Preliminary Results of Size and Slide-Roll Effect on the Kinematics of Total Knee Replacements

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Abstract: This paper deals with two fundamental questions with regard to total knee replacement kinematics. First, it provides quantitative information about the effect of knee prosthesis size on restored knee rotation by the so-called performance function. Second, the paper introduces a hypothesis which considers the effect of slide-roll on the performance function. By means of statistical methods, a strong linear correlation between slide-roll and performance-function of the examined total knee replacements was deduced. This result can be interpreted as follows: alteration of slide-roll ratio may enhance the overall performance of total knee replacements with regard to the restored kinematics, or in this specific case, the rotation.

Keywords: qualification method; total knee replacement; rotation; slide-roll; size-effect

1 Introduction

A wide range of choice regarding the brands (Stryker©, Zimmer©, BioTech©, CeramTec© or Sanatmetal©) and sizes (S, M, L, XL, etc.) of commercial knee replacements and supporting telesurgical technologies [1] are available for surgeons to carry out knee operations to restore closely the same kinematics of the physiological knee joint.

Multiple, substantial studies have been published about how total knee replacement (TKR) design affects the kinetics [2, 3] and kinematics [4] of the knee joint. It is also worth mentioning the indirect changes caused by TKR positioning during operation [5] or the effect of foot impairs in the general health of the knee joint [6]. However, no generally accepted methods have been introduced to qualify TKRs about their performance of restoring original knee joint kinematics.

The term of "TKR quality" should describe how closely the commercial TKRs can reproduce the rotation-ad/abduction of the physiological joint with respect to the original kinematics of the knee joint. This new area has been recently researched and a novel qualification method was introduced by the use of a so-called *performance-function* [7]. This function provides a percentile value of the measured rotation of a commercial prosthesis relative to a *reference-rotation* [8], which is the averaged and statistically determined rotation function based on a set of cadaver knee joints.

The basic idea of this qualification method can be further expanded to other knee related kinematical-kinetical values, such as ad/abduction, slide-roll or the acting tibiofemoral force between the contact surfaces. The above-mentioned parameters play key role in TKR lifetime. It has been proven that abnormally high adduction implies osteoarthritis progression in the medial compartment of the knee joint [9, 10], while the latter two phenomena are key-parameters in wear propagation between TKR surfaces. Based on the latest results, it was quantitatively determined that the effect of the tibiofemoral force and the slide-roll cause 65% and 15% more removed volume on TKR surfaces respectively [11, 12].

It is worth noting that the examined TKRs showed fairly low performance ratio compared to the reference-function, since they only achieved 18-35% of the original physiological rotation described by the reference rotation [7]. Whether TKR size has significant role in this performance, has not been further discussed.

The effect of implant size has only been focused on a few knee kinematics-related issues, e.g., the individual effect of the tibial implant thickness on the tibiofemoral angle (TFA) [13] or TKR wear [14]. With regard to wear, TKR size has been proven to be a contradictory parameter since the experimental results of Affatato et al. [15], demonstrated that under the same condition larger tibial UHMWPE inserts resulted in higher wear ratios than those of the small implants.

This is a significant contradiction since a large implant has also larger contact surface, which provides lower contact pressure. According to the literature, with regard to wear in implants, the precondition of low wear is low pressure [16].

These results support the fact that the effect of TKR size on wear propagation can be rather unexpected and controversial. Due to the lack of studies regarding the influence of knee implant size (small, medium, large, etc.) on restored kinematics, this paper aims to provide firsthand information on this topic.

Besides the analysis of the size-influence, a so-far undiscussed question between performance-function (considering only rotation) and slide-roll of commercial TKRs is also presented. It is assumed that correlation may exist between these parameters. If it does, then an overall enhancement could be achieved by altering the slide-roll as a parameter. Therefore, this existence will be statistically examined as well.

2 Methods

2.1 Concept of Qualification

The concept of the qualification method is based on the theoretical introduction of a so-called *performance-function* ($\boldsymbol{\kappa}$), which provides a percentile value of the measured rotation ($\rho_{pr}(\varphi)$) of a commercial prosthesis relative to the *reference-rotation* ($\rho_{ref}(\varphi)$). This has been introduced by Katona et al. [8]:

$$\kappa(\varphi) = \frac{\rho_{pr}(\varphi)}{\rho_{ref}(\varphi)} \cdot 100 \qquad (1)$$

where:

$\rho_{pr}(\varphi)$: measured rotation function of a commercial prosthesis, as a function of flexion angle,

$\rho_{ref}(\varphi)$: measured and averaged rotation function, obtained from multiple cadaver knee joints, as a function of flexion angle.

