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A greater reduction in the distal femoral anterior condyle improves flexion after total knee arthroplasty in patients with osteoarthritis

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ABSTRACT

Background: The effect of an anterior condylar height (ACH) change after total knee arthroplasty (TKA) is not well-known. The effect of an ACH change was evaluated on postoperative knee flexion, New Knee Society Scores (2011KSS), and patellofemoral contact force.

Methods: The study included 101 knees that underwent TKA. The medial or lateral ACH was measured using pre-operative and postoperative computed tomography. Pearson correlation between the change in ACH and knee flexion was calculated. The determinant of the change in flexion was evaluated using multivariable linear regression. The association between ACH and 2011KSS was assessed. Using the cases with the three highest and three lowest pre-operative medial ACHs, computer simulation was performed to detect the changes in patellofemoral contact forces.

Results: A postoperative reduction in ACH correlated with increased flexion at one year (medial ACH, $R = 0.58$; lateral ACH, $R = 0.48$). On multivariable linear regression, reductions in medial ACH ($\beta = 1.7$, $P < 0.001$) and pre-operative flexion ($\beta = -0.3$, $P < 0.001$) were associated with increased flexion. A decrease in ACH was associated with improvements in advanced activities (medial, $R^2 = 0.06$; lateral, $R^2 = 0.08$) in 2011KSS. On computer simulation, all three cases with reduced and increased medial ACHs showed decreased and increased patellofemoral contact forces, respectively.

Conclusions: A change in ACH was an independent predictor of knee flexion after TKA. Greater reduction in ACH was associated with improved flexion after TKA, whereas an increase in postoperative ACH may be a risk factor for flexion loss.

1. Introduction

Total knee arthroplasty (TKA) is the most successful treatment for decreasing pain and restoring quality of life in patients with severe knee osteoarthritis (OA) [1,2]. During TKA, much attention is paid to alignment and soft-tissue balancing of the tibiofemoral joint; however, the patellofemoral (PF) joint is also important for improvements in pain and function. Distal femoral anterior condyle anatomy varies in patients undergoing TKA. Some patients form very large osteophytes as a result of their OA,

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whereas others show almost no OA-related changes in the PF joint [3]. A size mismatch between the knee prosthesis and femur may affect the postoperative range of motion (ROM), but this relationship has not been fully clarified.

The ROM is one of the most important factors for a well-functioning TKA and postoperative patient satisfaction [4]. The effects of anatomical parameters, such as posterior condylar offset (PCO) or tibial slope, on postoperative ROM have been widely studied [5–11]. The effect of patellar thickness on ROM has also been discussed, but the relationship between anterior condyle anatomy and ROM before and after TKA has rarely been highlighted [12–14]. Since the current implant designs do not have much size variability in the anterior flange, mismatch in sizing can occur at the distal femoral anterior condyle during TKA. For example, if a thin anterior condyle is replaced with a thicker prosthetic anterior flange, overstuffing of the patellofemoral joint can occur. This overstuffing might increase the patellofemoral contact force, possibly decreasing ROM [15].

This study measured the change in distal femoral anterior condyle height (ACH) using pre-operative and postoperative computed tomography (CT) and other anatomic parameters likely to affect knee flexion [16]. It was hypothesised that the change in ACH is a determinant of knee flexion after TKA. The aims of this study were to: (1) determine the effect of the ACH change after TKA on knee flexion; (2) ascertain the effect of the ACH change on clinical outcomes after TKA; and (3) evaluate the change of PF contact force using computer simulation as a rationale for the change in knee flexion.

2. Materials and methods

2.1. Participation

This study was approved by the institutional Ethics Committee. All participants gave written informed consent. It retrospectively enrolled 106 knees from 88 patients who underwent TKA using the Bi-Surface knee prosthesis (Kyocera, Kyoto, Japan) between April 2012 and March 2016, and whose pre-operative and postoperative lower extremity CT scans were available. At one-year evaluation after TKA, the following were excluded: three knees that were lost to follow-up, one knee due to lack of data for the one-year ROM, and one knee due to death unrelated to TKA. Finally, data for 101 knees from 84 patients were available (Table 1). A physiotherapist who was not involved in this study measured knee flexion, using a handheld goniometer, before TKA and at the one-year follow-up. Anteroposterior and lateral X-rays of the knee, and full-length anteroposterior X-rays of the lower legs were taken pre-operatively and postoperatively. Kellgren–Lawrence (KL) grades of the tibiofemoral and PF joints were scored separately from the pre-operative plain X-ray [17]. The hip-knee-ankle angle (HKA) was also measured on the full-length X-rays of the lower extremity.

