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Original paper

Construction-conditioned rollback in total knee replacement: fluoroscopic results

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Firstly, the way of implementing approximatively the initial rollback of the natural tibiofemoral joint (TFJ) in a total knee replacement (AEQUOS G1 TKR) is discussed. By configuration of the curvatures of the medial and lateral articulating surfaces a cam gear mechanism with positive drive can be installed, which works under force closure of the femoral and tibial surfaces. Briefly the geometric design features in flexion/extension are described and construction-conditioned kinematical and functional properties that arise are discussed. Due to a positive drive of the cam gear under the force closure during the stance phase of gait the articulating surfaces predominantly roll. As a result of rolling, a sliding friction is avoided, thus the resistance to motion is reduced during the stance phase.

Secondly, in vivo fluoroscopic measurements of the patella tendon angle during flexion/extension are presented. The patella tendon angle/knee flexion angle characteristic and the *kinematic profile* in trend were similar to those observed in the native knee during gait (0°–60°).

Key words: *total knee replacement, kinematic profile, rollback, roll-back fluoroscopy, patella tendon angle, kinematics, knee*

1. Introduction

PANDIT et al. [1] raised the issue whether the total knee replacements (TKR) available on the market are able to reproduce the natural initial "rollback" of the femoral articulating surfaces observed with native knees flexing out of extension. This particular kinematic characteristic of the natural tibiofemoral joint (TFJ) was described by FISCHER [2] over a century ago. The natural initial rollback affects the backward migration of both contact spots on the tibial articulating surface, thus opens the anterior and closes the posterior joint spaces, and gives rise to the posterior slewing of both menisci. NÄGERL et al. [3], [4] pointed out that the initial rollback, which proceeds mainly in the first 30° of flexion [2], [5], [6], solves the problem of friction kinematically during the stance phase of gait when the TFJ is highly loaded in compression. Re-examing three major publications of FREEMAN et al. [7]–[9], who reported the in vivo measurements of TFJ flexion/extension using MRI, NÄGERL et al. [4] summarised that, in the stance phase of gait, the articulating surfaces were predominantly rolling in the lateral and medial compartments.

According to PANDIT et al. [1] the rollback of the femur induces posterior rotation of the patellar tendon. Thereby compression of the patellar femoral joint (PFJ) would be reduced because the angle ψ between the quadriceps and patellar tendons, and hence between the associated lines of the tendon forces, remains flat during flexion [10], [11].

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Anterior knee pain is often reported after conventional TKR. This complication may be due to mechanical reasons: the reduction in posterior rotation of the patellar tendon may lead to the acuteness of the angle ψ, thus to an increase in the load experienced in the PFJ [10], [11].

The complex biomechanical properties of the natural TFJ pose a significant challenge to researchers working on the development of total knee replacements. Previously our research group presented a novel TKR (AEQUOS G1) with four kinematical degrees of freedom (DOF) like the natural TFJ, and reported on its design in general: the data presented were based on some results of the approved tests performed to show mechanical stability of the kinematic DOFs at small ranges of motion [12], wear rates [13], and additionally on first clinical experiences [14]. Static fluoroscopic measurements could already be presented as the first hints about the presence of the constructional intended rollback in vivo [11]. In the current work, we discuss the question of an approximate implementation of the initial rollback of the natural TFJ in the AEQUOS G1 TKR by shaping the articulating surfaces. We explain briefly constructional features characterizing flexion/extension (four-bar linkage) and discuss its construction-conditioned kinematical and functional properties. Then, we present new in vivo measurements of the patellar tendon angle during flexion/extension.

2. Methods

Figure 1 presents a rough method of measuring the patella tendon angle (PTA = β), depending on the flexion angle φ in the lateral X-ray pictures. In extension (3°) and 46° flexion, X-ray pictures were taken from a patient who was provided with AEQUOS G1 TKR [15]. The patella tendon (PT) in flexion was oriented posteriorly. The measurements of angles suffered validity because the reference (tibia) was axially rotated during flexion (as can be seen by comparing both pictures).

