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In vitro measurement of tibiofemoral kinematics after patient-specific unicompartmental knee replacement

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ABSTRACT

It is suggested that unicompartmental knee replacement (UKR) offers the potential to restore normal knee kinematics better than total knee replacement (TKR) because of retaining the cruciate ligaments, and better preservation of the overall geometry. It was hypothesized that patient-specific UKR would restore normal knee kinematics even better because of a customised articular shape. A comparative kinematics study was conducted on three cadaver limbs using two different test setups, a loaded ankle rig and an unloaded ankle rig. Kinematics was compared between a patient-specific UKR and a conventional fixed-bearing UKR. Both the UKRs showed similar kinematic patterns to the normal knee using both the test apparatus. The patient-specific UKR showed good results and with the other benefits it shows potential to dramatically improve clinical outcomes of knee replacement surgery.

Keywords: Tibiofemoral Kinematics; Patient-Specific Knee; Unicompartmental Knee Replacement

1. INTRODUCTION

The knee joint is the largest and most complicated joint in the human body. Knee kinematics therefore is also complex and has been studied extensively to gain better understanding of the biomechanics [1-4]. Numerous *in vivo* methods have been used to investigate knee kinematics, including studies with magnetic resonance imaging [5-7], fluoroscopy combined with computed tomography [8,9] and roentgen stereophotogrammetry [10-12]. However, Victor *et al.* [4] argue that *in vivo* research is limited due to unknown loading conditions and variation in the performed activities between different studies.

In vitro studies overcome these limitations by applying known loads to the knee joint which is mounted in a specialized rig or frame. The two most commonly used *in vitro* systems are the Oxford knee rig (OKR) and the robotic knee testing system (RKTS), [2-4,13-19]. Both systems try to replicate the physiologic scenario by providing six-degree-of-freedom at the knee joint, allowing quadriceps loading, and providing a load at the ankle. In other studies either the tibia or the femur is fixed, and flexion/extension is achieved by loading the quadriceps [20-23]; while other studies follow a completely unloaded method where flexion/extension is achieved manually [24]. However, according to Victor *et al.* [4], different *in vitro* methods reveal different kinematic patterns.

The kinematic patterns of the normal knee describe the motion of the femur relative to the tibia with increasing flexion. Normal knee kinematics is believed to include some posterior translation of the femur, which is more pronounced on the lateral side, leading to relative internal tibial rotation. According to some studies, the majority of this rotation occurs at the beginning of the flexion cycle, between full extension and 15˚ flexion, indicating a screw-home mechanism [2,15,25]. Numerous studies have shown that the screw-home characteristic does not necessarily occur after total knee replacement, and that normal kinematics are lost [2,11,12,14,15,22,26]. The main reason for the change in kinematics after TKA is attributed to the change in articular geometry [2,14,15, 22].

It is suggested that unicompartmental knee replacement offers the potential to restore normal knee kinematics better than TKR because of retaining the cruciate ligaments, and better preservation of the overall geometry [14,27]. Most *in vivo* kinematic studies after UKR only consider the patellar tendon angle and conclude that normal kinematics is restored [27-29]. Akizuki *et al.* [30] investigated *in vivo* tibiofemoral kinematics of patients implanted with a UKR and found greater posterior translation than that reported for the normal knee. Patil *et al.* [14] investigated *in vitro* knee kinematics before implantation, after implantation with a UKR, and after implantation with a TKR. They found no significant differences in femoral rollback between the cases, but reported that TKR significantly affected tibial rotation. The UKR showed no significant difference in tibial rotation compared to the normal knee. However, UKR is a highly demanding surgical procedure and survivorship is dependent on precise alignment and component orientation [31-33]. The use of patient-specific instrumentation and implants is a newly developed method to address alignment problems prevalent in the use of current, off-the-shelf implant designs. Koeck *et al.* [31] investigated implant position and alignment after patient-specific UKR and concludes that the technique achieves near optimal implant positioning and an anatomical component orientation.