2.2. Computed tomography

Computed tomography scans of the affected lower extremity were taken pre-operatively and postoperatively. Three-dimensional reconstruction was performed, and the ACH and sulcus height were measured as previously described with some modification [18]. The anterior cortex of the femur was identified on the midline sagittal image of the distal femur. The plane that included the anterior cortex and was parallel to the surgical epicondylar axis was defined as Plane A. The length (in mm) of a perpendicular line from the most prominent point of the medial anterior condyle, trochlea sulcus, or lateral anterior condyle to Plane A was defined as the pre-operative medial ACH, sulcus height, or lateral ACH, respectively (Figure 1A). After TKA, the most prominent points of the medial flange, sulcus, and lateral flange of the implant to Plane A were measured, and defined as postoperative medial ACH, sulcus height, or lateral ACH, respectively (Figure 1B). Several other parameters possibly related to the ROM – that is, posterior tibial posterior slope [10], PCO [6], and Insall–Salvati ratio [19] – were measured as previously described. For those parameters that are directly affected by osteotomy or implant placement, such as tibial slope and PCO, the measurement was also performed on the postoperative CT scan. For the postoperative PCO, the most prominent point was in the ball-socket joint. The above-mentioned radiographic measurements were performed by KN and RH, who were blinded to the clinical outcomes.

The inter-observer correlations were determined to be 0.70 for the medial ACH, 0.64 for the sulcus height and 0.73 for the lateral ACH. The intra-observer correlations were determined using repeated measurement of the same patients after a one-week interval, and were determined to be 0.89 for the medial ACH, 0.80 for the sulcus height, and 0.86 for the lateral ACH.

Table 1
Demographic data of the 101 osteoarthritic knees.

Age	75.0 ± 6.9 years
Sex	Female: 87, Male: 14
BMI	27.5 ± 4.5
KL grade (TF)	Grade 4, 58; Grade 3, 22; Grade 2, 21; Grade 1, 0; Grade 0, 0
KL grade (PF)	Grade 4, 15; Grade 3, 24; Grade 2, 36; Grade 1, 22; Grade 0, 4

BMI, body mass index; KL, Kellgren-Lawrence; TF, tibiofemoral; PF, patellofemoral.
Age and BMI are presented as mean ± standard deviation.

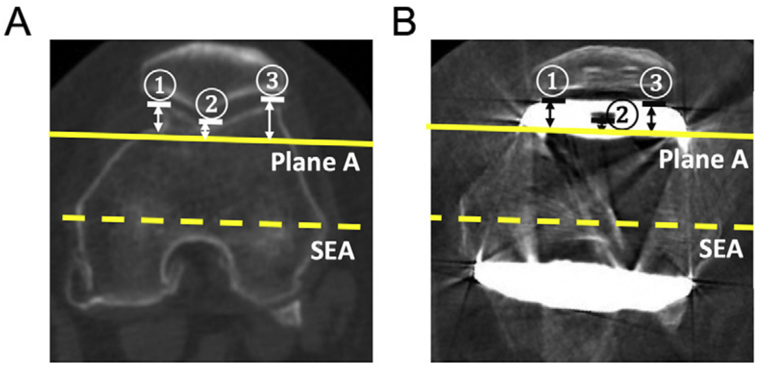

Figure 1. In the pre-operative and postoperative computed tomography scan, the plane containing the anterior cortex of the femur that is parallel to the surgical epicondylar axis (SEA, yellow dashed line in A, B) was defined as Plane A, and then this Plane A was drawn on the axial image (SEA, yellow solid line in A, B). The anterior condylar height (ACH) of the medial condyles (1), trochlea sulcus (2), and lateral condyles (3) of native bone (A) or medial flange (1), sulcus (2), and lateral flange (3) of the implant (B) to Plane A was evaluated from proximal to distal, and then the maximum height in each category in each time point was defined as the medial ACH, sulcus height, and lateral ACH, respectively.

