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■ **BIOMECHANICS**

The primary stability of the femoral component in cemented single and twin peg Oxford unicompartmental knee arthroplasty under adverse conditions

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Aims

The cemented Oxford unicompartmental knee arthroplasty (OUKA) features two variants: single and twin peg OUKA. The purpose of this study was to assess the stability of both variants in a worst-case scenario of bone defects and suboptimal cementation.

Methods

Single and twin pegs were implanted randomly allocated in 12 pairs of human fresh-frozen femora. We generated 5° bone defects at the posterior condyle. Relative movement was simulated using a servohydraulic pulser, and analyzed at 70°/115° knee flexion. Relative movement was surveyed at seven points of measurement on implant and bone, using an optic system.

Results

At the main fixation zone, the twin peg shows less relative movement at 70°/115°. At the transition zone, relative movements are smaller for the single peg for both angles. The single peg shows higher compression at 70° flexion, whereas the twin peg design shows higher compression at 115°. X-displacement is significantly higher for the single peg at 115°.

Conclusion

Bony defects should be avoided in OUKA. The twin peg shows high resilience against push-out force and should be preferred over the single peg.

Article summary

■ Bone defects can occur preoperatively as well as intraoperatively. It is crucial to determine whether both variants of peg design in the Oxford unicompartmental knee arthroplasty (OUKA) exhibit comparable stability in defect situations.

■ In this experimental study, the influence of peg design on implant stability was assessed, using an experimental cadaver model. A bone defect at the posterior condyle was artificially created to allow the study of implant stability in a worst-case scenario.

Key messages

■ The OUKA shows complex behaviour when implanted in a knee with a bone defect at the posterior condyle. Both single and twin peg designs show high micromotion, with the twin peg exhibiting less micromotion at the main fixation zone around the peg area and the anterior shield.

Strengths and limitations

■ This study was an experimental cadaver study, so neither bleeding nor kinematics could be simulated.

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Fig. 1

Comparison of the single and twin peg Oxford unicompartmental knee arthroplasty. The twin peg design contains an additional peg and wider radius (dark grey). The single peg design (light grey) features a smaller circumference than the twin peg.

- Micromotion was only assessed at 70° and 115° flexion.
- Although kinematics could not be simulated, results could be obtained in a very standardized manner for the two tested settings.
- This study shows good evidence that the additional peg could indeed be an advantage in defect situation.

Introduction

Due to demographic changes, osteoarthritis (OA) is an increasing problem in industrial nations,[1,2] the knee being the most commonly affected site.[3] For isolated medial OA of the knee, unicompartmental knee arthroplasty (UKA) is a widely used treatment option and comprises 7% to 13.3% of all primary knee arthroplasties.[4-7] While UKAs such as the Oxford UKA (OUKA, Zimmer Biomet, UK) show excellent long-term results,[5,8-12] it has been noted that UKAs show higher revision rates than total knee arthroplasties (TKAs).[5,13,14] Aseptic loosening – described as mechanical failure of the bone/cement or the cement/implant interface – of one or both components is among the most common reasons for revision surgery, accounting for 27%[4] to 37.6%[7] in large cohort studies; femoral aseptic loosening is described to occur more often than the tibial loosening.[15-18] However, factors such as component alignment[19] or tibiofemoral conformity[20] also impact clinical outcomes.

The twin peg design of the OUKA was introduced to improve primary stability by adding a second smaller
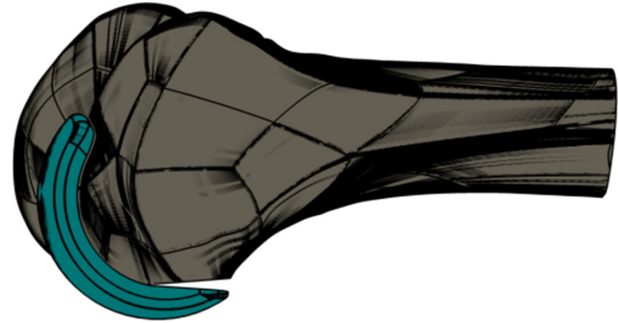

Fig. 2

Schematic illustration of the bone defect. A 5° saw cut was chosen to simulate bone defects without cement penetration as a worst-case scenario.