In this study, individual normal knee kinematics is compared to the kinematics after implantation with a patient-specific UKR and a conventional fixed-bearing UKR. We further investigate the effect of ankle load by using two different test setups; one based on the OKR and one where the femur is fixed and the tibia hangs freely, flexion/extension is achieved by loading the quadriceps.

2. MATERIALS AND METHODS

We tested three cadaver knee joints in two different rigs, comparing normal tibiofemoral kinematics to kinematics after implantation with a patient-specific UKR. Details of the patient-specific UKR can be found in van den Heever *et al*. [34]. Two knees received medial replacements while one knee received a lateral replacement. One of the medial replaced knees was only tested on the unloaded ankle test rig due to time and equipment constraints. Two of the knees were further implanted with a conventional, medial fixed-bearing prosthesis for comparison.

2.1. Specimens and Preparation

Three embalmed, lower limb specimens were used in this study. Ethical approval was obtained from the Faculty of Health Sciences, Stellenbosch University, South Africa. There were no macroscopic defects in the knees. Each knee was sectioned just below the femoral head, with the ankle and foot kept intact. The skin was removed around the knee and ankle joints. Threaded intermedullary rods were cemented into the femoral shafts for fixation to the testing rigs. Electromagnetic receiver sensors (Fastrak, Polhemus, Vermont, USA) were rigidly fixed to the femoral and tibial shafts. An electromagnetic transmitter sensor was rigidly fixed to the stationary testing rig frame. An additional stylus was used to digitise bony landmarks to create embedded coordinate systems in both the femur and tibia. The femoral X-axis was defined as the line passing through the centres of the medial and lateral condyles (the transepicondylar line), positive pointing laterally. The Y-axis was aligned with the shaft of the femur, positive pointing proximally. The Z-axis is the vector cross product of the mentioned two axes, positive pointing anteriorly. The tibial X-axis is defined as a line connecting the approximate centre of each plateau, positive pointing laterally. The tibial Y-axis is aligned with the tibial shaft, positive pointing proximally. The tibial Z-axis is the vector cross product of the mentioned two tibial axes, with positive pointing anteriorly. Tibiofemoral relative motion is then calculated as follows: flexion/extension was calculated about the femoral X-axis; tibial internal/external rotation was calculated about the tibial Z-axis; tibial varus/valgus was calculated about a floating axis perpendicular to the femoral X-axis and the tibial Z-axis; femoral rollback was defined as the posterior translation of the center of the transepicondylar line of the femur relative to the fixed tibial coordinate system.

2.2. Loaded Ankle Apparatus

The first rig is a dynamic knee simulator based on the Oxford knee rig design (**Figure 1**). The femoral intermedullary rod is fixed to the hip joint. The hip joint provided all rotational degrees-of-freedom as well as limited medial-lateral movement. The ankle was kept intact, with the foot strapped to a moveable platform. This ensured normal ankle rotations with rotational freedom in flexion/extension, internal/external rotation and limited range of varus-valgus motion [2]. The quadriceps tendon was loaded via a pulley and weight system with a static load of 200 N as done in previous studies [19,22]. Knee flexion/extension was achieved by translating the moveable platform along vertical rails controlled by a linear actuator. To eliminate interference with the electromagnetic sensors, all metallic components of the fixture were made from either aluminium or stainless.

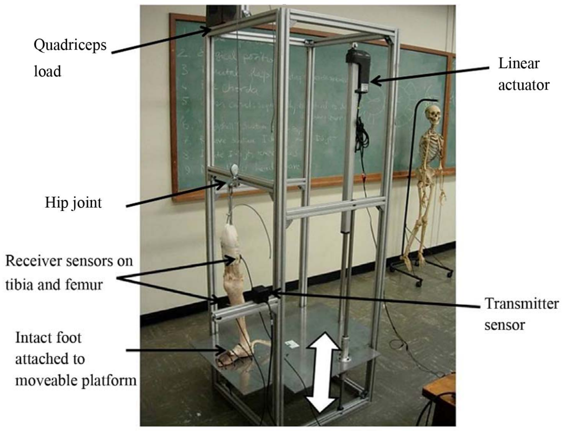

Figure 1. Loaded ankle apparatus.