2.3. Surgery

Total knee arthroplasty was performed using the Bi-Surface Knee System and the standard measured resection technique with a medial parapatellar approach. The Bi-Surface Knee System is a unique prosthesis with promising long-term durability that has a ball-socket joint as a third condyle, which allows for contact between the femoral component and the polyethylene dish, even in deep flexion [20,21]. A sulcus cut, which was perpendicular to the distal femoral axis, was performed for the distal femoral resection. An anterior reference was used for cutting and sizing the distal femur, and the anterior condyle was cut flush so as not to remain notched. Rotation of the femoral component was set parallel to the surgical epicondylar axis. Patella replacement was routinely performed. To determine the thickness of the patella, thickness was directly measured perioperatively using a calliper before and after patellar resection. For postoperative patellar thickness, the residual bone thickness and known thickness of the polyethylene component were summed. The tibial, femoral, and polyethylene patella components were cemented, and a cruciate-substituting dish was inserted.

Postoperative rehabilitation was commenced by a physical therapist one day after surgery. After discharge, patients were routinely followed at outpatient clinics and their ROM was checked by a physical therapist at one year after surgery.

2.4. Clinical scores

For pre-operative and postoperative clinical outcomes, the New Knee Society Score (2011KSS) was used [22]. The Japanese version of the 2011KSS is a patient-reported outcome measure, which has already been validated [23]. Briefly: 2011KSS comprises symptoms (0–25 points), patient satisfaction (0–40 points), expectations (0–15 points), and functional activities (0–100 points). Functional activities comprise: walking and standing (0–30 points), standard activities (0–30 points), advanced activities (0–25 points), and discretionary activities (0–15 points); a higher score indicates higher outcomes. Pre-operative and postoperative 2011KSS were available in 99 cases and 89 cases, respectively. Thereafter, the one-year change of the 2011KSS was calculated in 87 cases.

2.5. Computer simulation

A computer simulation (LifeMOD/KneeSIM 2010; LifeModeler Inc., San Clemente, CA, USA) to evaluate the change in the PF contact force was performed using the cases with the three highest and three lowest pre-operative medial ACHs as representative cases. The simulation model comprised a dynamic musculoskeletal program modelling the knee, which has been validated to ensure the appropriate estimates of the kinematics, contact status, and contact force [24,25]. The three-dimensional bone model was constructed from pre-operative whole-leg CT images, and each TKA was mimicked by computer simulation using MIMICS (Materialise HQ, Leuven, Belgium) and KneeSIM with postoperative X-ray and CT images, as previously described [25]. Computer simulation with or without TKA was used to simulate two cycles of active squatting in a weight-bearing deep knee bend according to an Oxford-type knee rig, which was validated in a cadaveric study [26], and maximum PF contact force was recorded within the ROM of each patient at each time point.

2.6. Statistical analysis

To compare pre-operative and postoperative parameters, a paired *t*-test or Wilcoxon signed-rank test was used. For the correlation between knee flexion and ACHs, Pearson correlation coefficient was determined. To compare knee flexion among groups

Table 2
Pre-operative and postoperative radiographic parameters and knee range of motion.

	Pre-operation	One-year postoperation
Radiographic parameters		
HKA (°)	Varus 10.2 ± 6.0	Valgus 0.5 ± 3.6*
Medial ACH (mm)	8.3 ± 3.9	8.4 ± 1.5
Sulcus height (mm)	4.5 ± 2.3	5.7 ± 1.5*
Lateral ACH (mm)	10.6 ± 2.6	9.6 ± 1.6*
Knee range of motion		
Knee extension (°)	−9.3 ± 7.6	−2.7 ± 4.3*
Knee flexion (°)	114.8 ± 17.3	115.6 ± 16.1

HKA, hip-knee-ankle angle; ACH, anterior condylar height.
Data are presented as mean ± standard deviation.
* $P < 0.001$ by paired *t*-test compared with pre-operatively.

according to the change in ACH (ACH increase >5 mm, ACH change ≤5 mm, ACH decrease >5 mm), one-way ANOVA with Tukey's post-hoc test was used. Multivariable linear regression analysis was performed with improvements in flexion as the dependent variables; explanatory variables were: age, sex, body mass index, pre-operative Kellgren–Lawrence grade, pre-operative knee flexion, change in HKA, Insall–Salvati ratio, decrease in medial ACH, increase in PCO, decrease in medial tibial slope, and decrease in patella thickness. A backward-stepwise approach to minimise the Akaike information criterion for optimal model fit was used. For the association between ACH and clinical outcomes, a simple linear regression analysis was used. For the correlation between PF contact force and postoperative knee flexion, Pearson correlation was determined. Statistical analyses were performed using R 3.3.1 (R foundation, Vienna, Austria) with the EZR (Saitama Medical Center, Jichi Medical University, Saitama, Japan) plug-in. Statistical significance was set at $P < 0.05$.