peg. Additionally, it provides rotational stability and allows for a higher flexion, as the arc of the implant was increased by 15° (Figure 1). In an experimental cadaver study, both designs of the OUKA showed equal stability.[21] This was, however, assessed in an ideal laboratory setting with an optimal surgical result and highly standardized cementing. It is known that the success of UKA is highly dependent on the expertise of the surgeon performing the procedure.[22,23] This observation is confirmed by results of Clarius et al,[24] obtained during an instructional course, showing a variety of sawing errors produced by inexperienced surgeons. Apart from sawing errors, bony defects of the condyle can also be caused by spontaneous osteonecrosis of the knee ((SONK), Ahlbaeck's disease) as well as removal of large posterior osteophytes. Furthermore, the posterior plane facet of the femoral component is known to be the weak spot of cementation.[25] Insufficient cementation, however, can lead to early loosening of endoprosthetic components and persistent knee pain, causing worse outcome and shorter survival time.

In this experimental cadaver study, we aimed to assess differences of primary stability in single and twin peg OUKA in bones with bony defects of the posterior medial condyle in addition to suboptimal cementing on the posterior plane facet. We hypothesized that the second peg would positively influence the primary stability under adverse conditions.

Methods

In 12 paired fresh-frozen human femora, medial OUKA was performed by an experienced surgeon (RGB) with the original Oxford Phase III instrumentation. Exclusion criteria for donors were bone tumours or other known malignancies, infectious diseases (e.g. HIV, Hepatitis C), and previous surgical procedures involving the knees.

Bone mineral density (BMD) was assessed by dual energy X-ray absorptiometry (DXA) using the bone densitometer Hologic QDR-2000 (Hologic, USA). The respective femora of each pair were randomly assigned to study group A (single peg) or study group B (twin peg) using a computer-generated list compiled by Randlist 1.2 (Datinf GmbH, Germany). Pre- and postoperative anterior and
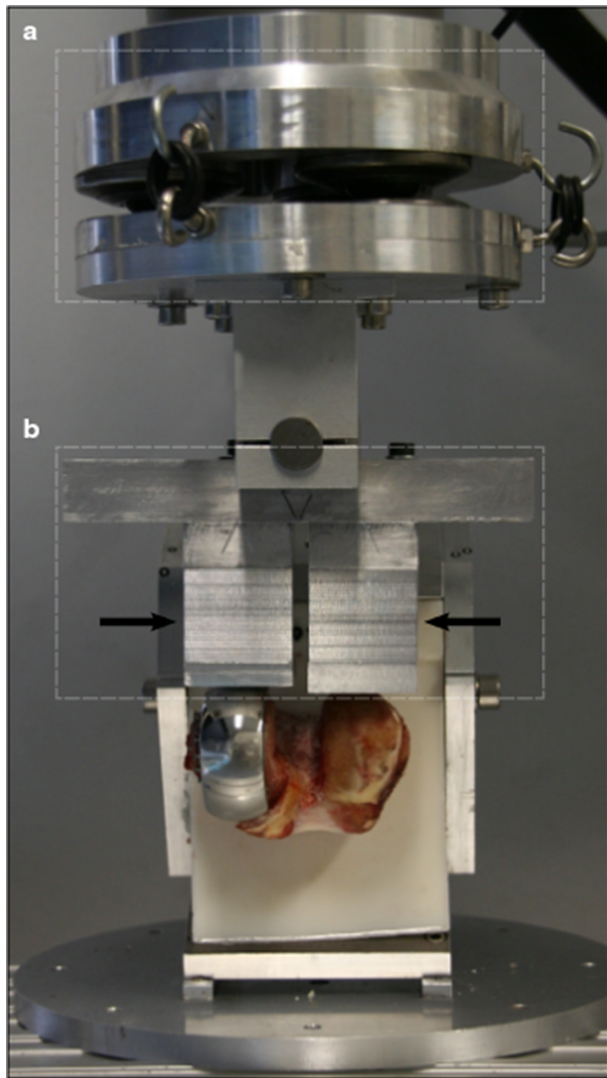
Fig. 3

General setup of testing station. The servohydraulic pulser was equipped with a shearing force compensation (a), as well as an integrated rocker bearing (b) allowing for donor-specific adjustment.
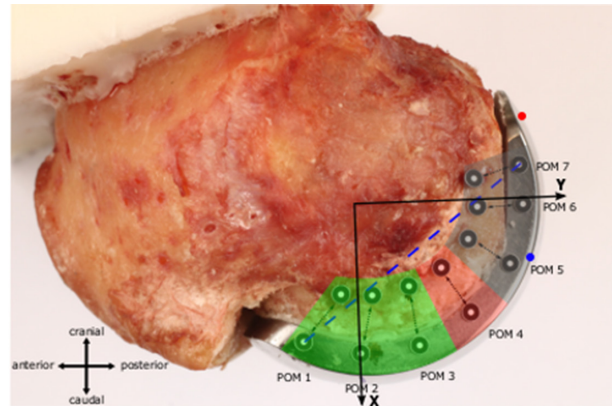

