mode and vice versa by applying a short impulse of a small axially directed torque. We emphasise once more: The BKJP (Fig. 2b) are kinematically optimised under high external loads for extensional or flexional motions because the femoral articular surfaces predominantly roll along the tibial surfaces in both kinematic modes. Using an open 6R position measuring chain, Heine [6] localised the migrating IRA in one fresh BKJP for the extensional mode (Fig. 5). He found that, in the extension mode out of home position, the IRA was positioned close to the articular surfaces (minimising friction under the high compressing load of the jumping pig).

Other quadrupeds, such as horses or sheep, also possess convex lateral and medial tibial articular surfaces. The mechanisms of these BKJ appear to be similar to that of the pig.

BKJM: For more than 100 years, it has been clear that the articular surfaces in the BKJM roll in the stance phase of human gait. As early as in 1836, the Weber Brothers observed that, in knee flexion out of extension, the contact spots migrated to the posterior not only on the femoral but also on the tibial articular surfaces [25]. From that observation, they inferred that the femoral articular surfaces were rolling on the tibial articular surfaces. Fischer [5] summarised previous *in vivo*, *in vitro*, and radiographic measurements of knee movement and determined that from full extension the articular surfaces initially roll and then predominantly slide medially for angles of flexion >15° and laterally for angles >20°, whereupon the contact points become fixed on the "tibia plateau". Walker et al. [24] confirmed the initial contact migration on both tibial sides to the posterior at angles of flexion up to 25°. Li et al. [11] reported that, laterally and medially, the contacts on the tibia plateau would migrate for angles of flexion up to 30°. For their studies, they used a computer model based on *in vivo* measurements made by Dual-Orthogonal Fluoroscopy and Magnetic Resonance. Nägerl et al. [15] re-analysed the MRT-data of the Freeman group [18]. Their data confirmed the initial rolling for angles up to approximately 20°. Wismans et al. [26] developed a computer model based on empirically recorded articular surface morphologies and reported similar results for the contact migrations. They implicitly showed that specifics of articular surface morphology were responsible for this unique knee kinematics, which is adapted to the human gait. Friction is minimised by rolling when the BKJM is under a high compressive load during the stance phase. During the unloaded swing phase, the BKJM is sliding and the contact points are stationary on the tibial articular surfaces. However, medical students are commonly instructed that the human knee operates like a hinge, and in conventional TKR-families a femoral knee axis is implemented. In these arbitrary assumptions, the relation between the well-known rolling of the BKJM in the stance phase and the geometric arrangement of the articular surfaces are factored out. Our data substantiate the anterior shift of the medial femoral condyle and disclose the crucial constructional element in the BKJM with which the initial rolling of the loaded knee during a human gait is made possible by both the shapes and the arrangement of the articular surfaces. Thus, the presented data prove the assumptions used by Nägerl et al. [14] to describe basic mechanical properties of the BKJM, and empirically support the design principle of a novel total knee replacement with initial rolling articular surfaces [13].

4.2. General constructional hints

As discussed in the introduction, concavely shaped tibial articular surfaces produce paradoxical knee kinematics. A common axis of the lateral and medial femoral articular surfaces inevitably leads to a hinge joint in the case of different articular tibial curvature morphology at the medial and lateral sides. In developing total knee endoprostheses for the BKJM that functionally imitate the natural initial rolling of the articular surfaces, two aspects are important: (a) the medial femoral articular surface must be shifted to the anterior, and (b) the lateral tibial articular surface must be sagittally convex. Thus, natural knee kinematics in flexion/extension can be achieved for a TKR by implementing a constrained cam mechanism with a suitable asymmetric shaping of the guiding structures.

In the AEQUOS G1-prosthesis, these two constructional aspects were taken into account. The medial femoral condyle is shifted to the anterior and the lateral "tibia plateau" is sagittally convex. Wachowski et al. [22], [23] have shown, through *in vivo* kinematic measurements based on lateral fluoroscopy, that this TKR rolls to a high degree during small intervals of knee flexion.