A more valid method for recording the patella tendon angle as the function of knee flexion angle (i.e., the function $\beta = \beta(\varphi)$) was presented by PANDIT et al. [1] and REES et al. [16]. Instead of two single X-ray pictures in lateral projection, an entire video fluoroscopy is performed. Then, the well-known 3D-data of the implanted TKR is used to correct the errors in the sequent fluoroscopic frames which are caused by the changing of the internal reference of the TKR. The errors are as

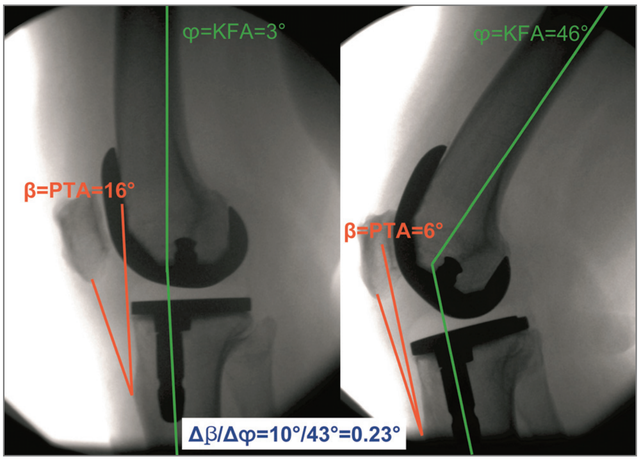


Fig. 1. Two X-ray pictures of the same patient with implanted AEQUOS G1. Left – knee nearly in extension: flexion angle $\varphi = 3°$. Patellar tendon angle $\beta = 16°$ (reference: tibia). Right – flexed knee, $\varphi = 46°$. The patellar tendon pivoted backwards by 10° around its insertion at the tibial tuberosity: $\beta = 6°$

follows: a) the changing of TKR position in the X-ray beam, b) the rotation of the prosthesis and respectively of the whole system position (including patella position), and c) an additional tilt. By means of these corrections the validity of the measurements of patella tendon angle (PTA = β) and knee flexion angle (KFA = φ) could be enhanced. To do so one line representing the tibia and a second one – the femur were marked in approved frames by lines along the dorsal margins of the bones [1], [17] in order to measure the knee flexion angle φ. Then the tibial tuberosity and the distal pole of the patella were connected with a line to mark the line of action of the patella tendon. The patella tendon angle β was taken to be that between the tibial line and the line of action of the patella tendon (figure 1). Thus, the patella tendon angle/knee flexion angle relationship or characteristics ($\beta = \beta(\varphi)$) of each individual could be recorded.

During the video fluoroscopy 8 frames per second were recorded (Arcadis Varis, Siemens Healthcare, Erlangen, Germany). The patients with the operated leg stood on an approximately 250-mm high step, hence the initial knee flexion angle (φ) was approximately 90°. Each patient was then asked to perform a step exercise on one leg until full extension. They were allowed to use a side bar for stability and safety. Furthermore they were asked to practice till they felt confident. Then the video fluoroscopy recording of the activity was performed. In the second exercise, a deep knee bend (lunge) was done on the same step to achieve a maximum knee flexion. Two observers analysed the same images.

Patients

14 patients (7 females, 7 males; 64.9 ±6.5 years; median: 66 years, range: 73–51 years) participated in the examination. All of them received an AEQUOS G1 TKR by the same surgeon, at least one year prior to the measurement. Three patients had bilateral TKR. Consequently 17 AEQUOS G1 were measured. The outcome of all implantations was assessed by the following clinical scores: a) American Knee Society Score (KSS; 0–200 points; 0: worst, 200: best), b) Oxford Knee Score (OKS; 0–48 points, 0: worst, 48: best), and c) Visual Analogue Scale Pain Score (VAS: 0–10 points; 0: best, no pain, 10: worst, maximal pain).