3. Results

After TKA, the mean value of the medial ACH did not significantly change, but the sulcus height slightly increased and the lateral ACH slightly decreased (Table 2). There was no significant change in average knee flexion (Table 2).

The decrease in the medial ACH, sulcus height, and lateral ACH showed a moderate correlation with the increase in flexion (medial ACH, $R = 0.58$; sulcus height, $R = 0.51$; lateral ACH, $R = 0.48$) (Figure 2A–C). Among the 13 cases whose postoperative medial ACH decreased >5 mm after TKA, 12 cases showed improved one-year postoperative flexion (14.6 ± 10.1°), and among 10 cases whose postoperative medial ACH increased >5 mm, nine cases showed worsened one-year postoperative flexion (−21.5 ± 20.8°) (Figure 3). To identify whether perioperative changes in anatomical parameters and pre-operative characteristics independently affected the change in knee flexion, a multivariate linear regression analysis with minimum Akaike information criterion was performed. In this analysis, the best-fit model had an adjusted $R^2 = 0.45$, in which the decrease in medial ACH ($\beta = 1.7$, $P < 0.001$) and pre-operative flexion ($\beta = -0.3$, $P < 0.001$) remained as significant independent variables (Table 3).

The 2011KSS had improvements in all sub-scores except expectations (Table 4). A greater reduction in the ACHs was partly related to an improvement in clinical outcome. In the subcategories, decreases in the medial ACH ($R^2 = 0.06$), sulcus height ($R^2 = 0.05$), and lateral ACHs ($R^2 = 0.08$) were positively associated with the improvement of advanced activities in the 2011KSS (Table 5). The ACHs or sulcus height did not show a negative association with any sub-scores in the 2011KSS.

In computer simulation (Figure 4), all three representative cases with reduced medial ACH (−11.6, −9.0, and −8.2 mm) showed decreased PF contact forces (−42, −642, −101 N, respectively), and the knee flexion of these patients increased after

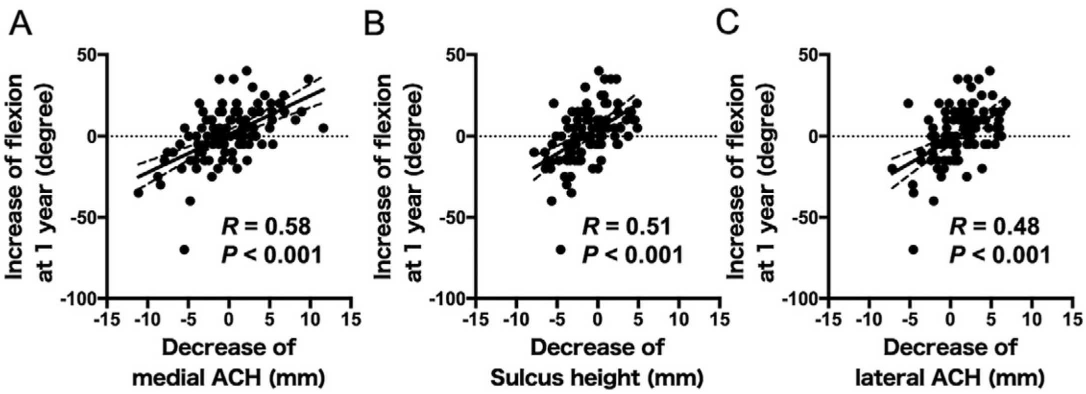

Figure 2. Scatter plots between the decrease in medial anterior condylar height (ACH) (A), sulcus height (B), or lateral ACH (C) and the increase of flexion at 1-year after surgery. The decrease in each ACH showed a moderate correlation with the increase of flexion at 1-year post surgery.