Fig. 4

Standardized application of marker points. Seven marker points were applied to implant and bone respectively. We define three zones of fixation: green – main fixation zone, red – transition zone, grey – defect zone. Blue dotted line indicates the connection between points of measurements (POMs) 1 and 7, which were used for the approximation of the implant compression. Blue dot indicates application of force at 70° flexion; red dot indicates application of force at 115° flexion.

Table I. Maximal relative motion at 70° knee flexion.

Zone	Single peg	Twin peg	p-value*
POM 1			0.009
Mean measurement, µm (SD; range)	100 (8; 85 to 109)	62 (8; 49 to 72)	
POM 2			0.009
Mean measurement, µm (SD; range)	49 (5; 42 to 54)	38 (4; 31 to 43)	
POM 3			0.009
Mean measurement, µm (SD; range)	42 (2; 39 to 45)	60 (8; 47 to 72)	
POM 4 (transition)			0.009
Mean measurement, µm (SD; range)	89 (5; 80 to 94)	101 (14; 78 to 120)	
POM 1 to 3 (main fixation)			0.009
Mean measurement, µm (SD; range)	64 (5; 56 to 69)	53 (7; 42 to 62)	

*Wilcoxon's matched pair signed-ranks test.
POM, point of measurement; SD, standard deviation.

lateral radiographs were obtained. Prior to implantation, digital planning of the procedure was conducted using TraumaCad (Voyant Health, Israel). In three pairs, a large OUKA was used, and nine pairs were planned for a medium-sized OUKA. In both study groups, similar implant sizes were used in each pair of femora.

The femoral cutting block of the original instrumentation was modified to achieve a standardized 5° bone defect (Figure 2). An angle of 5° for worst-case simulation of the femoral bone defect was chosen as it represents the maximal bone defect seen by Clarius et al[24] in their series of sawbone preparations. Eight anchorage holes were drilled around the central peg hole.[25] Bone lavage was performed using OptiLavage (Biomet Cement and Cementing Systems, Sweden). A total of 500 ml of 0.9% sodium chloride solution was used to clean the cancellous bone. Prior to cementation, the specimens were cut to a length of 13 cm measured from the distal tip of the medial condyle.

Cementation was realized under standardized conditions at 45° flexion, 180 N compression force,[26] using Hi-Fatigue G Bone Cement (Zimmer Biomet, USA). The mean room temperature was 20.1°C (standard deviation (SD) 0.3), and mean humidity was 28.3% (SD 8.3%). Cement was used according to the manufacturer's instructions.
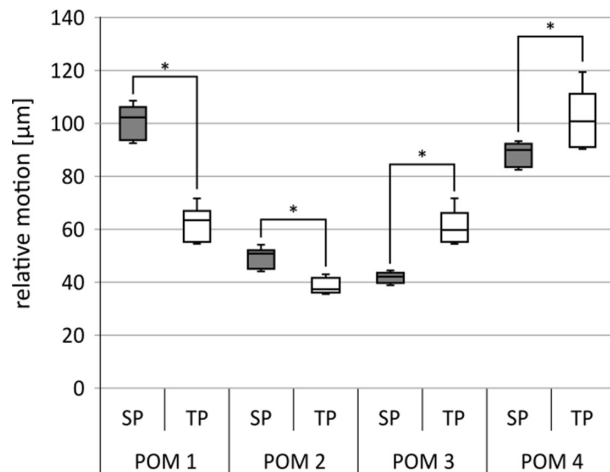
Fig. 5

Relative motion at 70° for point of measurement (POM) 1 to 4. SP, single peg; TP, twin peg. *p < 0.05. N = 12.
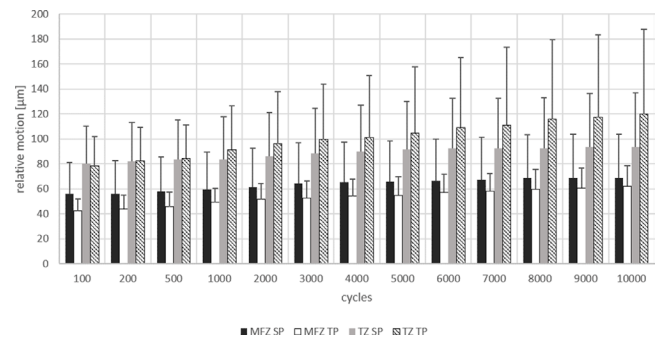

Fig. 6

Maximum relative motion at 70° over 10,000 cycles. Relative motion shown at main fixation zone (MFZ) and transition zone (TZ) for single peg (SP) and twin peg (TP) design over 10,000 cycles at 70° knee flexion. N = 12.

