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Total knee arthroplasty reduces knee extension torque in-vitro and patellofemoral arthroplasty does not ☆

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ABSTRACT

Patients often have difficulty recovering knee extension strength post total knee arthroplasty (TKA), and that may reflect alteration of the mechanics including geometry and rollback kinematics, so the purpose of this work was to explore this by comparing the knee extension torque (KET) of the native knee, TKA and patellofemoral arthroplasty (PFA) in response to quadriceps tension. Eight fresh-frozen knees were mounted in a knee extension rig with quadriceps loading and tibial extension torque measurement. Each knee was subject to four conditions: native knee, PFA, cruciate-retaining (CR) and posterior-stabilized (PS) TKA. The KET was measured from 120° to 0° knee flexion. Data were analyzed using one-way ANOVA and post-hoc paired *t*-tests. The native KET was lowest in terminal extension and 70–100° flexion, and maximal at 20–30° flexion. PFA produced the greatest KET ($p < 0.008$) compared with native, CR- and PS-TKA, at 30–40° flexion. CR- and PS-TKA had lower KET across 0–50° flexion ($p < 0.001$ across 0–30°), falling to 25% of the native knee KET or the PFA at full extension. PFA had the highest KET in early flexion possibly due to increased trochlear offset and/or preservation of the cruciate mechanism, so PFA may be more beneficial during the functional range of motion. The claimed benefits of PS- over CR-TKA in deep flexion were not detected. Both CR- and PS-TKAs led to lower KET than the native and PFA knee states across 0–50° flexion. This mechanical effect may help to explain clinical findings of knee extension weakness post-TKA.
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1. Introduction

Patients often have difficulty in recovering knee extension strength post total knee arthroplasty (TKA), and that may reflect alteration of the knee extension mechanics, including implant geometry and rollback kinematics (Bercik et al., 2013; Hirsch et al., 1994). Quadriceps weakness following TKA is a well-recognized problem, and rates of 30–40% have been reported (Huang et al., 1996). The function of the extensor mechanism is the most important factor determining a patient's ability to climb stairs or rise from a chair (Whiting and Zernicke, 2008). These activities, along with walking, are an integral part of daily living, and it can be disabling if they are compromised. Reduced walking and stair climbing speeds result from quadriceps weakness (Mizner and Snyder-Mackler, 2005; Suh et al., 2019; Walsh et al., 1998). These losses persist post-TKA and are disabling (Noble et al., 2005; Nilsdotter et al., 2009). Theoretically, prostheses that increase the extensor moment arm decrease the quadriceps force required, and thus may compensate for quadriceps weakness. While this could potentially improve post-operative function, a larger lever arm may cause PF overstuffing, which may increase PF contact pressure and cause anterior knee pain post-TKA (Ghosh et al., 2009). Identifying which type of prosthesis produces a more mechanically effective knee extensor mechanism may further inform the development and choice of partial and total knee prostheses.

The surgical and biomechanical literature do not include any useful definition to allow the biomechanical *effectiveness* of the knee extensor mechanism to be measured. Knee extension torque

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(KET) is measured routinely during rehabilitation, but the relationship between quadriceps strength and KET is affected by the mechanics of the knee, and how the kinematics are altered by arthroplasty. The extensor moment arm is defined as the perpendicular distance from the instantaneous axis of extension to the resultant line of force in the patellar tendon. However, there is a variable ratio between the quadriceps and patellar tendon tensions, which varies from approximately 1 near knee extension to 0.7 in flexion in the native knee (Ellis et al., 1980; Huberti and Hayes, 1984). The kinematics are likely to alter post-arthroplasty, in response to the new articular geometry and changes to roll-back (Fantozzi et al., 2006) and related effects on the instantaneous axis of knee extension, which also moves while the knee is extending. Although implant manufacturers may claim beneficial effects from their specific designs, there is no standardized method to measure or compare the effectiveness of the muscle tension in producing the desired output – the knee extension torque. Therefore, this paper describes the use of the Knee Extension Torque (KET (N. m)) produced per unit of extensor (quadriceps) muscle tension (N_{QT}).