2.3. Unloaded Ankle Apparatus

In the unloaded ankle test rig (**Figure 2**), the femoral intermedullary rod is fixed horizontally with the tibia hanging freely. Flexion/extension is achieved by controlling a linear actuator attached to one end of a cable, while the other end of the cable is attached to the quadriceps tendon. A load cell was attached between the cable and the actuator, measuring the force transmitted to the quadriceps tendon. The rig allows for unconstrained tibial movement relative to the femur with only flexion/extension controlled.

2.4. Knee Implants

Normal knee kinematics was compared to kinematics after implantation with two types of unicompartmental knee replacements. The first type is a patient-specific UKR. Prior to testing, CT data of the cadaver knees were obtained in order to develop patient-specific implants [34]. The conventional implant used was a nonconforming fixed-bearing UKR. The accompanying instrumentation was used for implantation.

2.5. Knee Implants

Each specimen was preconditioned by manually flexing the knee at least 10 times between full extension and full flexion. First, knee kinematics was recorded with an intact joint capsule on both the test rigs. Next, the patient-specific knee replacement was implanted and tested on both test rigs and the kinematics was recorded. The femoral component was implanted by removing the cadaver femoral cartilage beneath the implantation region and making the fixation hole with help of the custom instrumentation. The tibia was prepared as per standard surgical technique using the fixed-bearing instrumentation. The system uses a tibial cut perpendicular to the tibial shaft axis. The fixation hole was prepared using the custom instrumentation.

The patient-specific components were removed and the cadaver knee implanted with the fixed-bearing components as per standard surgical technique with the accompanying instrumentation. The knees were again tested on both test rigs and the kinematics recorded.

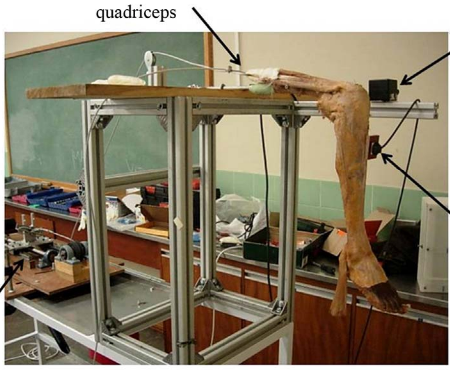

Figure 2. Unloaded ankle apparatus.

3. RESULTS

For all three the different knee specimens, and both the test-setups, the normal knee displayed femoral rollback and internal tibial rotation. However, the loaded ankle results showed slightly more femoral posterior translation, as well as considerably more internal tibial rotation. Similar kinematics patterns were also present after implantation with both the patient-specific and conventional fixed-bearing UKRs. Some interspecimen variation was also visible. Cadavers 1 and 3 received medial replacements while cadaver 2 received a lateral replacement.

3.1. Unloaded Ankle Apparatus

Figures 3-**5** show the tibial rotation and femoral translation of the three knee specimens using the unloaded ankle apparatus. For cadaver 2, only the normal knee and patient-specific UKR kinematics were available (**Figure 4**). Cadavers 1 and 2 showed tibial rotation of more than 20˚ over a flexion range of 70˚. The patient-specific UKR showed very similar patterns to the normal knee. The conventional UKR showed slightly more rotation for cadaver 1 while still following a similar pattern. Cadaver 3 showed tibial rotation of about 10˚ after 70˚ flexion. Both the UKRs showed higher rotations over the range of flexion.

For all three normal knees femoral rollback ranged between 4 mm and 5 mm. The UKRs showed similar but slightly more femoral rollback for cadaver 1. For cadaver 2 the patient-specific translation was very similar to that of the normal knee. For cadaver 3 the conventional UKR followed a similar pattern to that of the normal knee, with slightly more posterior translation. The patient-specific UKR also followed a similar pattern, with even more posterior translation.