After cementation, the specimens were embedded in a casting mould, using polyurethane (RenCast FC 53 A/B, Huntsman Advanced Materials, Switzerland). As the present study was planned as a worst-case scenario, care was taken to create a suboptimal cement mantle at the posterior condyle (i.e. no immediate contact between cement and bone; a phase II saw guide with a 5° angle attached was used to ensure no adhesion would form).

Specimens were mounted into a hydraulic testing machine (Bosch Rexroth, Germany) and physiological-like loading conditions were applied. The load was applied at 70° and 115° knee flexion, simulating two activities of daily life: rising from a chair and deep squatting. The loads of 70° and 115° were chosen, as the force vector is directed onto the posterior part of the condyle where the artificial bone defect was created. While rising from a chair, the highest force (2.5 × body weight) is measured at a knee flexion angle of 70°, with a medial to lateral load ratio of 2.2:1. The highest medial to lateral load ratio reached while deep squatting is measured at 115° knee flexion (7.6:1) with a force that reaches 78% of the peak force (resembling approximately 2.1 × body weight) measured for this activity.[27] The force was applied donor-dependently to account for differences in body weight (44.4 kg to 145.1 kg). The specimens were loaded sinusoidally with a frequency of 1 Hz for 10,000 cycles, according to the respective medial to lateral load ratio using an integrated rocker bearing, allowing for the donor-specific adjustment of the COR (Figure 3).

The experimental setup was adapted based on the setup used by Reiner et al.[21] The relative motion between bone and implant was measured and analyzed using an optical measurement device (PONTOS, Gesellschaft für optische Messtechnik mbH, Germany). The terms 'relative motion' and 'relative movement' in this study represent the resulting relative motion with six degrees of freedom. Whenever a singular degree of freedom is specifically assessed, it is marked accordingly. Measurements

were obtained prior to loading (as a reference) and then automatically triggered at 100, 200, 500, 1,000, and then every 1,000 cycles until the end of the test at 10,000 cycles. For each measurement, 60 pictures were taken by the two integrated high-resolution cameras with 15 frames per second. Seven markers were placed on femoral component and bone (points of measurement (POM) 1 to 7, Figure 4), respectively, and with a special software (PONTOS, Gesellschaft für optische Messtechnik mbH), relative motion between the associated marker points was analyzed.[21]

To further characterize the movement of the two designs, the resulting relative motion was broken down into the individual degrees of freedom, and the motion along the x-axis (defined as the axis of the peg) was analyzed. Additionally, we measured the compression of the femoral component by approximation, analyzing the changes in the distance between POM 1 (anterior) and POM 7 (posterior).

The implants were kindly provided by Zimmer-Biomet. Sponsoring bodies did not take part in study design, analysis, or interpretation of the study data. The study was ethically approved by the local ethics committee, prior to the start of the study (S 328/2014).

Statistical analysis. The cohort size was chosen following a previous study by Jaeger et al,[28] who measured micromotion and subsidence of a tibial component under cyclical loading as well as the aforementioned study by Reiner et al.[21] Of the 12 prepared pairs of femora, four pairs had to be excluded from the analysis at 115° knee flexion, as one of the respective femora fractured early during this measurement.

Descriptive analysis, as well as Wilcoxon's matched pair signed-ranks test, was conducted to investigate statistically significant differences between the study groups A and B. The alpha-level was chosen as 0.05 for all analyses.