In order to estimate a performance-function of an arbitrary TKR, e.g. with regard to rotation, both the rotation function ($\rho_{pr}(\varphi)$) of the examined prosthesis and the reference-rotation function ($\rho_{ref}(\varphi)$) needed to be determined. To carry out the necessary experiments our research group designed and manufactured a multi-purpose test rig [17] which allowed us to carry out measurements both on cadavers and TKRs as well (Fig. 1).

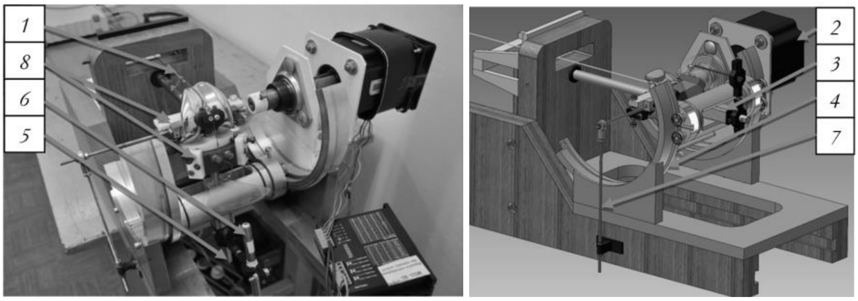

Figure 1
The test rig

To fulfill other purposes, the design was carried out in a way that the test rig, together with the measuring and processing method, would be identically adequate to measure cadaver knees or TKR systems. The fixture in the test rig ensures that during the flexion of cadaver knee or TKR system, which is exerted by the quadriceps under the effect of self-weight or the stepper motor, the same type of movement would be carried out.

The test rig includes the following main parts:

1. The loading system (1), together with the bending mechanism of the knee joint. The load is transmitted through a rubber-muscle model, while the bending movement is exerted by a DPM 110SH99 stepper motor.
2. The stepper motor (2) with a maximum 11.5 Nm holding torque. With this motor, the knee joint can be bent up to 80^o of flexion angle. Due to the design of the test rig, the tibia can carry out unconstrained movement. This feature is essential since the movement has to be controlled only by the quadriceps, the self-weight and the surfaces of the condyles.
3. The bushing and the rail. The unconstrained movement is secured by the use of bushing- and planar bearings (3). The flexion is performed along a controlled curved rail (4).
4. The measuring system. The rotation can be directly measured by a laser (6), which shows the rotation on the attached plexiglass plate. In case of TKR measurement, the tibia plateau is attached to the tibial shaft (5). The tibial shaft represents the direction of the medullar cavity or canal (containing the bone marrow). During the experiments, both TKRs and cadavers are measured in the same anatomical system.
5. Additional fixture system. The test rig also includes a special fixture system (8), which ensures that the inserted TKRs (or cadavers) can be secured identically, and the experiment can be carried out according to a pre-defined protocol [8].

During the experiments, first the reference-rotation function was determined based on multiple cadavers, which was followed by the rotation functions of several commercial TKRs, and eventually the statistical determination of the performance-function [7, 8].

To carry out the test qualification, the following TKRs were tested: three cruciate-retaining TKR from the manufacturer of Bio-Tech (prostheses 1, 3 and 5), one cruciate-retaining and posterior-stabilized TKR from Sanatmetal (prosthesis 7) and two cruciate-retaining TKRs (prosthesis 0 and 4), from unknown manufacturer (Table 1).

Table 1
Tested prostheses [7]

Number	**Manufacturer**	**Femoral size**	**Tibia plateu size**	**Leg**	**Type**
0	Unknown	L-LARGE	XLGE 12	L	CR
1	BioTech	Med. Right B140	B105 M10	R	CR
3	BioTech	B102 XL-L	B106 L10	L	CR
4	Unknown	M-LARGE	MED 10	L	CR
5	BioTech	Med. Right B146	B104 S10	R	CR
7	Sanatmetal	D	EF 5-6 10 PE	L	PS

After the cadaver measurements and the determination of the reference-function, the rotation of six commercial TKRs were measured as a function of flexion angle (Fig. 2).