The study was approved by the local ethic committee and the Federal Office for Radiation Protection. Each patient gave informed consent before participation.

3. Results

3.1. Clinical data

All the patients participating in the study achieved good to excellent results in the clinical scores (the table). Mean values: 190.6 points in the American Knee Society Score (KSS), 0.9 point in the Visual Analogue Scale Pain (VAS), 45.2 points in the Oxford Knee Score (OKS).

The mean Body Mass Index (BMI) of the patients was 30.2 kg/m^2 (±3.8 kg/m^2): all of them were either overweight (25<BMI<30) or obese (BMI > 30).

3.2. Patella tendon angle–knee flexion angle characteristics

Figure 2 shows the measured patella tendon angle–knee flexion angle characteristics ($\beta = \beta(\varphi)$): a) the normal group characteristic measured from extension up to 130° flexion by PANDIT et al. [26], b) AEQUOS group step experiment from 90° flexion to extension, c) AEQUOS group lunge experiment from 60° to 120°. Considering the error bars it can be seen that the patella tendon angle/flexion angle relationship of the AEQUOS group and that of the normal group were similar, particularly in the range from 0 to 80° flexion. The trends of the characteristics of the normal group and the AEQUOS group for the step-up activity were similar up to 60° of knee flexion.

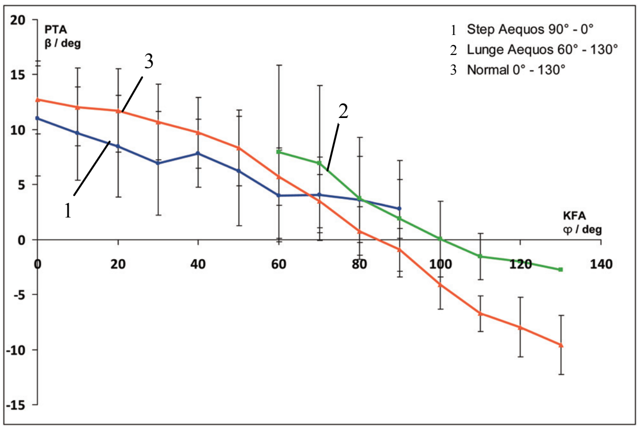


Fig. 2. In vivo measurements of patella tendon angle–flexion angle characteristics ($\beta = \beta(\varphi)$, β = PTA = patella tendon angle, φ = KFA = knee flexion angle). Normal group 3; AEQUOS group, step experiment 1; AEQUOS group, lunge experiment 2

Table. AEQUOS group: clinical and personal data

No.	Inital	Sex	Side	Weight/kg	Height/m	BMI/kgm^{-2}	Age/yrs	KSS	VAS	OKS
1	GA	f	l	84	1.76	27	73	195	0	44
2	MA	f	r	73	1.65	27	73	194	1.3	46
3	WB	f	b	72	1.60	28	62	200	0	48
4	KB	m	r	100	1.78	32	71	178	2.4	43
5	EB	f	r	95	1.65	35	71	179	0	46
6	KF	m	l	85	1.75	28	59	199	0	46
7	HF	m	l	90	1.72	30	68	199	0	45
8	RH	f	r	100	1.58	40	65	170	2.8	42
9	WoS	m	r	87	1.69	30	62	199	0	48
10	WeS	m	l	100	1.85	29	51	198	0	48
11	GS	m	b	100	1.82	30	56	199	0	48
12	MS	m	l	76	1.76	25	67	198	1	44
13	WW	f	b	85	1.67	30	68	195	1	48
14	BZ	f	r	75	1.55	31	63	165	3,7	37
Mean				**87.3**	**1.7**	**30.2**	**64.9**	**190.6**	**0.9**	**45.2**
SD				**10.6**	**0.1**	**3.8**	**6.5**	**12.1**	**1.3**	**3.1**