The maximal relative motion between corresponding marker POMs 1 and 7 was averaged for the 12 (70°) and eight (115°) paired femora, respectively. In the context of femoral bone defects, we defined three zones of fixation, with different fixation characteristics: the anterior main fixation zone, the intermediate transition zone,
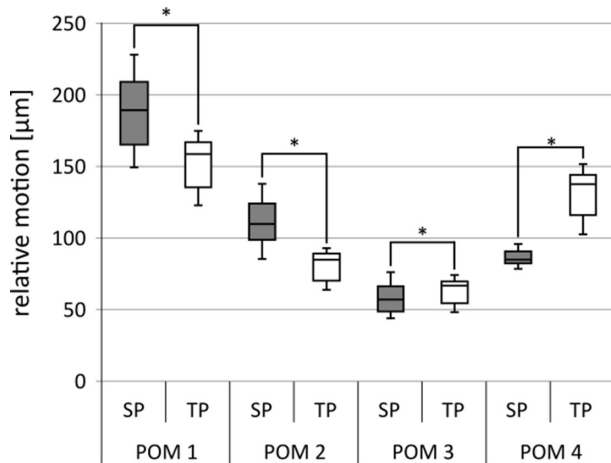
Fig. 7

Relative motion at 115° point of measurement (POM) 1 to 4. SP, single peg; TP, twin peg. *p < 0.05. N = 8.

Table II. Maximal relative motion at 115° knee flexion.

Zone	Single peg	Twin peg	p-value*
POM 1			< 0.01
Mean measurement, µm (SD; range)	188 (27; 149 to 228)	152 (19; 123 to 175)	
POM 2			< 0.01
Mean measurement, µm (SD; range)	111 (17; 85 to 138)	80 (11; 64 to 93)	
POM 3			< 0.01
Mean measurement, µm (SD; range)	58 (10; 44 to 76)	63 (9; 48 to 74)	
POM 4 (transition)			< 0.01
Mean measurement, µm (SD; range)	86 (5; 78 to 95)	133 (16; 104 to 151)	
POM 1 to 3 (main fixation)			< 0.01
Mean measurement, µm (SD; range)	119 (18; 93 to 147)	98 (13; 78 to 114)	

*Wilcoxon's matched pair signed-ranks test.
POM, point of measurement; SD, standard deviation.

and the posterior defect zone (Figure 4). To account for those different fixation patterns, we calculated the mean maximal relative motion for the three anterior POMs, situated in the main fixation zone as well as the defect zone.

Implant movement is generally composed of different types of movement, a dynamic (i.e. reversible) and a plastic (i.e. irreversible) movement. In this study, we do not look at these different types of movement, but rather the maximal relative movement without differentiation.

For statistical analysis, SPSS v25 (IBM, USA) and Microsoft Excel (Microsoft, USA) were used. Two-tailed p-values below 0.05 were assumed to denote statistical significance.

Results

The specimens showed no significant difference in BMD between left and right hip (T-score left hip: -1.89 (SD 1.13), T-score right hip: -1.88 (SD 1.17), p = 0.859, Wilcoxon's matched pair signed-ranks test).

At 70° knee flexion, the single peg design exhibited significantly higher relative motion at POM 1 and 2. Further towards the bony defect zone, at POM 3 and 4, the twin peg design showed significantly higher relative motion (p = 0.010, Wilcoxon's matched pair signed-ranks test). The composite main fixation zone (POM 1 to 3) showed in total a significantly higher relative motion for the single peg design (Table I, Figure 5). This was consistent over the whole measuring period (Figure 6).

At 115° knee flexion, as mentioned above, during the loading, four of the specimens fractured and subsequently had to be excluded from further analysis. In this setting, the single peg design also showed significantly higher relative motion at the anterior POM 1 and 2, as well as the main fixation zone. At POM 3 and at the transition zone (POM 4), the twin peg design exhibited significantly higher relative motion (Table II, Figure 7). Again,

this was consistent throughout the measuring period (Figure 8).

The measuring points around the defect area (POM 5, 6, and 7, and POM 5 to 7 combined) were also analyzed for relative motion. At 70° flexion, measurements at POM 5 showed similar results for single peg and twin peg. For POM 6, the single peg showed significantly higher measurements than the twin peg. That was consistent with the data at POM 7, which showed significantly higher relative movement for the single peg. POM 5 to 7 combined exhibited higher relative motion for the single peg as well (Table III). At 115° flexion, the twin peg consistently showed higher measurements for all the POM as well as for the combined POM 5 to 7 (Table IV).

The measurement of the implant compression revealed a significantly higher minimal (which corresponded to the moment of load removal) as well as maximal compression of the single peg at 70° knee flexion (p = 0.010, Wilcoxon's matched pair signed-ranks test). Likewise, the difference (δ) was significantly higher for the single peg. At 115°, the proportions reversed and the twin peg showed significantly higher maximal compression (p = 0.017, Wilcoxon's matched pair signed-ranks test), as well as a higher δ. Minimal compression at 115° was not significantly different (p = 0.056, Wilcoxon's matched pair signed-ranks test) (Table V, Figure 9).