3.2. Loaded Ankle Apparatus

Only cadavers 2 and 3 were tested on the loaded ankle apparatus and only cadaver 3 was implanted with the conventional UKR (**Figures 6** and **7**). The normal knees displayed more internal tibial rotation compared to the unloaded ankle, with cadaver 3 showing four times more rotation. After 70˚ flexion both knees showed internal tibial rotation of about 40˚. For cadaver 2 the patient-specific UKR showed a similar pattern to that of the normal knee, with slightly less rotation. For cadaver 3 both the UKRs showed a similar pattern to the normal knee up to 60˚ flexion after which the normal knee's rotation stopped.

Cadavers 1 and 2 showed femoral rollback of close to 8 mm after a slight anterior translation at the beginning. For cadaver 2 the patient-specific UKR showed a similar pattern to that of the normal knee, with slightly more posterior translation. For cadaver 3, both the UKRs showed considerably less posterior translation. However, the patient-specific UKR showed a similar pattern to that of the normal knee, with a slight anterior translation at first before a steeper posterior translation.

4. DISCUSSION

Total knee replacements offer excellent survival rates but numerous studies have reported that normal knee kinematics is not achieved after TKR [2,14,15,22,26]. It has been suggested that unicompartmental knee replacement offers the potential to restore knee kinematics comparable to that of the normal knee due to soft-tissue stability and better preservation of the overall geometry

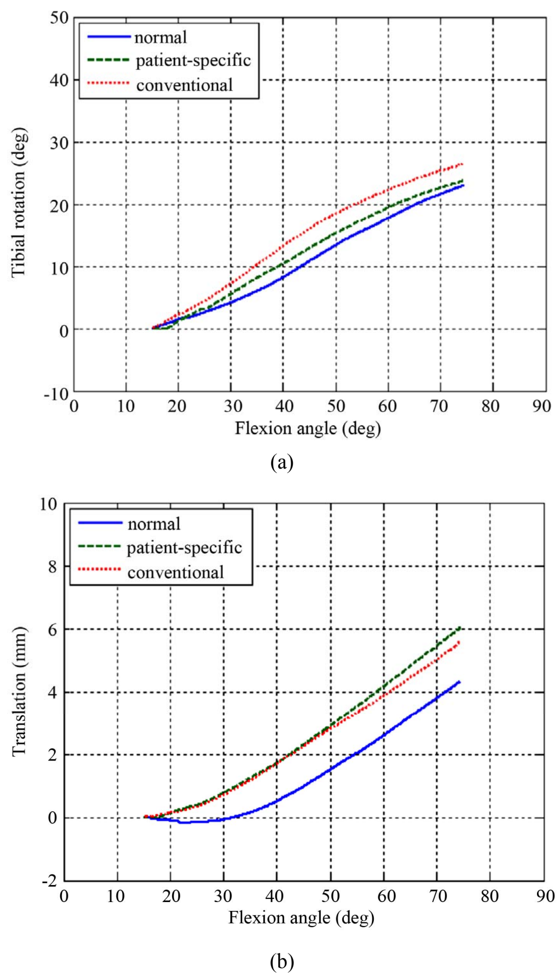

Figure 3. Cadaver 1 measurements on unloaded ankle apparatus: a) Tibial rotation; b) Femoral translation.