4. Discussion and conclusions

4.1. AEQUOS G1: Design and implementation of functional parameters

Under force closure, as it occurs in the stance phase of gait, the natural TFJ has two contact spots. Hence, according to spatial kinematics of a rigid body [18], the entire set of possible TFJ positions has four kinematic degrees of freedom. The main DOF, flexion/extension, is actively controlled by the muscles. The three further DOFs, however, cannot actively be set by the muscular system. These are ab/adduction and the two rotations around the normals of the respective contact spots. The respective changes of position can only be induced by external forces and moments. These three DOFs can, however, be parametrically stabilized by compressing the forces generated by muscles. In other words, when the TFJ is displaced by external perturbations, the manifest *stiffness* of the TFJ, associated with these DOFs, is controlled by the muscular system. The stiffness can be increased by increasing muscular force, as it was shown by in vivo measurements [19], [20]: increased muscle force reduces displacements following the given external perturbations. Finally, the TFJ returns automatically to its original position as soon as the perturbation ends (the mechanism of self-stabilization of the TFG [3], [12]).

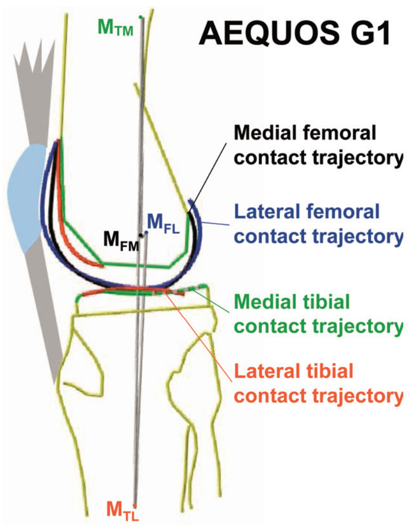


Fig. 3. Lateral view of the AEQUOS G1 total knee replacement, extended position. Dotted lines: kinematically equivalent four-bar-linkage defined by the centres of curvature of the contact trajectories: M_{FL}, M_{FM}, M_{TL}, M_{TM}
Material: Cc = cobalt chrome (femur) and PE = polyethylene (tibia)

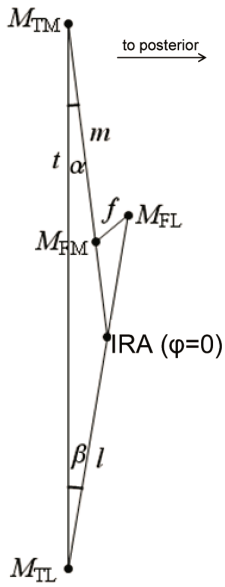


Fig. 4. Equivalent four-bar-linkage of the AEQUOS G1 TKR in extensional position: flexional angle $\varphi = 0$.
Pivots M_{TM}, M_{TL}, M_{FM}, and M_{FL} are defined by the curvature centres of the respective contact trajectories
Line $t = M_{TM}M_{TL}$, fixed in relation to the tibial bone, defines the position of the tibia
Line $f = M_{FM}M_{FL}$, fixed in relation to the femoral bone, defines the position of the femur
Line $m = M_{TM}M_{FM}$ defines the medial connecting rod
Line $l = M_{TL}M_{FL}$ defines the lateral connecting rod.
The intersection of the prolongations of line m and line f determines the position of the instantaneous rotational axis (IRA)