A more-posterior tibiofemoral contact point may result in a longer extensor moment arm (Insall et al., 1982). The cruciate-retaining TKA (CR-TKA) has a less-posterior tibiofemoral contact point than the posterior-stabilized TKA (PS-TKA) and thus may have a shorter extensor moment arm if it is assumed that post-cam engagement drives the contact point and instant axis of rotation of PS-TKA posteriorly (Dennis et al., 1996; Kim et al., 1997; Stiehl et al., 1995). However, the contact point and kinematics are implant geometry-specific, and PS-TKA designs have not been shown to provide an extension moment arm greater than the native knee (Dennis et al., 1996; D'Lima et al., 2001). In isolated patellofemoral arthritis, a patellofemoral arthroplasty (PFA) may be used (Ackroyd et al., 2007; van Jonbergen et al., 2010; Odumenya et al., 2010), preserving the normal tibio-femoral joint and cruciate ligaments. Thus, PFA could be expected to maintain the physiological extensor moment arm. Therefore, it was hypothesized that the knee extension torque (KET) produced at a given quadriceps tension would be greater following PFA compared with CR-TKA, and greater following PS-TKA compared with CR-TKA.

The aims of this investigation were to measure the KET across the range of extension of the native knee, and then to determine whether the PFA, CR-TKA and PS-TKA would change the KET.

2. Material and methods

2.1. Materials: Specimens and preparation

Ten fresh-frozen human cadaveric knees with intact soft tissues were obtained (Science Care, Phoenix, AZ) following research ethical committee approval. They were stored at −20 °C and thawed for 24 h in a refrigerator prior to use. Two knees were used for finalizing the methodology. Eight knees, 5 male (2 right, 3 left) and 3 female (1 right, 2 left) with a mean age of 74.6 years (61–82), were used for data analysis.

All knees were devoid of macroscopic arthritis and other bony anatomical defects, confirmed on lateral, AP and skyline radiographs, physical examination to check ligamentous stability, and surgical examination during dissection. None had undergone previous surgery or had articular surface erosion that might have affected their mechanical behaviour. The skin and subcutaneous fat were excised, all other structures remained intact. The quadriceps was separated into six components: rectus femoris, vastus intermedius, vastus lateralis longus, vastus lateralis obliquus, vastus medialis longus and vastus medialis obliquus. The distal tendinous fibres of the muscles were left intact to ensure their actions on the patella were as physiological as possible.

Approximately 200 mm of femur and 150 mm of tibia were preserved. The fibular head was transfixed to the tibia using two cortical screws to maintain its anatomical position. Intramedullary (IM) rods were cemented into the femur and tibia, using polymethylmethacrylate bone cement, for mounting and load application, respectively.

2.2. Apparatus

Each knee was tested with the anterior aspect facing upwards in the knee extension test rig by clamping the femoral rod into a fixed mounting (Fig. 1). The femoral transepicondylar axis was aligned with the axis of rotation of the test rig. This rig allowed for manual passive knee flexion-extension movement; the tibia remained unconstrained, hanging vertically at 90° flexion. To extend the knee, 205 N was applied to the quadriceps muscle groups (175 N) and ITB (30 N) by hanging weights on a rope and pulley mechanism (Stephen et al., 2013). Cloth strips were sutured to the proximal end of the ITB and each muscle component to provide attachments for the loading ropes. Each muscle was loaded according to its mean physiological cross-sectional area in its physiological direction (Farahmand et al., 1998a). Similarly, the tension and orientation of the ITB, 6° posterior to the axis of the distal femur, had been determined previously (Bull et al., 1999; Merican and Amis, 2009).