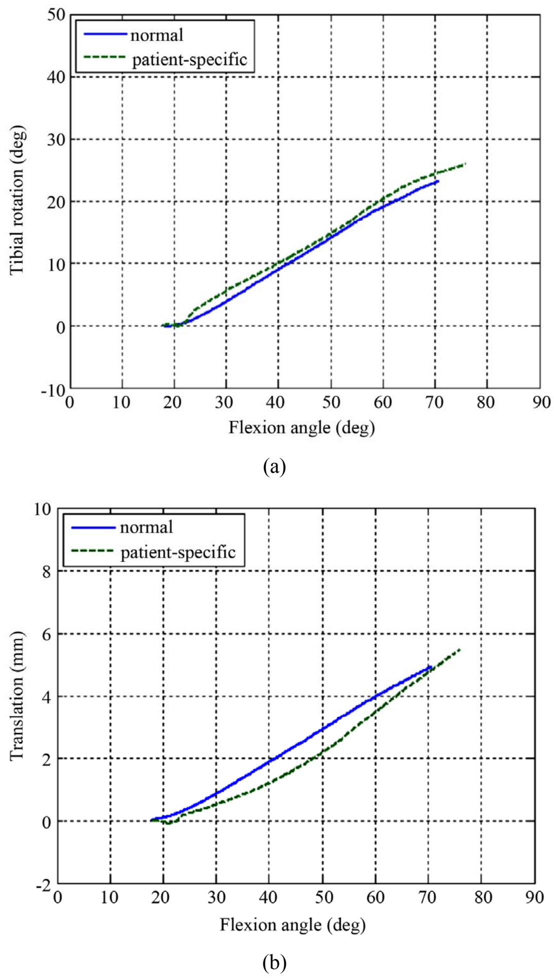

Figure 4. Cadaver 2 measurements on unloaded ankle apparatus: a) Tibial rotation; b) Femoral translation.

[14,27]. In this study we compared normal knee kinematics to knee kinematics after implantation with a patient-specific UKR and a conventional UKR. This was done using two different testing apparatus providing different loading conditions. The first one is based on the OKR and provides a load at the ankle joint while the second design provides an unloaded ankle. The results showed that there are significant differences between the two *in vitro* methods for the same knees. The loaded ankle tests showed more internal tibial rotations and more femoral rollback for the same knees compared to the unloaded ankle tests. The tibial rotations found with the loaded ankle tests tended to be higher than that reported in the literature [2-4,14-15]. A possible cause is that the embalmed specimens used in this study tended to be stiffer than fresh frozen specimens. However, the results confirm the observation made by Victor *et al.* [4] that different *in vitro* methods reveal different kinematic patterns, and this fact must be kept in mind in future kinematic studies.

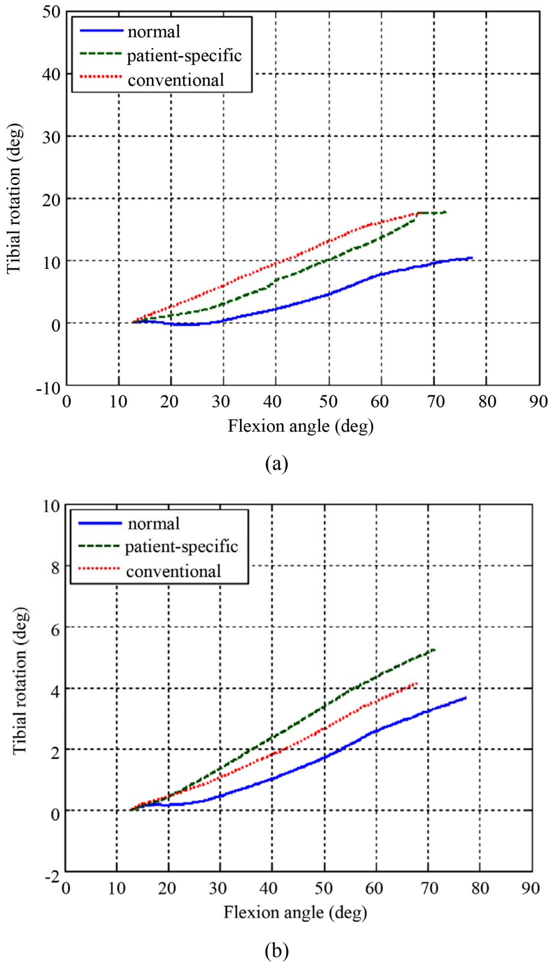

Figure 5. Cadaver 3 measurements on unloaded ankle apparatus: a) tibial rotation; b) femoral translation.