The only directly muscle-controlled kinematical DOF of the TFJ defines a set of flexion/extension positions. Neglecting the small [21] internal/external rotations, it is possible to move between the given set of the flexion/extension positions by the sole application of planar motions [7]–[9], [22], [23]. Therefore, it is generally possible to reproduce approximatively natural flexion/extension kinematics by means of a positive cam gear mechanism. This mechanism can be designed by a lateral and a medial pair of plane contact trajectories parallel to the sagittal plane along the articulating surfaces of femur and tibia. Under force closure the anterior/posterior positions of the contact trajectories and the specifications of their curvatures determine the kinematical properties of the cam mechanism. In order to approximate natural TFJ kinematics, the contact trajectories in the AEQUOS G1 TKR have unique shapes and particular relative positions (figure 3). The lateral tibial contact trajectory is convexly curved like the natural lateral tibial articulating in anterior/posterior direction as was first reported by the WEBER brothers [24] in 1836 and then by FISCHER [2] in 1907. Both femoral trajectories are almost circular. But, the medial circle is displaced slightly forward compared to the lateral one (figure 3). This feature is functionally indispensable. It causes the articulating surfaces of the AEQUOS G1 to predominantly roll out of extension up to 25° flexion and thus during the stance phase of gait. This statement is directly obvious, when the kinematically equivalent four-bar-linkage is considered [3] (figure 4) whose four pivots are defined by the centres of curvature of the four contact trajectories. Rationale: a) If the femoral pivots coincide and thus only one femoral axis exists (as is mostly assumed throughout the anatomical and orthopaedic literature), the TFJ or the respective TKR would be a pure hinge joint around this femoral axis (figure 4 for $f = 0$). b) Due to the anteriorly shifted position of M_{FM} in relation to M_{FL} and due to the convex shape of the lateral tibial contact trajectory the instantaneous rotational axis (IRA) can be positioned near by or slightly below the instantaneous contact spots (figure 5) for the extended knee. Hence, the cam gear mechanism spontaneously rolls out of extension. c) The anterior position of the pivot M_{FM} additionally gives rise to such a condition that, like the natural knee, the AEQUOS G1 can only be flexed out of extension [3].

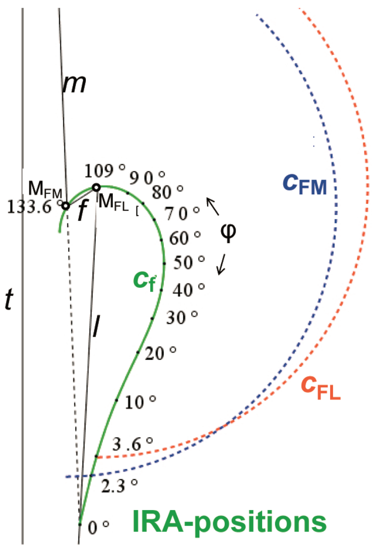


Fig. 5. AEQUOS G1: c_{FL} = femoral lateral contact trajectory, c_{FM} = femoral medial contact trajectory, c_f = construction-conditioned femorally fixed centrode, parameter φ = flexional angle. In extension ($\varphi = 0$), the IRA lies somewhat below both trajectories. The centrode of the migrating IRA intersects the medial trajectory at $\varphi = 2.3°$, and the lateral trajectory at 3.6°

4.2. AEQUOS G1: kinematic features

Main construction-conditioned kinematic characteristics of AEQUOS G1 are centrode, roll/slip ratios and migration of both contact spots on the tibial polyethylene articulating surface as function of the flexion angle. The detailed mathematical derivations of the relations from the dimensions of AEQUOS G1 can be found in Fiedler et al. (submitted to Acta of Bioengineering and Biomechanics in 2011).

Figure 5 shows the femorally fixed centrode of AEQUOS G1, for small flexions (angle φ) the IRA remains close to the femoral contact trajectories c_l and c_m: the motion is dominated mainly by rolling as is illustrated by the respective roll–slide relation (figure 6a) and by the respective positions of the lateral and medial contact spots quantified by the arc length of the respective tibial trajectory as the function of flexion angle φ (figure 6b). These construction-conditioned rolling–sliding relationships ensure that both tibial contact spots migrate back and forth during the stance phase of gait (figure 7). Thus, for the gait under load, the problem of friction is kinematically solved by the AEQUOS G1: a) The high sliding friction is converted into rolling friction. b) Static friction, occurring at the points of the reversal of motion (figure 7), and shear-stress of the polyethylene (PE) do not take place at all. Additionally, these periodic contact migrations on the tibia allow