The mean x-deviation at 115° was significantly higher for single pegs measured at the main fixation zone throughout the measurement (Table VI; Figure 10), revealing a higher push-out movement for the single
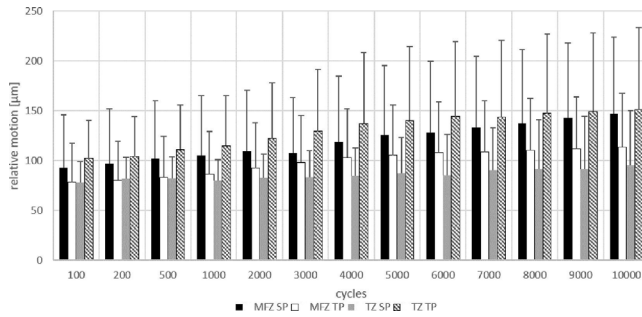
Fig. 8

Maximum relative motion at 115° over 10,000 cycles. Relative motion shown at main fixation zone (MFZ) and transition zone (TZ) for single peg (SP) and twin peg (TP) design over 10,000 cycles at 115° knee flexion. N = 8.

Table IV. Maximal relative motion at 115°. Defect Zone.

Zone	Single peg	Twin peg	p-value*
POM 5			0.001
Mean measurement, µm (SD)	159 (12)	203 (26)	
POM 6			0.001
Mean measurement, µm (SD)	232 (20)	273 (35)	
POM 7			0.002
Mean measurement, µm (SD)	281 (26)	317 (41)	
POM 5 to 7 (Defect zone)			0.001
Mean measurement, µm (SD)	231 (18)	264 (34)	

*Wilcoxon's matched pair signed-ranks test.
POM, point of measurement; SD, standard deviation.

Table III. Maximal relative motion at 70°. Defect Zone.

Zone	Single peg	Twin peg	p-value*
POM 5			0.600
Mean measurement, µm (SD)	139 (8)	141 (19)	
POM 6			0.013
Mean measurement, µm (SD)	187 (12)	177 (24)	
POM 7			0.001
Mean measurement, µm (SD)	217 (14)	191 (24)	
POM 5 to 7 (Defect zone)			0.007
Mean measurement, µm (SD)	181 (11)	170 (22)	

*Wilcoxon's matched pair signed-ranks test.
POM, point of measurement; SD, standard deviation.

Table V. Implant compression.

Flexion	Compression	Single peg	Twin peg	p-value*
70°	**Minimum**			< 0.01
	Mean measurement, µm (SD; range)	23 (2; 20 to 25)	16 (4; 10 to 21)	
	Maximum			< 0.01
	Mean measurement, µm (SD; range)	75 (2; 72 to 77)	53 (7; 42 to 62)	
	δ			< 0.01
	Mean measurement, µm (SD; range)	52 (1; 51 to 53)	37 (3; 32 to 41)	
115°	**Minimum**			0.056
	Mean measurement, µm (SD; range)	59 (3; 53 to 64)	64 (10; 47 to 76)	
	Maximum			0.017
	Mean measurement, µm (SD; range)	195 (3; 192 to 203)	210 (18; 182 to 230)	
	δ			0.013
	Mean measurement, µm (SD; range)	136 (3; 133 to 141)	145 (8; 134 to 154)	

*Wilcoxon's matched pair signed-ranks test.
SD, standard deviation; δ, difference (maximum – minimum).

peg design. Figure 11 depicts the displacement vectors for the single and twin peg; the single peg shows higher displacement for all POMs.

Discussion

The outcome of OUKA is highly surgeon-dependent and correlates significantly with the number of cases.[23] Reiner et al[21] showed that in an ideal, controlled environment, single peg and twin peg OUKA do not exhibit different characteristics concerning primary stability. However, they note that primary stability, apart from being influenced by the design itself, can be affected by surgical technique and penetration of cement – issues that we aimed to address in this study. To our knowledge, no study has been published describing the correlation of adverse conditions with primary stability in the two designs of the OUKA.