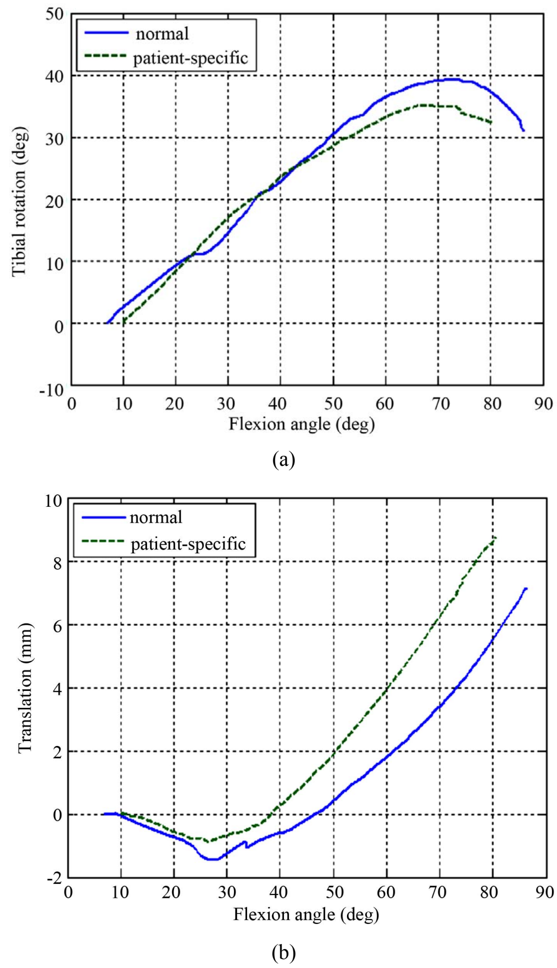

Figure 6. Cadaver 2 measurements on loaded ankle apparatus: a) tibial rotation; b) femoral translation.

Both the UKRs showed similar kinematic patterns to the normal knee using both the test apparatus. Cadaver 1 was only tested on the unloaded ankle apparatus, and the patient-specific UKR showed slightly better results compared to the conventional UKR (**Figure 3**). Cadaver 2 received a lateral implant and it was seen that the kinematics were similar to that of the normal knee. In the loaded ankle test, the patient-specific UKR followed the same anterior translation before posterior translation as with the normal knee. The patient-specific UKR also showed a slight external rotation after 70˚ flexion, similar to the normal knee **(Figure 6**). The geometry and kinematics of the lateral compartment are different to that of the medial compartment, and lower survival rates and other complications have been reported when using conventional UKRs for the treatment of lateral osteoarthritis [35-37]. Unfortunately, conventional UKR kinematics was not available for cadaver 2. The conventional UKR showed slightly better results for cadaver 3 in the unloaded ankle apparatus, with both UKRs showing similar kinematic patterns to that of the normal knee (**Figure 5**). In the loaded ankle apparatus, the tibial rotation was very similar for all the cases, with the patient-specific UKR showing a similar pattern to that of the normal knee during translation albeit a few millimeters off. From the results it is evident that both patient specific and conventional UKR kinematics are similar to normal knee kinematics. Patil *et al.* [14] compared normal knee kinematics with kinematics after implantation with a low conforming, fixed-bearing UKR and a TKR in six human cadavers. They also found very good results for the UKR, remarking that near normal function may be expected after UKR.