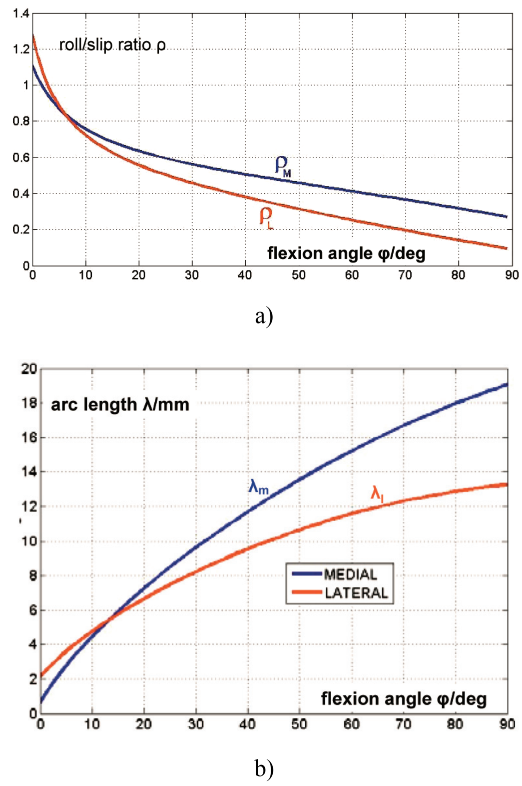


Fig. 6. Construction-conditioned roll/slip ratio of AEQUOS G1: rolling is dominant for flexion angles < 25 deg (a). Construction-conditioned positions of the contact spots on the tibial contact trajectories specified in arc lengths (b)

the synovial fluid to flow back and forth over the PE surfaces and to dissipate the heat generated during dynamic loading. As a direct consequence, the temperature of PE hardly increases though it is periodically deformed [25]. Since the rigidity and internal stability of PE are sensitive to temperature increases, the rolling also produces the necessary "cooling mechanism". These reductions of strain and stress of the PE due to a geometric design are demonstrated by a tibia–inlay which was explanted after 3.75 years: the patient died due to the reasons unrelated to the knee replacement. Figure 8 shows that the explanted inlay looks almost as new.

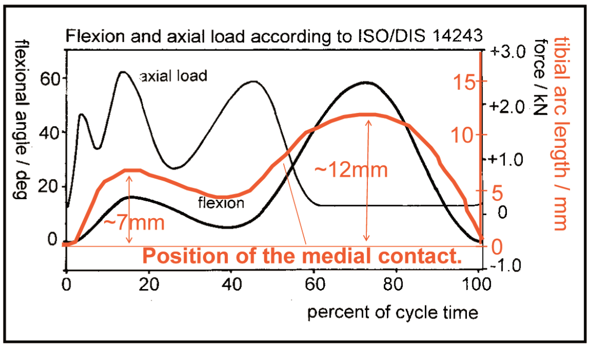


Fig. 7. Gait characteristics and construction-conditioned position of the contact along the medial tibial trajectory, specified by the running arc length. In the stance phase, the knee effectively flexes between 0–25° under high compressive loads and rolls here to a large extent: the tibial joint contacts move by ~7 mm. In 35–60° flexion, the shift of the contacts is decreased to ~2.5 mm: The ratio of sliding is increased