4.3. Articular guidance and the ligamentous apparatus

4.3.1. Morphological and functional pre-conditions

In the lateral and medial condyle, the contact points between the femoral and tibial articular surfaces are located on the median slopes of the tibial articular surface (Fig. 4). Thus, the passive DOF of BKJ (axial rotation, abduction/adduction) are stabilised like a travelling trolley when a compressive force is acting. In the case of the unloaded knee, the ligamentous apparatus holds the articular surfaces close to their physiological spatial allocations, which are determined by the muscular force closure. Simultaneously, the ligamentous apparatus represents a sensory device. It records the actual relative spatial positions of the femur and the tibia. As shown by Zimny et al. [27], the cruciate ligaments are settled by Ruffini and Pacini mechanoreceptors that are located between the ligament fibres, as Nägerl et al. [12] have ascertained. This explains the receptors' sensitivity to shear strain. The receptors localise the transition layer between regions of slack and tensed fibres. The size and location of these regions and the position of the transition layer in the bundles of cruciate ligaments depend on the actual spatial knee position, particularly with regard to the degree of flexion/extension. Taking the entire ligamentous apparatus into account in search of mechanoreceptors, Nägerl et al. [12] proved, using fresh BKJP, that not only the cruciate but also the collateral ligaments and the tibial suspensions of the menisci are settled by Ruffini receptors, especially nearby the origin and insertion of the ligamentous bundles. They could exclude Ruffini settlements in force transferring ligaments such as the patella, and therefore showed that only those ligamentous bundles in which the distribution of tensed and slack fibres is correlated with the instantaneous relative spatial allocation of the femoral and tibial articular surfaces are settled by mechanoreceptors. They concluded that the apparatus of this ligamentous bundle represents a 6D measuring device recording the actual relative spatial position of femur and tibia. The different ligament bundles are thereby focused to measure certain DOF of BKJM-position: the suspensions of the menisci are mainly related to axial rotation and the cruciate ligaments to flexion/extension.

Johansson et al. [7] noted that the afferent signals of the mechanoreceptors control, via the CNS, the distribution of muscular tone in the muscular apparatus acting over the knee. Thus, the resulting force of the muscular apparatus must be adjusted in terms of the absolute values of force and torque applied plus the spatial position of the screw axis. As this control of muscular tone requires approximately 40 ms (the signal relay time via the CNS), the resulting force can only be forecasted for future knee positions. Nägerl et al. [14] have noted that each given flexional/extensional BKJM position can be balanced by diverse muscularly adjusted resulting wrenches (force screws) belonging to a distinct set. Each balancing wrench of this set is correlated with a certain degree of mechanical stability of the related BKJM position. By adjusting these force screws, the degree of stability can be altered from instability to stability and vice versa. When a given BKJM position is put into a certain degree of instability by a particular force screw, this force system may also be able to balance a second BKJM position, which is then definitely mechanically stable. Or, when a current BKJM position is made instable by a certain distribution of the muscular tone in the muscular apparatus, it is possible that the future knee position is held in a stable equilibrium by the related force screw. The adjustment of a mechanically stable future knee position simultaneously generates a certain degree of instability in the initial BKJM position.

In [9], it has been have shown that, for arbitrarily chosen positions of a BKJP, the equilibrium in flexion/extension can vary from stability to instability (and vice versa) through variations of the distribution of muscular forces. This variation of the degree of stability is possible because the number of DOF of the muscular apparatus is higher than that of the DOF of knee position. The *in vitro* measurements required for these conclusions were performed using seven fresh BKJP.

4.4. General functional hints

For a functioning knee endoprosthesis, which should largely restore natural knee function, one must not only reconstruct the natural guidance of the articular surfaces but also care for the approximately physiological allocations of the artificial articular surfaces by the ligament apparatus and preserve the sensory apparatus in the ligament bundles as much as possible. At minimum, the posterior cruciate ligament and the collateral ligaments should not be sacrificed. The remaining ligament bundles must not be "balanced" by cutting small parts of these bundles because these cuts deactivate parts of the sensory function within these bundles. It is similarly beneficial to preserve the anterior cruciate ligament.

5. Conclusions

To achieve approximately natural knee kinematics with artificial knee endoprostheses, the lateral tibial articular surface must be sagittally convex and the curvature of the lateral and medial compartments must not be symmetrically related.

The ligamentous apparatus should largely be preserved to achieve physiological allocations of the artificial articular surfaces.

Ligament balancing should be avoided to preserve the sensory function of the remaining ligament bundles.

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