2.3. Approach for prosthesis implantation

A previously validated transpatellar approach was used to ensure the integrity of the extensor mechanism remained equal between conditions (Merican et al., 2009). This reduced confounding factors, such as variation in suture tensioning, affecting the extensor retinacula and patellar kinematics following closure of a standard medial parapatellar approach. Two holes were drilled mediolaterally across the patella for accurate screw fixation prior to cutting the bone. The patella was cut in the sagittal plane 10 mm lateral to the midline. The two fragments were approximated with two 4 mm partially threaded cannulated cancellous screws. The split in the quadriceps tendon was opposed with a continuous stitch, which was released to ease prosthesis implantation. This approach was performed prior to all experiments including the 'native knee' condition. The patellar cut and screws were placed so that they would not interfere with implantation of the patellar component.

2.4. Knee extension torque measurement

The KET was found by measuring the force applied by the tibial intramedullary rod to a cross-bar which blocked knee extension motion (Fig. 1). This bar was part of a strain-gauged crank mechanism aligned to the transepicondylar axis. The strain gauges were calibrated by hanging weights and their output was calibrated in terms of the KET (Nm) imposed on it by the tibial IM rod. Measurements were taken at 10° increments from 120° to 0° knee flexion while the extensor mechanism was tensed. This was repeated four times for each condition of the knee. The transverse rod did not inhibit secondary tibial motions, such as internal-external rotation.

Before testing, each knee underwent ten preconditioning cycles of flexion-extension while under load. Each knee was then moved in flexion-extension, against the extending action of the tension in the quadriceps muscles and ITB, in the four states: native, then post- PFA, CR-TKA and PS-TKA. It was not possible to randomize the testing order, because of the increasing bone destruction in the sequence listed. Therefore, it was also not possible to verify

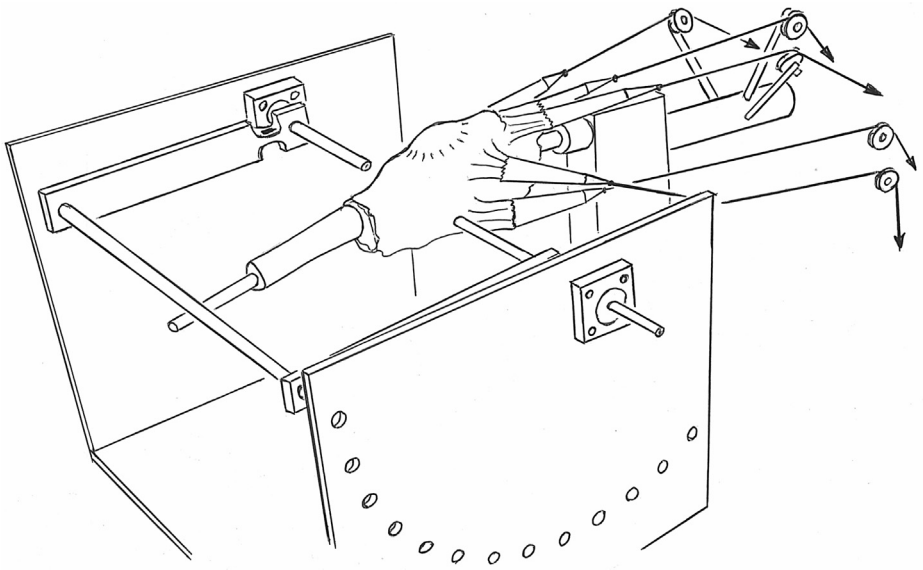


Fig. 1. Schematic of the knee extension test rig. The muscle tensions are applied using cables tensed in physiological directions, shown as arrows. The knee extension motion is controlled by the cross-bar anterior to the tibial intramedullary rod, which is linked to the pivot on the side-plate of the rig by a strain-gauged beam. The trans-epicondylar axis of the femur was aligned to the pivots on the side-plates.

the absence of permanent changes in the knees, which may introduce bias, by repeated earlier stages.