The good kinematic results of UKRs are thought to be because of retaining the cruciate ligaments, the balance of other soft-tissue tension, and better preservation of the overall geometry [14,27]. The results obtained in this study further validate this train of thought and may indicate that the soft-tissue balance plays a more important role than UKR geometry. This can be seen by the similar kinematic results between the two UKRs even though the patient-specific UKR had a more normal geometry. It

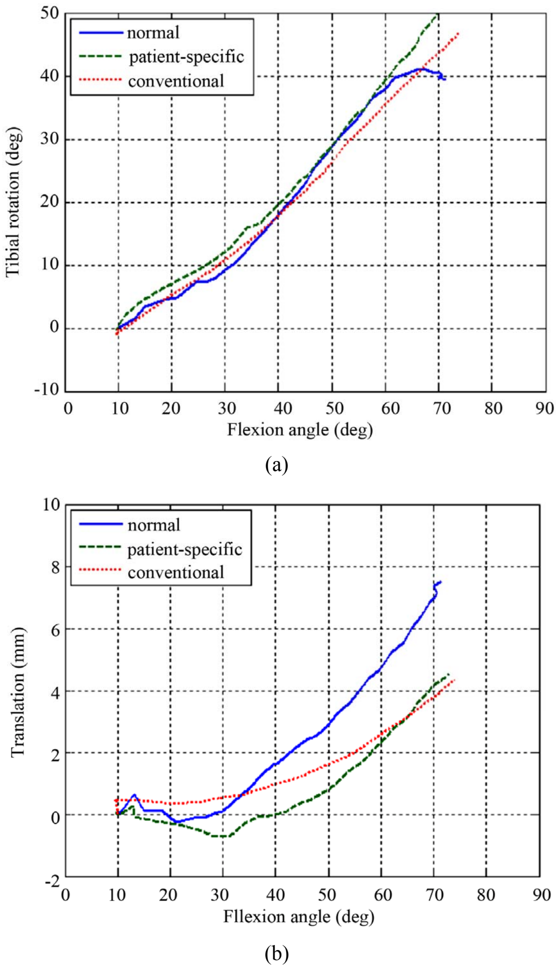

Figure 7. Cadaver 3 measurements on loaded ankle apparatus: a) tibial rotation; b) femoral translation.

should further be noted that different bearing types were used in this study (mobile-bearing in the patient-specific UKR compared to the fixed-bearing in the conventional UKR), this can further influence kinematic results. Another limitation in this study is the small sample size. However, the intend was not to draw statistical conclusions, but rather to show that patient-specific UKRs can have near normal kinematics comparable to conventional UKRs. Future research should include more samples, use fresh cadaver knees and could compare similar bearing types to look at the effect on knee kinematics. It is important to note though, that kinematics varies from knee to knee and also between different testing methods. There is also high variability between knee kinematics in the literature.

The variability found in knee kinematic studies may be attributed to interspecimen variability [2]. D'Lima *et al.* [13,38] obtained different intact knee kinematics in two different studies using identical protocol and OKR setup. Victor *et al.* [3] showed that interspecimen variability was greater than interload variability. They further argue that a correct description of normal knee kinematics for clinical applications remain a major challenge. It seems that referring to normal knee kinematics is inherently flawed, since individual knees will behave differently. Rovick *et al.* [23] argue that average behaviour is a useful reference, but it does not describe the individual variations. It is therefore difficult to compare different kinematic studies due to the influence of the *in vitro* method used and the high variability between individual knees. It is suggested here that reference should rather be made to individual normal knee kinematics.

UKR have several advantages over TKR including less bone loss, retention of cruciate ligaments and better kinematics. The use of UKR is also increasing in younger, more active patients with localized disease because of these potential advantages [14]. However, UKR remains a highly demanding surgical procedure and survivorship is dependent on precise alignment and component orientation [31-33]. Koeck *et al.* [31] demonstrated that patient-specific UKR can provide near optimal implant positioning and anatomical component orientation. This is due to the variation in healthy knee anatomies and current implant designs. In this study it was also experienced that the patient-specific UKR femoral component was easily implanted once the cartilage was removed and had a very good fit. The cutting guides aided in making the correct cut for the fixation peg. The process was much simpler than with the conventional UKR, which required additional cutting of the femur. With the huge variability in knee kinematics between individuals and the other advantages provided by patient-specific UKR, it is suggested that there is significant potential for this technique.

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