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(Citation)
Journal of Joint Surgery and Research,1(1):186-191

(Issue Date)
2023-12

(Resource Type)
journal article

(Version)
Version of Record

Journal of Joint Surgery and Research 1 (2023) 186–191

Contents lists available at ScienceDirect

Journal of Joint Surgery and Research

journal homepage: www.journals.elsevier.com/journal-of-joint-surgery-and-research

Original Article

The influence of patellar height on patellofemoral contact force during total knee arthroplasty

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ARTICLE INFO

Keywords:
Patellar height
Total knee arthroplasty
Patellofemoral contact force
Patella alta
Patellofemoral joint

ABSTRACT

Purpose: Residual anterior knee pain following total knee arthroplasty was reported to be related to high patellofemoral contact force. This study tried to show the relationship between patellar height and patellofemoral contact force *in vivo*, which has been demonstrated only *in vitro* thus far.

Methods: Fifty-five patients who had undergone a primary mobile-bearing posterior-stabilized total knee arthroplasty (28 cases using PFC Sigma and 27 cases using Attune) were included. After all the trial prostheses were placed, the patellar contact forces on the medial and lateral sides were measured using specially designed two uniaxial ultrathin force transducers at 0°–135° of knee flexion guided by the navigation system. Correlations between the pre-operative Insall-Salvati index and the medial or lateral patellar contact force in each flexion angle were analyzed using linear regression. Correlations between each patellar contact force and postoperative flexion angle were also assessed.

Result: There was a positive correlation between Insall-Salvati index and the lateral patellar contact force at 135° of flexion in all the patients, at 120° and 135° of flexion in patients with PFC Sigma and 135° of flexion in patients with Attune. The lateral patellar contact force at 120° and 135° of flexion in patients with PFC Sigma inversely correlated with postoperative flexion angle.

Conclusions: Patients with patella alta tended to demonstrate high lateral patellar contact force in deep knee flexion after total knee arthroplasty, which can affect the post operative flexion angle and should be treated to prevent residual anterior knee pain.

1. Introduction

Total knee arthroplasty (TKA) has been proven to be a successful surgical treatment for knee osteoarthritis [1,2], and high rates of satisfaction varying between 85.2% and 92.0% after TKA have been reported [3–6]. However, approximately 5%–10% of patients experience residual pain, especially anterior knee pain (AKP) [7,8]. AKP has been reported to be strongly associated with patients' dissatisfaction and impaired quality of life [5,8,9]. Even though significant knowledge exists about AKP after TKA, its etiology and pathogenesis are still not fully understood.

Patellofemoral kinematics are important issues after TKA and excessive patellofemoral contact force was discussed to be one of the main factors for AKP after TKA [7,8,10]. Patella alta, which is characterized by a superior patellar position relative to the trochlear groove of the femur, has increasingly been considered to be a predisposing factor for the development of AKP thus far [8]. It has been suggested that persons with patella alta have altered knee extensor mechanics which leads to elevated patellofemoral contact force [11,12]. Patella alta was demonstrated to be associated with the high maximal patellofemoral contact force by using sagittal and axial magnetic resonance images of the knee and instrumented gait data [13] and by using a dynamic knee simulator system [14]. One of the reasons of this has been described to be the delayed or non-contact between the quadriceps tendon and the front part of the femur, which normally occurs in mid to deep flexion of the knee. This contact caused a reduction in contact force on the patellofemoral joint thanks to the load sharing by the quadriceps tendon [14]. These *in vitro*

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https://doi.org/10.1016/j.jjoisr.2023.08.001
Received 19 April 2023; Received in revised form 17 July 2023; Accepted 3 August 2023
Available online 18 August 2023

studies partially provided a consensus on the precise effect of patella height on patellofemoral contact force, however, no *in vivo* study has been conducted to clarify this so far. Also, we suppose it may not be appropriate to apply those past study's data of normal knees to the knees after TKA.

Therefore, in this study, we tried to test the hypothesis that the patellar height shows a positive correlation with the patellar contact force in knees after TKA. In order to quantify the patellar contact force intraoperatively, the special force transducers which were placed side by side between a trial component of the patella and a metal plate fixed to the patellar osteotomy surface was used. The relationship between postoperative knee flexion angle and patellar contact force was also assessed because high patellar contact force at deep flexion was reported to reduce postoperative flexion angle in patient undergoing TKA [15]. Furthermore, as the previous study showed that the patellar contact force was shown to vary depending on the prosthesis used [16], patients were divided based on the types of prosthesis and the same analysis was conducted in each group.

2. Materials and methods

This study was approved by the institutional review board of the authors' institutions. Patients who agreed to participate were included in this study and informed consent was obtained from all the patients. The inclusion criteria were substantial pain and loss of function due to end-stage (Kellgren-Lawrence grade: 4) varus-type osteoarthritis of the knee. To make a fair assessment and minimize the influence of clinical variables, valgus deformity of the knee, severe bony defects requiring bone graft or augmentation, revision TKA, and active knee joint infection were excluded.