2.5. Interventions

A patello-femoral joint replacement (PFA), CR-Flex cruciate-retaining and LPS-Flex posterior-stabilized total knee replacements (CR-TKA and PS-TKA) (NexGen® Gender Solutions™, Zimmer®, Warsaw, IN) were used. All three prostheses had the same femoral trochlear geometry and patellar component, which allowed for direct comparative analysis. The patellar resection removed the same thickness of cartilage/bone as that of the patellar component, leading to a construct within 1 mm of the native thickness. The CR- and PS-TKA had the same tibiofemoral geometry, but differed in the presence of the post-cam mechanism. Both tibial components were placed onto the same tibial cut surface, so there was no difference in posterior slope. The implantations were in accordance with the manufacturer's guidelines and were performed by a single consultant surgeon. Implant alignment consistency was aided by the knees having been aligned such that the trans-epicondylar axis was coaxial with the axis of the test rig and the anatomical axis of the femur horizontal; this fixed alignment aided precision in all three planes of rotation: flexion-extension, varus-valgus and internal-external.

2.6. Data analysis

A sample size calculation was based on previous cadaveric test data on patellofemoral (PF) contact pressures, there being no data on KET at that time. This established that 8 knees could detect a 0.2 ± 0.3 MPa significant change in PF contact pressure, using the same measurement systems, with 80% power and 95% confidence (Stephen et al., 2013). A post-hoc analysis found that a change of KET of 0.0156 Nm per N_{QT} could be found with 80% power and 95% confidence (G Power v3.1, Baden-Württemberg, Germany). Kinematic data were analysed using one-way repeated measures ANOVA. The single factor evaluated was the knee condition: native, PFA, CR-TKA, PS-TKA, at each 10° increment of knee extension. The dependent variable was the primary outcome: the KET per N_{QT}. When the F test was significant ($P < 0.05$) the null hypothesis was rejected and post hoc paired t tests were used to identify which condition differed from the others at each angle of flexion for the dependent variable. The significance level was corrected to 0.00833 for comparison of the four knee conditions to each other via the Bonferroni factor. Data were analysed in SPSS® (IBM® Corp., Armonk, NY) and Excel® (Microsoft® Corp.).

3. Results

The KET per quadriceps tension (Nm/N_{QT}) varied similarly for all four conditions, with a minimum around 90° flexion, a maximum around 30° and then dropping rapidly as the knee approached full extension (Fig. 2).

Near to knee extension, both the native knee and the PFA had significantly higher KET per quadriceps tension than the two TKAs (Table 1).

When the mean KET per quadriceps tension data were normalised versus the native knee, it became clear that the PFA

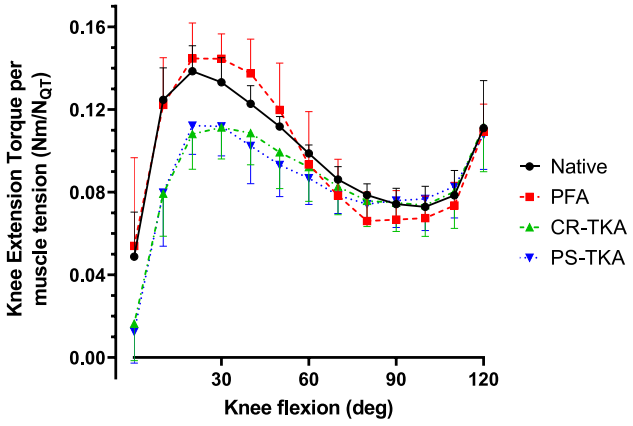


Fig. 2. The Knee Extension Torque (KET) per unit muscle tension (Nm/N_{QT}) shown for the native knee, patellofemoral arthroplasty (PFA), cruciate-retaining total knee arthroplasty (CR) and posterior cruciate sacrificing (PS) total knee arthroplasty (TKA). (Mean + or − SD; n = 8). Statistical differences are shown in Table 1 for clarity.

Table 1
Knee Extension Torque per unit quadriceps tension (KET): Statistically Significant Mean Differences between Native Knee, PFA, CR-TKA and PS-TKA conditions shown in Fig. 2.