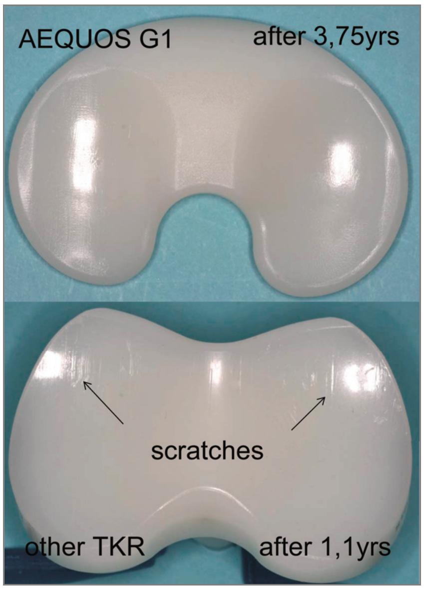


Fig. 8. Explanted tibia-inlays. Above: AEQUOS-inlay explanted after 3.75 years. Scratches could not be seen. Below: inlay from a one of the most common conventional TKR explanted after 1.1 years in which significant stress marks were seen

4.3. AEQUOS-design and functional properties

By a unique shaping of the contact trajectories in the AEQUOS-G1 TKR, a wide back and forth migration of the contact spots on the tibial polyethylene inlay occurs due to the geometric design during the stance phase of gait (figure 7). The problem of friction during the high dynamic loading in the stance phase is diminished by the positive motion of the cam gear mechanism: a) the predominant rolling of the articulating surfaces minimizes the relative velocity v_r of the tibial and femoral contact spots, b) simultaneously the polyethylene is rinsed and cooled by the back and forth motions. GALETZ et al. [25] proved by in vitro tribological testing that for the material pairing of CoCrMo/polyethylene (as it is given in the AEQUOS-G1 TKR) temperature rise ΔT in the polyethylene linearly depends on relative velocity v_r of the contact spots on the metal and polyethylene surfaces. In an experiment of rolling, the velocity v_r equalled zero. Consequently, temperature rise ΔT was practically zero. Galetz et al. concluded: "A design (of TKR) should be favourable that allows high degrees of rolling when high loads are applied". Note: temperature rise affects the material stability of polyethylene [25]. The explanted AEQUOS inlay (figure 8) supports the advantages of predominant rolling during the stance phase. Also the approved tests resulted in small wear rates [13], when the tibia inlay was loaded according to the scheme of ISO/DIS 14243 (figure 7). Hence, AEQUOS G1 is tribologically adapted to main features of human gait.

4.4. Patella tendon angle–knee flexion angle characteristics

The normal group characteristic [26] shows a significant increase of its derivative $d\beta/d\varphi$ (figure 1). Mathematically, it holds:

$$\frac{d\beta}{d\varphi} = \frac{d\beta/dt}{d\varphi/dt} = \frac{\omega_\beta}{\omega_\varphi}.$$

This means that the derived function of the characteristic represents the instantaneous ratio of the angular velocity (ω_β) of the patella tendon angle (PTA = β) to the angular velocity (ω_φ) of the knee flexion angle (KFA = φ). This kinematic ratio was termed the *kinematic profile* (KP) by PANDIT et al. [1].

$$\mathrm{KP} = \frac{d\beta}{d\varphi}$$

is mostly roughly approximated by the difference quotient:

$$\mathrm{KP} \approx \frac{\Delta\beta}{\Delta\varphi} = \frac{\Delta\mathrm{PTA}}{\Delta\mathrm{KFA}}.$$

The shape of the patella tendon angle/flexion angle characteristic of the normal group is at the first glance surprising because: a) the kinematic profile is flat for small flexion angles, when the femur predominantly rolls on the tibial plateau and b) it is steep for higher values of flexion, when the tibial contact spots are practically stationary. Therefore, two mechanisms must be responsible for the kinematic profile. Initially, KP is certainly dominated by the rollback mechanism. But when the tibial contact spots become stationary, KP can hardly be affected further by internal TFJ kinematics. Now the PFJ seems to play the main role.

Therefore it is justified to compare the kinematic profiles of the AEQUOS and the normal groups in respect of two separated ranges of flexion angle φ. They are: a) $0 < \varphi < 60°$, which corresponds to the flexion range during gait (figure 7), and b) $60° < \varphi < 120°$, which meets the range of squats. Figure 9 presents the results.