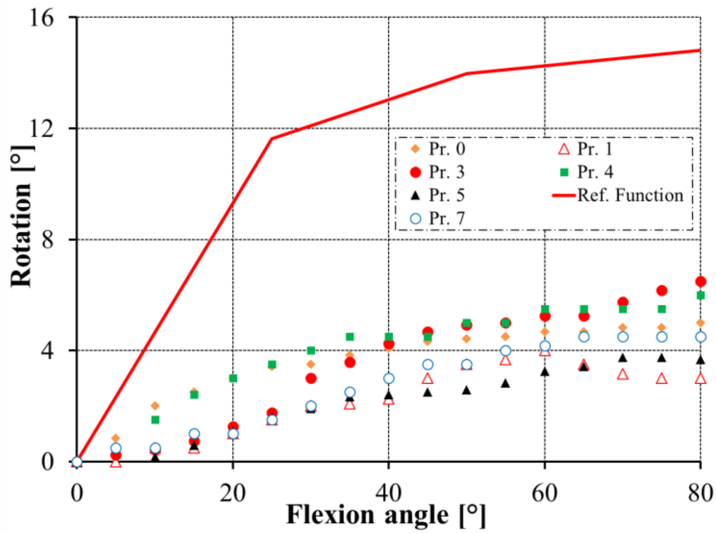

Figure 2
Reference-function and the rotations of the commerical TKRs [6]

The reference-function is approximated as a tri-linear function, which includes three major breakpoints at 25˚, 50˚ and 80˚ of flexion angle. These breakpoints have been statistically determined [8].

2.2 Effect of TKR Size

To classify the results and draw a more appropriate conclusion regarding the kinematical performance of the tested TKRs, an averaged performance ratio has been introduced (Eq. (2)). This ratio was determined based on the values of the major breakpoints (25˚, 50˚ and 80˚of flexion angle). Therefore, it can provide a general overview about the performance of each TKR.

$$\kappa_{Av.pro.i}(\varphi) = \frac{\kappa_i(25^\circ) + \kappa_i(50^\circ) + \kappa_i(80^\circ)}{3} \quad (2)$$

Where *i* denotes the tested prosthesis.

Data for the evaluation of the TKR size effect have been taken from contemporary literature [7], where examined six TKRs were chosen to demonstrate the phenomenon (Table 2). The TKRs were separated as follows: prosthesis 1, 5, and 7 were medium sized TKRs, while prosthesis 0, 3, and 4 were large sized. By the separation of the TKRs according to their sizes, the possible effect can be detected.

Table 2
Values of performance-function [7] and the calculated average performances

i	κ (25°) [%]	κ (50°) [%]	κ (80°) [%]	$\kappa_{averaged}$ [%]	Size [-]
Pr. 0	32.4	31.1	34.1	32.5	L
Pr. 1	10.9	24.3	21.6	18.9	M
Pr. 3	13.3	39	41.3	31.2	L
Pr. 4	31.5	35.7	39.9	35.7	L
Pr. 5	10.9	20.6	26.2	19.2	M
Pr. 7	12.5	27.1	31.9	23.8	M

After determining the averaged performance value of each TKR, the results have been summarized in Figure 3 as a function of TKR size. By separating the results based on their size, a clear difference can be distinguished between the sizes, which confirm the hypothesis that TKR size has a significant effect on the functionality of the prosthesis and the restored kinematics.

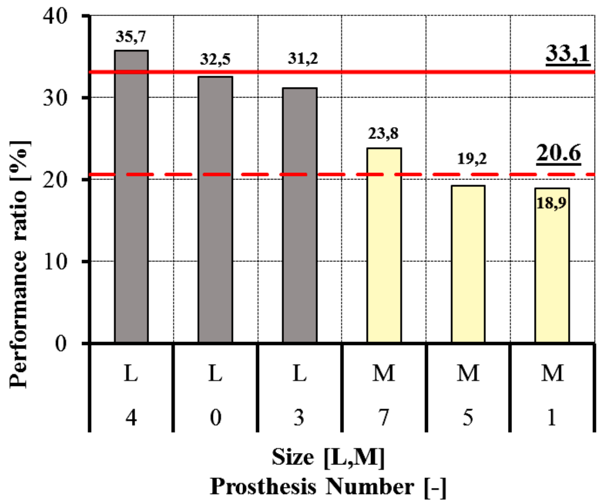

Figure 3
Averaged performance ratio of the commercial TKRs

2.3 Correlation between Performance-Function and Slide-Roll

When the averaged performances in the major breakpoints were plotted in Figure 4, an interesting trend was observed. If the function of the averaged slide-roll ratio [4], which has been deduced from actual TKR geometries, was compared to these discrete points (0°, 25°, 50°, and 80°), then it became apparent that the observed functions had similar tendency (Fig. 4).