Knee flexion (°)	Condition (A)	Condition (B)	Mean difference (A-B) (Nm/N_{EM})	Standard deviation	Significance
80°	Native	PFA	0.1256	0.0027	0.000
80°	PFA	CR-TKA	−0.0098	0.0027	0.002
50°	Native	PS-TKA	0.1859	0.0040	0.000
50°	PFA	CR-TKA	0.0205	0.0040	0.000
50°	PFA	PS-TKA	0.0266	0.0040	0.000
40°	Native	PFA	−0.0147	0.0040	0.002
40°	Native	CR-TKA	0.0143	0.0040	0.003
40°	Native	PS-TKA	0.0204	0.0040	0.000
40°	PFA	CR-TKA	0.0290	0.0040	0.000
40°	PFA	PS-TKA	0.0351	0.0040	0.000
30°	Native	PFA	−0.0114	0.0035	0.008
30°	Native	CR-TKA	0.0219	0.0035	0.000
30°	Native	PS-TKA	0.0214	0.0035	0.000
30°	PFA	CR-TKA	0.0332	0.0035	0.000
30°	PFA	PS-TKA	0.0327	0.0035	0.000
20°	Native	CR-TKA	0.0304	0.0038	0.000
20°	Native	PS-TKA	0.0263	0.0038	0.000
20°	PFA	CR-TKA	0.0366	0.0038	0.000
20°	PFA	PS-TKA	0.0325	0.0038	0.000
10°	Native	CR-TKA	0.0455	0.0052	0.000
10°	Native	PS-TKA	0.0449	0.0052	0.000
10°	PFA	CR-TKA	0.0430	0.0052	0.000
10°	PFA	PS-TKA	0.0424	0.0052	0.000
0°	Native	CR-TKA	0.0324	0.0064	0.000
0°	Native	PS-TKA	0.0363	0.0064	0.000
0°	PFA	CR-TKA	0.0376	0.0064	0.000
0°	PFA	PS-TKA	0.0415	0.0064	0.000

remained close to the native knee performance across the range of knee extension, while both the CR- and PS-TKAs dropped to approximately 25–30% of the KET per quadriceps tension of the native knee or the PFA at full extension (Fig. 3).

The greatest KET per quadriceps tension was produced by PFA between 50° and 10° flexion, reaching 0.145 ± 0.017 Nm/N_{QT} at 20° knee flexion. The PFA had significantly greater KET per quadriceps tension than the native knee at 30° and 40° knee flexion, but significantly less than the native knee at 80° flexion. Significant differences between the four knee states were not found above 80° flexion. No differences of KET per quadriceps tension were found between CR- and PS-TKA at any angle of knee flexion (Table 1).

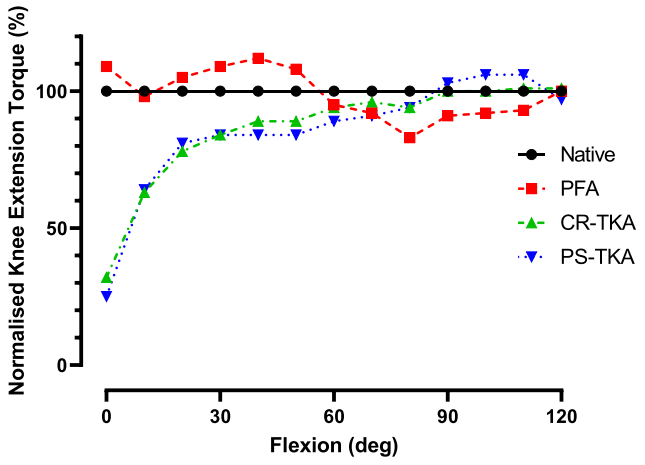


Fig. 3. Mean Knee Extension Torques (KET) per unit muscle tension normalised to the native knee (100%), which highlights that the patellofemoral arthroplasty (PFA) remained at similar levels to the native knee, whereas the CR-TKA and PS-TKA fell below the native KET as the knee extended. Mean values from Fig. 2, n = 8.