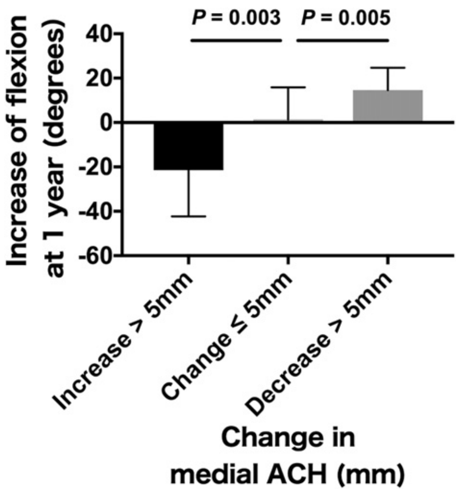

Figure 3. Cases were divided into three groups according to the change in medial anterior condylar height (ACH): ACH increase >5 mm (n = 10), ACH change ≤5 mm (n = 78), or ACH decrease <5 mm (n = 13), and the change of flexion at 1 year in each group is shown.

one year (+5°, +25°, and + 10°, respectively). All three representative cases with increased medial ACH (+11.1, +8.8, and +8.4 mm) showed increased PF contact forces (+497, +288, and + 326 N, respectively), and the knee flexion of these patients decreased after one year (−35°, −25°, and −30°, respectively). The change in PF contact force negatively correlated with one-year postoperative knee flexion ($R = -0.96$, $P = 0.002$) (Figure 4C).

4. Discussion

This study demonstrated the change in ACH related to knee flexion in patients with knee OA who underwent TKA. Anterior condylar height reduction by TKA contributed to an improvement in knee flexion, and an ACH increase contributed to loss of flexion. The change in ACH or sulcus height did not negatively affect clinical outcomes, and even the reductions of ACHs were associated with improvements in advanced activities in the 2011KSS. To show the mechanism, changes in PF contact forces before and after TKA were analysed using computer simulation, in which reductions in ACHs yielded decreases in PF contact forces, and increases in ACHs yielded increments in PF contact forces.

This is the first study to determine the effect of ACH changes after TKA on knee flexion. Resection of the large anterior protuberance during TKA gave good results in terms of flexion. Most patients whose ACH increased by >5 mm lost their flexion, presumably due to overstuffing of the PF joint after TKA. Previous reports have suggested that overstuffing is a risk factor for restricted flexion after TKA [27,28]. Overstuffing increases PF compression and shear forces, which may contribute to component wear and anterior knee pain [15,27,28]. This problem is often discussed as patella resurfacing [15,29–31]. While the shape of the distal femur was also shown to be an important contributor in the current study, the effect size of the change in ACH was not so great: a one-millimetre change in the medial ACH resulted in a 1.7° change in flexion. However, a previous report describes a knee flexion decrease of one degree for every one-millimetre increment of patella thickness [13], and another cadaveric study reported a flexion loss of 1.28° per one-millimetre increment of patella thickness [32]. The effect size of the change in ACH was comparable with that of patellar thickness. In a recent report, the change in anterior patellar offset (height from sulcus to anterior surface of the patella) did not correlate with the ROM or outcome scores; however, it did not report the relation to ACH, although the change of ACH was variable after TKA [33]. Of note, the current study successfully demonstrated the change in ACH related to knee flexion after TKA.

It is unknown how ACH affects the clinical symptoms and functions after TKA. Because there is a fulcrum effect in the quadriceps mechanism, a decrease in ACH or sulcus height possibly exhibited risk of the poorer clinical outcomes due to a decrease in the lever arm [34]. For this reason, pre-operative and one-year postoperative clinical scores were reviewed. The positive correlations were only found in parts of the scores; however, the decreases in ACHs were never associated with poor clinical outcomes.

Table 3
Multiple regression analysis of 1-year increase in flexion with stepwise reduction by AIC.

	Coefficient	95% CI	*T* value	*P*	Adjusted R^2
(Intercept)	22.1	−7.8 to 52.1	1.5	0.15	0.45
BMI	0.6	−0.1 to 1.2	1.8	0.07	($P < 0.001$)
Decrease in medial ACH	1.7	1.0 to 2.3	5.0	<0.001	
Decrease in patella thickness	−1.1	−2.5 to 0.3	−1.5	0.14	
Pre-operative flexion	−0.3	−0.5 to −0.1	−3.6	<0.001	

AIC, Akaike information criterion; BMI, body mass index; ACH, anterior condylar height.