The relative motion we measured in this study was higher than in previously published data for UKA, particularly in 115° flexion. Reiner et al[21] described micromotion between 10 µm and 57 µm, and Miskovsky et al[29] measured between 11 µm and 61 µm. Our higher values were expected, given the large posterior defect we used to simulate suboptimal bone stock and surgical result. In an experimental animal model, Jasty et al[30] identified the threshold for continuous micromotion allowing for osseointegration in cementless implants at 40 µm. For cemented implants, no scientifically proven thresholds

exist. Both designs exhibited higher relative motion in this study, although not for every point of measurement. The area around the additional peg in particular showed significantly less relative motion in the twin peg design, albeit still more than 40 µm. The fact that the anterior portion of the OUKA was significantly more stable in the twin peg design needed further investigation, hence we assessed the compression of the implant designs to determine whether it might influence the relative motion, especially in the intermediate transition zone, which showed higher measurements for the twin peg design. Interestingly, at 70°, the twin peg exhibited less implant compression than the single peg; this might be explained by the fact that the effective point of force differed slightly for the two different designs. However, at 115°, the twin peg in turn showed higher implant compression.
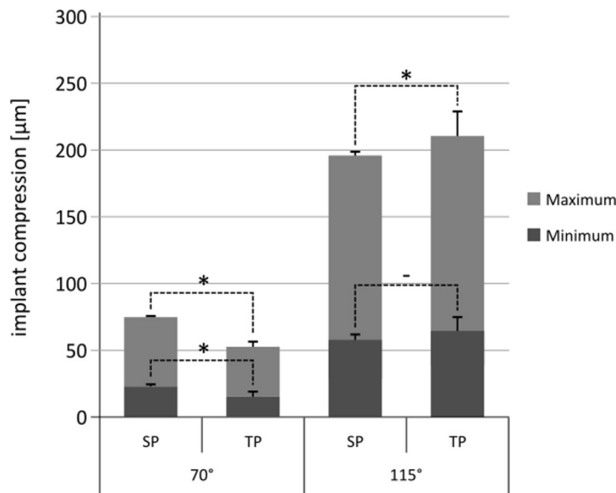
Fig. 9

Implant compression shown for single peg (SP) and twin peg (TP) design for 70° (n = 12) and 115° (n = 12) knee flexion. *p < 0.05; "−" denotes a p-value > 0.05.

Table VI. X-displacement at 115° at the main fixation zone.

Measurement	Single peg	Twin peg	p-value*
Mean, μm (SD; range)	80 (15; 56 to 103)	46 (7; 35 to 55)	< 0.01

*Wilcoxon's matched pair signed-ranks test.
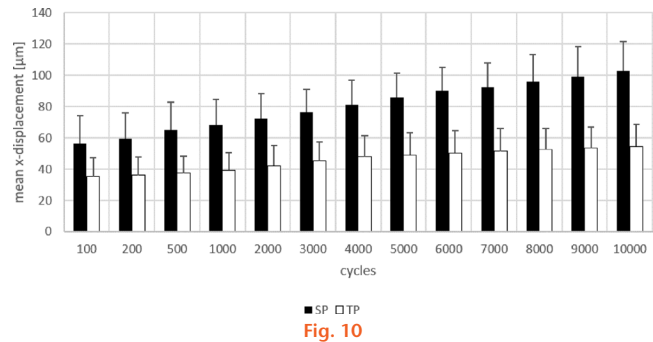SD, standard deviation.

■ SP □ TP

Fig. 10

X-displacement at 115° for main fixation zone (point of measurement (POM) 1 to 3). The mean displacement on the x-axis is shown for single peg (SP) and twin peg (TP) at 115° flexion for the main fixation zone. N = 8.

Thus, at high flexion, the twin peg seems to bend more. Combined with the information that the single peg showed a higher push-out movement (80 μm vs 46 μm; p = 0.010, Wilcoxon's matched pair signed-ranks test) along the femoral axis, this seems to explain the higher resulting relative movement in the intermediate part of the femoral component of the twin peg design.

As expected, we observed a significant increase in relative motion in the POM 5 to 7 range for both groups investigated. We attribute the differences between the two groups in the posterior part to the different stabilities in the anterior and PEG fixation, respectively. Improved fixation at the anterior region may increase the relative movement and deformation at the posterior part of the implant. A higher relative motion anteriorly reduces the posterior relative motion and deformation. This is most evident with a load application of 115°.

Due to better integration at the anterior part (quite possibly due to the additional peg), the compression of the twin peg (especially at 115°) is higher, causing the twin peg to 'sink in' to the bone at the zone between main fixation and defect zone – the transition zone.

Out of 12 pairs tested, four had to be excluded due to fracture of one of the respective specimens. As mentioned before, the specimens were individually loaded using patients' body weight. In the respective cases, the BMIs of the donors ranged between 32.7 kg/m^2 and 53.3 kg/m^2. It is safe to assume that, without any stabilizing function of adjacent joints, the continuous loading with a high force caused the femora to break. Of note, of the fractured femora, three had been implanted with a single peg OUKA.