In the step experiment, both kinematic profiles coincided (figure 9). But patella tendon angle β showed a mean offset $\Delta\beta \approx -2.5°$. In further development, this offset can probably be diminished by changing the initial positions of both tibial contact spots to anterior.

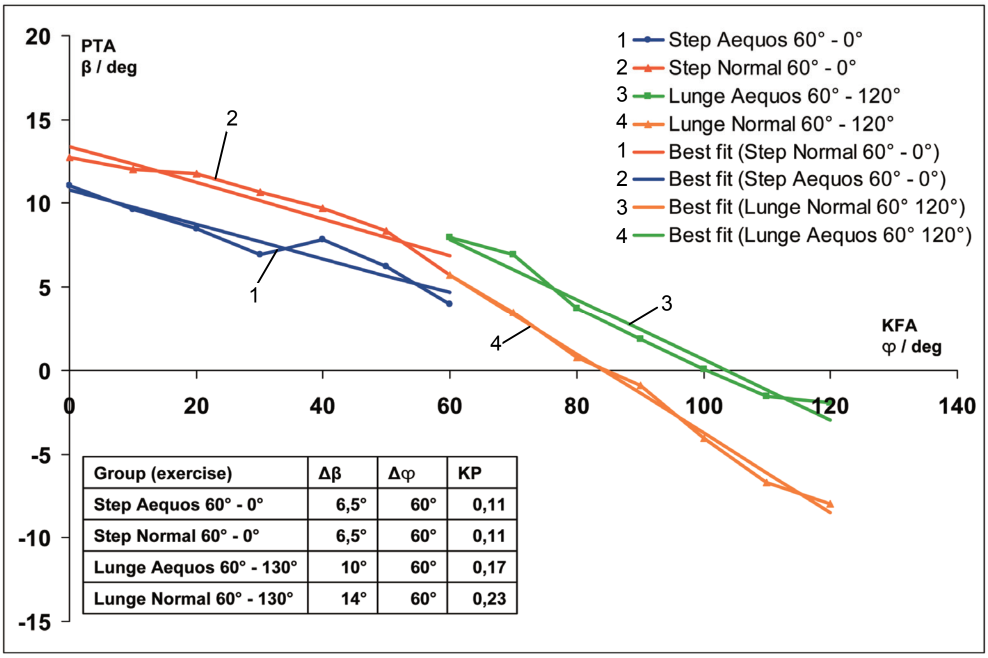
In the lunge exercise, the AEQOUS group showed significantly smaller KP. At flexion $\varphi = 60°$ the offset started with $\Delta\beta \approx +2.5°$. This observation suggests that the femoral articulating surface of AEQUOS G1 should be modified in future developments.

5. Conclusions

1. The fluoroscopic investigations indicate that the natural kinematic profile is approximated by the AEQUOS G1 TKR during gait.

2. The positive cam gear mechanism of AEQUOS G1 TKR implements kinematic features which are comparable to those of the natural TFJ during gait.

3. The measurements of the patella tendon angle/knee flexion angle characteristics suggest that in further developments the design of the femoral articulating surface of the patella femoral joint should be modified.



Group (exercise)	Δβ	Δφ	KP
Step Aequos 60° - 0°	6,5°	60°	0,11
Step Normal 60° - 0°	6,5°	60°	0,11
Lunge Aequos 60° - 130°	10°	60°	0,17
Lunge Normal 60° - 130°	14°	60°	0,23

Fig. 9. Patella tendon angle–flexion angle characteristics ($\beta = \beta(\varphi)$) with best-fit lines. 2/4: normal group; 1: AEQUOS group, step experiment; 3: AEQUOS group, lunge experiment = kinematic profile.

$$\mathrm{KP} \approx \frac{\Delta\beta}{\Delta\varphi} = \frac{\Delta\mathrm{PTA}}{\Delta\mathrm{KFA}} = \text{kinematic profile}$$

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