Table 4
Pre-operative and postoperative patient-reported outcome measures (2011KSS).[a]

Sub-score	Pre-operation	One-year postoperation
Symptoms	8.0 ± 5.4	19.0 ± 5.0*
Satisfaction	13.6 ± 5.7	25.3 ± 8.4*
Expectations	13.2 ± 2.1	9.5 ± 3.0*
Walking and standing	11.5 ± 8.4	18.4 ± 8.6*
Standard activities	14.6 ± 5.5	21.3 ± 5.7*
Advanced activities	5.9 ± 4.9	10.3 ± 5.9*
Discretionary activities	6.4 ± 4.0	9.5 ± 4.3*
Functional activities total score	38.3 ± 18.3	59.5 ± 18.5*

Data are presented as mean ± standard deviation.
[a] Data of 87 cases with pre-operative and postoperative 2011KSS.
* $P < 0.001$ by Wilcoxon signed-rank test.

Therefore, the decrease in ACH was clinically insignificant for the fulcrum effect of the quadriceps mechanism. Interestingly, an association with ACH and sulcus height was found in advanced activities in the 2011KSS. This subcategory comprises questions involving squatting and kneeling, which require deep knee flexion, and reduced PF pressure by the reduction in ACH and sulcus height would contribute to a better score.

To evaluate the influence of an ACH and sulcus change on PF contact force, a computer simulation was used. Until now, biomechanical studies have evaluated changes in patella thickness, reporting an advantageous effect of a thin patella on flexion [13,15,32]. However, no studies have investigated the effect of ACH on patellofemoral contact force. More importantly, the current study simulated the contact force of the actual patient and compared the biomechanical evaluations and clinical results. It found a decrease in the contact force according to decrease in ACH. Moreover, the change in PF contact force negatively correlated with the change in knee flexion. These findings suggest that the ACH changes that occur during TKA meaningfully change the biomechanical conditions.

The operative procedure for TKA affects postoperative ACH. Too little resection of the anterior trochlea causes excessive ACH. However, excessive resection causes anterior femoral notching, which should be avoided because of the risk of a periprosthetic fracture [35,36]. The positions of the femoral component, such as flexion or posterior replacement, affect ACH as well as PCO, which may be related to knee flexion [5,8], although its contribution on knee flexion is still controversial [7,37]. When the implant is placed posteriorly, the changes in PCO can be finely managed by size selection because, in many of the currently-available knee prostheses, there is a two-millimetre difference (anteroposterior dimension) between two successive sizes.

The design of the implant also affects the postoperative ACH. There are slight differences in the height of the anterior flange among commercially available implants, which differ according to implant size: the thickest part of the anterior flange is 8.0–8.5 mm in Bi-Surface, 6.2–6.6 mm in Genesis II (Smith and Nephew, London, UK), 5.5–6.3 mm in Journey II (Smith and Nephew), 5.1–6.4 mm in NexGen LPS-Flex (Zimmer-Biomet, Warsaw, IN, USA), and 6.3–7.1 mm in Persona (Zimmer-Biomet). On the other hand, the flange is thinner in gender-specific implants such as NexGen LPS-Flex Gender (5.0–5.3 mm) (Zimmer-Biomet) and Persona Narrow (4.7–6.0 mm) (Zimmer-Biomet). An implant with a low anterior flange would be advantageous for patients with low pre-operative ACH.

Table 5
Association of the decrease in each anterior condylar height against the improvement of 2011KSS.