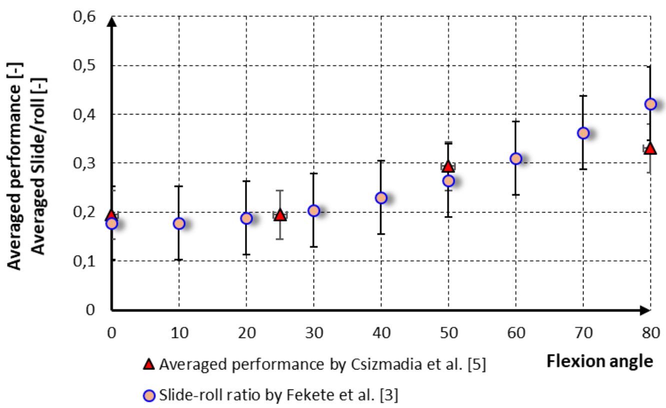

Figure 4
Averaged performance and slide-roll ratio of the prostheses

According to Figure 4, a possible correlation can exist between the averaged slide-roll and the averaged performance-function. If this correlation exists, it can be assumed that the alteration of TKR slide-roll may also lead to better performance in TKR rotation.

To statistically prove and qualify the level of correlation, the Pearson correlation coefficient (r) was determined, which equaled to 0.9774. The analysis considered all the examined TKRs regardless their sizes. The obtained result showed strong positive correlation, which was further analyzed in order to decide whether the result significant was. Since the data were available in four points (0°, 25°, 50°, and 80°), the degree of freedom of the set was 4 ($n = 4$), with an r score of 0.9774 while the significance level was set to 0.05.

P-value, which denotes the probability of an observed result assuming a true null hypothesis, was found to be 0.0226. Thereby it was confirmed that the result was significant at the level of $p < 0.05$. To investigate a size-based dependence as well, prostheses with size L and M were investigated separately (Fig. 5).

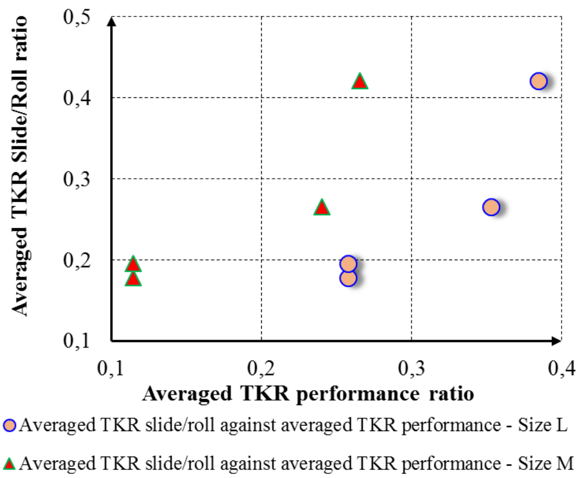

Figure 5
Correlation analysis between TKR performance and slide-roll

By carrying out the same statistical analysis on the data set, the following results were obtained and summarized in Table 3.

Table 3
Pearson correlation coefficients and significance on the examined TKRs

	n [-]	**r [-]**	**p-value [-]**	**Significant at 0.05?**
All TKRs	4	0.9774	0.0226	Yes
TKRs (size M)	4	0.8273	0.1727	No
TKRs (size L)	4	0.9657	0.0343	Yes

Conclusions

The averaged performance-function of all six prostheses were calculated, and their results were summarized in a cluster column chart (Fig. 3) as a function of prosthesis size (L, M). The continuous line, with a percentile value of 33.1%, represented the averaged performance-function of the large-sized prostheses, while the dashed line, with a percentile value of 20.6%, represented the averaged performance-function of the medium-sized prostheses. The effect of TKR size became immediately apparent since by this study it has been quantitatively determined that TKRs with large size (L) can restore the functional kinematics 12.5% superior than TKRs of medium size (M).

In fact, this result means that large-sized prostheses have a 60.7% ({33.1 – 20.6}/20.6) superior performance than medium-sized prostheses. Therefore, it has been confirmed that among other factors, e.g., tibial implant thickness [13, 14], TKR size also has a significant effect on knee kinematics, or more precisely on the restored rotation.

Nevertheless, the question why larger TKRs behave kinematically differently is still not answered. According to Affatato et al. [15], large prostheses are characterized by a wider area that undergoes more sliding, therefore, more friction and wear, which could produce discrepancies in their kinematics. This size-related phenomenon was also confirmed by Kang et al., [18] in case of hip prostheses. The authors found higher volumetric wear rate in large size hip replacements, possibly due to the result of higher sliding distance and lower contact pressure. Even though a confirmed explanation is still missing, the problem may be partially answered if a separated analysis on the rotation segments [8] and on slide-roll function would be carried out as a future step.

Another important hypothesis has also been proven, namely the strong linear correlation between the averaged slide-roll ratio and the averaged performance-function. Separately, the TKRs were also investigated according to their size; the results showed significance in the case of large sized TKRs, however they did not indicate the same condition in the case of middle sized TKRs.

This last result can be interpreted as follows: alteration of slide-roll ratio may enhance positively the overall performance of total knee replacements with regard to the restored kinematics. This question will be further analyzed on multibody modell.

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