There are some limitations to our study. First, we could not simulate bleeding. However, this aspect seems to be negligible, as in cemented knee arthroplasties the use of a tourniquet is recommended, and pulsatile lavage is used in vivo as well as in this study. Second, in order to minimize movement of the femora, a large portion had to be included in the polyurethane cast, causing a high constraint of the femora. This might have influenced the occurrence of the abovementioned fractures. Third, the setting for the experimental setup was derived from an elaborate study by Mündermann et al[27] with an instrumented total knee arthroplasty. In this study, an instrumented TKA in a 81-year-old patient was used to determine loading and loading ratios in the knee. While we adapted these conditions for our setup, it has to be noted that UKA patients are on average 60 to 65 years old,[31-33] which is younger than the 81-year-old patient in the study. Also, UKA allows for movement of the femoral condyle on the medial tibial compartment, and the anterior cruciate ligament is still in place; for this reason, the kinematics are closer to the physiological kinematics of the knee than those of a TKA.[34,35] We only measured relative motion in 70° and 115° knee flexion in this experimental setup; relative motion during regular movement will exhibit more complex patterns. Nonetheless, the data obtained in our experiments are valid, as we minimized the influence of the abovementioned effects by using paired specimen.

In our data, the twin peg design seems to be more stable than the single peg design. The increasing magnitude of the measurement towards the posterior part of the implant can be explained by the bone defect. Also, UKAs are increasingly used in patients with spontaneous osteonecrosis of the knee,[36-38] a condition in which, by definition, bad bone stock can be assumed.

In conclusion, the twin peg design of the OUKA seems to exhibit less relative motion, albeit not over the whole
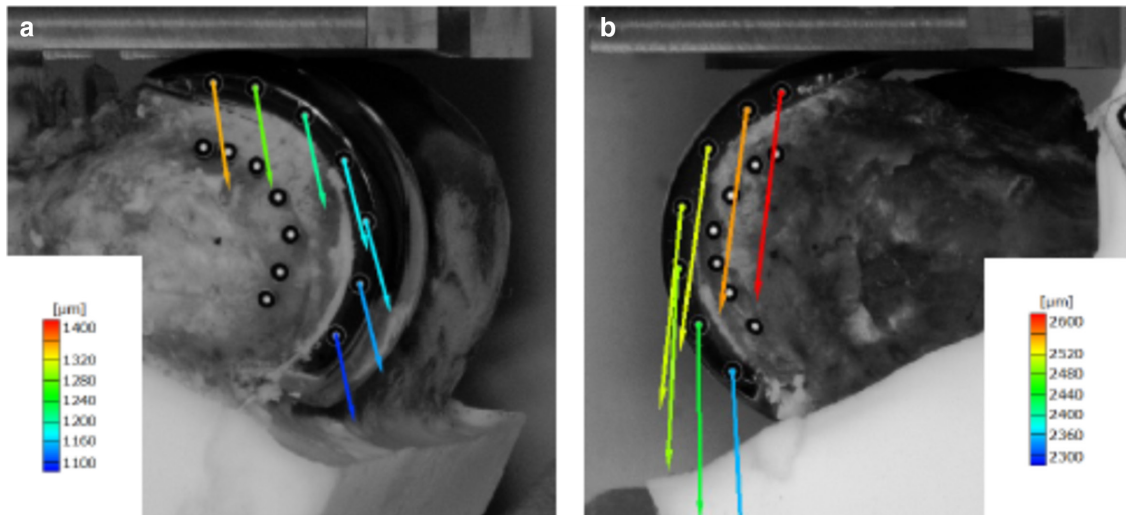
Fig. 11

a) Displacement vectors for the twin peg. b) Displacement vectors for the single peg at 115° (c80011; vectors shown with factor 10 for demonstrative purposes). The single peg shows higher displacement over all point of measurements (POMs).

radius, which can be explained by the differential fixation pattern and the higher push-out movement of the single peg design. Also, the amplitude of the relative motion was high in both cases, especially for 115° knee flexion. This underlines the importance of a proper bony fixation and cementation, respectively, at the posterior condyle. Nevertheless, surgical procedure and loss of bone stock are comparable for the two designs. Additionally, with its larger radius, the twin peg design allows for a higher flexion. Hence, the twin peg design seems to be the more logical decision when performing OUKA surgery. The hypothesis, that the second peg positively influences the primary stability under adverse conditions, can be accepted.

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