	Medial ACH	Sulcus height	Lateral ACH
	β (95% CI) R^2	β (95% CI) R^2	β (95% CI) R^2
Symptoms	0.23 (−0.14 to 0.59) 0.02	0.34 (−0.22 to 0.89) 0.02	0.16 (−0.39 to 0.72) 0.00
Satisfaction	0.17 (−0.29 to 0.63) 0.01	0.28 (−0.40 to 0.97) 0.01	0.22 (−0.47 to 0.90) 0.00
Expectations	0.06 (−0.11 to 0.23) 0.01	−0.03 (−0.29 to 0.23) 0.00	0.09 (−0.17 to 0.35) 0.01
Walking and standing	0.14 (−0.27 to 0.55) 0.01	0.40 (−0.21 to 1.01) 0.02	0.13 (−0.48 to 0.74) 0.00
Standard activities	0.14 (−0.19 to 0.48) 0.01	0.07 (−0.44 to 0.58) 0.00	0.06 (−0.45 to 0.56) 0.00
Advanced activities	0.33 (0.04 to 0.61) 0.06*	0.44 (0.01 to 0.87) 0.05*	0.59 (0.17 to 1.01) 0.08**
Discretionary activities	−0.04 (−0.27 to 0.20) 0.00	−0.09 (−0.45 to 0.26) 0.00	−0.05 (−0.40 to 0.30) 0.00
Functional activities total score	0.57 (−0.37 to 1.51) 0.02	0.82 (−0.59 to 2.24) 0.02	0.73 (−0.68 to 2.14) 0.01

2011KSS, New Knee Society Score; ACH, anterior condylar height.
* $P < 0.05$.
** $P < 0.01$.

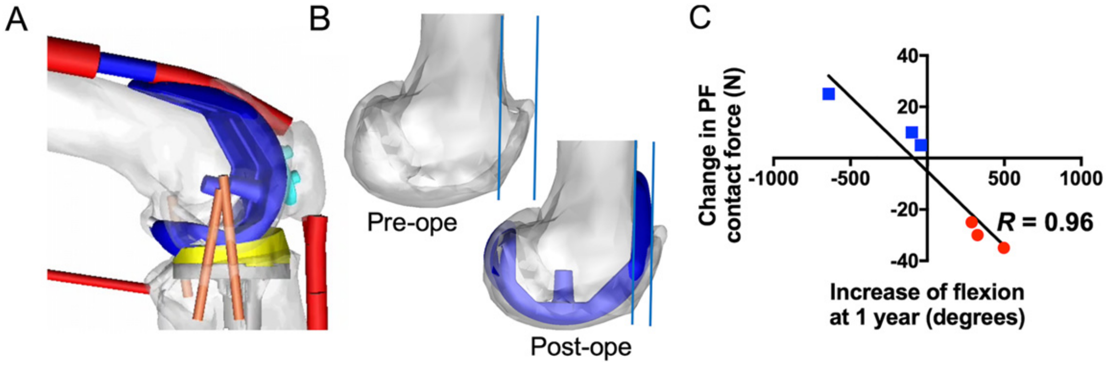

Figure 4. The computer-rendered image around the knee is shown in A. The pre-operative (pre-ope) and postoperative (postope) image of the representative case (medial ACH decreased by 11.6 mm) is shown in B. The interval of the blue line, which shows the anterior condylar height (ACH) in each image, decreased after TKA. The Pearson correlation between an increase of flexion at 1 year and the patellofemoral contact force was plotted in C, in which a negative correlation was observed. Three cases whose ACH decreased after TKA are indicated with the blue rectangles, and three cases whose ACH increased after TKA are indicated with the red circles.

This study had some limitations. First, data on the clinical outcomes were missing for some of the patients. Thus, there might have been a selection bias due to data deficit. Second, the follow-up period was short at one year. The potential of long-term negative effects due to decreases in ACHs, such as instability of the PF joint or notching-related fracture during long follow-up, was not evaluated. Third, all surgery was performed using a cruciate-substituting implant, and there was no indication whether the relationship between ACH and flexion would hold for cruciate-retaining or posterior-stabilised implants. Fourth, because of the implant artefact seen on the CT scan, the postoperative ACH may have been overestimated. The mean postoperative ACHs were about one millimetre larger than the thickness of the anterior flange of the implant. Fifth, in terms of the postoperative PCO, the most prominent point was in the ball-socket joint of the femoral component, which differed from that of other implants.

5. Conclusions

In conclusion, this study identified the importance of anterior condyle anatomy of the femur in patients with OA. A decrease in ACH after TKA was a predictor of improvement in postoperative flexion without exacerbating clinical outcomes. Although a greater reduction in ACH improved postoperative flexion, patients who have a low ACH are at risk of a loss of flexion because of an increase in postoperative ACH. During TKA, adequate resection of the anterior condyle should be performed for those who have an extremely low ACH before surgery. For these patients, a femoral component with a low-profile anterior flange would be beneficial, and a personalised implant to maintain or decrease the anterior trochlea may be ideal.

Declaration of competing interest

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Findings

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