4. Discussion

The most important finding of this work is that the total knee arthroplasties (both CR and PS types) had significantly lower knee extension torque (KET) per unit of quadriceps tension than the native knee, while the PFA did not differ from the native knee, towards knee extension. The data did not support the hypothesis that PS-TKA would have greater KET per unit of quadriceps tension than the CR-TKA. The rapid loss of KET as the TKAs approached full extension suggests that they may not help the patients to fully-extend their knees.

Although knee extension is integral to all locomotion activities, the mechanical performance measured in this paper in terms of KET per unit of quadriceps tension is a novel measure to allow comparison of differing knee states in-vitro. Knee extension function is essential for a successful outcome following knee arthroplasty. Weakness of the quadriceps post-TKA significantly impacts activities of daily living (Huang et al., 1996; Berman et al., 1991; Silva et al., 2003; Almeida et al., 2010; Harada et al., 1999). Hirsch et al. (1994) found that CR-TKA was less accommodating of a weak extensor mechanism than the PS-TKA, and suggested that this was due to posterior cruciate ligament insufficiency. However, others did not find a difference in knee extension function between the two TKAs (Becker et al., 1991; Bolanos et al., 1998). The extensor mechanism function following PFA has not been reported previously.

The variation of KET per quadriceps tension as the knee extended was bimodal in distribution for all four conditions, and fell towards terminal knee extension. The greatest mean difference occurred between the PFA and CR-TKA at 10° knee flexion. Unexpectedly, the PFA also produced significantly greater KET per quadriceps tension than the native knee in this range of motion. This may have been due to the onlay design of the PFA causing the patella to track more anteriorly than in the native knee, thus increasing the extensor moment arm. That may not be entirely positive, since overstuffing stretches the peripatellar retinacula

(Ghosh et al., 2009). Although PFA is not used in large numbers, several designs have greater than 95% survival at 5-years follow-up (Strickland et al., 2018). It is possible to use the femoral component without resurfacing the patella, but that has not been examined in the present study. Although TKA for tibiofemoral arthritis is sometimes performed without resurfacing the patella, that is rare in PFA where the indications include bone-on-bone contact confirmed radiographically, and the recommendation is that all patellae that can be replaced should be (Odgaard et al., 2019; Johnson and Turner, 2019). The experimental procedures meant that it was not possible to examine the isolated effect of patellar resurfacing on knee extension post-TKA; that could be examined in further work.

The KET advantage of PFA from mid flexion to full extension would theoretically make activities performed in this range of motion, such as level walking and ascending/descending inclines, less challenging. In a randomized blinded trial of PFA versus TKA in isolated PFOA patients the PFA had significantly better range of motion and function (Odgaard et al., 2014). In deep to mid flexion, the KET for PFA was lower. This may have been due to the relatively short extensor moment arm occurring as the patellar button of the PFA sat in the native intercondylar notch in deeper flexion. Loss of knee extension is associated with reduced gait (Pua et al., 2017) and poor functional outcomes (Harato et al., 2008).

The change from the intact PCL to the cam-post mechanism was the only difference between the TKA conditions, and no difference in KET was identified between them. Previous studies have also found that PS-TKA had no advantage over CR-TKA (Becker et al., 1991; Bolanos et al., 1998). That was despite the cam-post mechanism being intended to control the kinematics and force femoral roll-back with knee flexion (Fantozzi et al., 2006). However, Arnout et al. (2015) showed that post-cam engagement only occurred beyond 100° knee flexion with the Nexgen TKA used in the present study. Therefore, the similar behaviour of the CR and PS-TKA as the knee moved into extension was unlikely to be artefactual up to 100° flexion. Further, as Arnout et al. (2015) noted, other designs of PS-TKA had much earlier post-cam engagement than with the NexGen used in the present study (at the other extreme in their study of eight TKA designs, the Triathlon post-cam engagement was at 43° flexion, for example) and that the post-cam contact forces were smallest in the NexGen design. Therefore, differences between CR- and PS-TKA would likely be clearer with studies of other designs than the NexGen used in the present study, and with other load-bearing activities. In future work to compare the behaviour of TKA designs optical tracking could provide more detailed understanding of the effects of bearing geometry on knee extension kinematics.

The results of this study should be interpreted in the light of its strengths and limitations. Cadaveric knees only offer an approximation of what occurs *in vivo* thus limiting translation to the clinical setting. The flexion-extension cycle was quasi-static and did not include a functional weight bearing component. Rather, the loads imposed and the test configuration mimicked a straight-leg raising exercise, because that is the standard clinical test to evaluate the ability to extend the knee post-arthroplasty. Although lack of hamstrings loading may affect kinematics, Gomez-Barrena et al. (2010) found that prosthetic geometry and cruciate function had a greater influence on changes in extensor moment arm than the hamstrings. The hamstrings remained unloaded for this experiment, therefore this is unlikely to have altered the comparative outcomes significantly.

An advantage of this work, however, was that, because we were testing knee extension, care was taken to load the extensor muscles in anatomical directions and with the forces shared according to the physiological cross-sectional areas among the six heads of the quadriceps and the ITB in accordance with published data (Farahmand et al., 1998a; 1998b; Bull et al., 1999; Merican and Amis, 2009). Although some groups have used motorised rigs to test the knee in-vitro, usually based on the 'Oxford' squatting rig (Zavatsky, 1997), those studies (such as Lowry et al., 2016; Schroeder et al., 2015; Arnout et al., 2015) have their own limitations. Among these, only Lowry et al. (2016) tested knee extension motion, and none of those studies examined the full knee extension arc, with maximum knee extension angles of 10°, 20°, and 30°, respectively. They did not impose physiological loads akin to those seen during gait, with 'body weights' of 180 N, 50 N and 150 N, respectively. The squatting rig of Maletsky and Hillberry (2005) could impose larger (gait) forces in flexion and extension, and added an ankle plantarflexion actuator that would increase the post-cam interaction of a PS-TKA in the extending knee when rising from a squat. While that difference would not be relevant to the present study simulating knee extension without foot-floor contact, it could be expected that different loading to simulate weight-bearing actions would lead to different knee kinematics and, hence, post-cam interaction. All four 'squatting rigs' cited above drove knee motion via a strap that represented the quadriceps, aligned parallel to the femur, and so did not impose physiological extensor muscle loading, likely affecting patellofemoral kinematics. Schroeder et al. (2015) quoted two previous studies which had shown that the magnitude of the muscle load did not affect the progression of the resulting data, but only changed the amplitude, thus the effects found with low-load experiments should be scalable up to the clinical loads.

Stretching of the soft tissues may have occurred during the trials performed on each knee, but the protocol of bone resections prevented re-testing to check this. The loads chosen for the experiment were intended to avoid tissue stretching. Although the patellar-splitting anterior approach is not usually used in knee arthroplasty, it allowed the soft tissue retinacula to remain undisturbed by the repeated opening and closing of the joint, and does not create significant changes in patellar kinematics in-vitro (Merican et al., 2009). A strength of the study was the repeated-measures statistical analysis used for each knee, so inter-specimen differences did not affect the outcomes. Although the KET per quadriceps tension shows clear changes across states within a set of knees, it may be appropriate in future studies to further normalize the KET in terms of the physical size of each specimen, to allow direct inter-study comparison. Finally, it is possible that the relatively poor terminal knee extension function post-TKA was influenced by the prosthesis design or the surgical procedure, so further work with other designs is appropriate. Nevertheless, reduced knee extension function is an important factor in reduced functional recovery post-TKA (Suh et al., 2019).

5. Conclusions

Both CR- and PS-TKAs led to lower knee extension torque (KET) than the native and PFA knee states across 0–50° flexion. This mechanical effect may help to explain clinical findings of knee extension weakness post-TKA.

Combined conflict of interest declaration and acknowledgements

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