Twenty-eight consecutive mobile-bearing posterior-stabilized (PS) TKA cases (28 patients; 25 women, three men) with a mean age of 79.1 years (range, 66–88 years) using the Press-Fit Condylar Sigma (PFC Sigma) (DePuy Synthes, Warsaw, IN) between April 2013 and December 2013 and 27 consecutive mobile-bearing PS TKA cases (27 patients; 24 women, three men) with a mean age of 77.1 years (range, 65–85 years) using the Attune Primary Total Knee System (Attune) (DePuy Synthes, Warsaw, IN) between May 2016 and February 2017 met the above criteria. In total, 55 TKA cases (55 patients; 49 women, six men) were included in this study. All TKAs were performed using the computed tomography (CT)-based free-hand navigation system (Vector Vision, DePuy-BrainLAB, Heimstetten, Germany) by T.M. with an experience of >20 years with TKA. Pre-operative Insall-Salvati index [17,18] was measured using lateral radiographs of the knee with 90° of flexion. In this study, we wanted to clarify if preoperative Insall-Salvati index was a predisposing factor affecting intraoperative patellofemoral contact force, so we decided to measure Insall-Salvati index preoperatively.

2.1. Operative procedure and intraoperative measurement

All surgeries were performed using the measured resection technique. A distal femoral osteotomy was performed perpendicular to the femoral mechanical axis according to the planned resection height and angle on the navigation system. A proximal tibial osteotomy was performed ensuring that each cut was made perpendicular to the mechanical axis in the coronal plane, with 3° of posterior inclination along the sagittal plane and 10 mm below the highest point of the lateral tibial plateau. The extension gap was checked using a standard rectangular block after removal of osteophytes and appropriate release of medial soft tissue were performed, and residual lateral laxity was permitted [19]. The femoral rotation angle was targeted to the surgical *trans*-epicondylar axis. At the time of patellar resurfacing, the bone resection thickness of the patella was adjusted to that of the patellar component. To obtain better tracking, the patellar component was placed medially and the remaining lateral edge was trimmed and resected. After all the trial prostheses were placed, the patellar contact force was measured medially and laterally using two uniaxial ultrathin (100 μm) force transducers (minimum measurable contact force: 0.045 kgf) (FlexiForce; Nitta Corporation, Osaka, Japan) (Fig. 1). Two FlexiForce devices were placed side by side between a trial component of the patella and a metal plate fixed to the patellar osteotomy surface, as the past study previously reported [15]. One was installed on the medial half and the other on the lateral half of the trial component. In assessing the patellar contact force, the medial parapatellar arthrotomy was repaired by suturing with more than five stitches. The real-time assessment of the patellar contact force was performed at 0°, 10°, 30°, 60°, 90°, 120°, and 135° of knee flexion, guided by the navigation system. No lateral retinacular release was needed in all the cases based on the assessment of patellar tracking.

Fig. 1. Measurement system of patellar contact force. The patellar contact force was measured medially and laterally using two uniaxial ultrathin force transducers, which were placed side by side between a trial component of the patella and a metal plate fixed to the patellar osteotomy surface.

2.2. Statistical analyses

All measurements were expressed as the mean ± standard error of the mean. To determine the intra-observer and inter-observer reliability of the measurements of the patellar contact force as well as Insall-Salvati index, two investigators assessed the first 10 patients twice and calculated intra-class correlation coefficients (ICCs). The ICCs for intra-observer reliability were >0.82 (range, 0.82–1.00) and those for inter-observer reliability were >0.84 (range, 0.84–0.96) for all measurements. Correlations between Insall-Salvati index and the patellar contact force at each flexion angle in all the patients were analyzed using linear regression. Correlations between each patellar contact force and knee flexion angle at one year postoperatively were assessed as well. As the past study previously showed that the patellar contact force was significantly lower in patients using the Attune than in patients using the PFC Sigma [16], patients were divided into two groups based on the types of prosthesis and the same analysis was conducted in each group. Data analyses were performed using BellCurve for Excel (Social Survey Research Information Co., Ltd., Tokyo, Japan). The sample size calculation was also performed using G*Power 3 (Heinrich Heine Universität Düsseldorf, Germany). Based on our calculations, a minimum sample size of 26 patients was required to observe a correlation between the preoperative Insall-Salvati index and the patellar contact force at each flexion angle with a type I error (α) of 0.05, a power (1 − β) of 0.80, and a correlation ρ H1 of 0.5. Correlations of $P < 0.05$ were considered statistically significant.

3. Results

Pre- and postoperative range of motion of the knee, hip-knee-ankle (HKA) angle and Insall-Salvati index are shown in Table 1. Medial and lateral patellar contact forces at each flexion angle are shown in Table 2. The relationships between Insall-Salvati index and the patellar contact force at each flexion angle are shown in Table 3 and Fig. 2. There was a positive correlation between Insall-Salvati index and the lateral patellar contact force at 135° of flexion in all the patients (Fig. 2a), at 120° and 135° of flexion in patients with PFC Sigma (Fig. 2b and c) and at 135° of flexion in patients with Attune (Fig. 2d). At the other flexion angles, the lateral patellar contact force showed no significant relationship with Insall-Salvati index. In any flexion angle, the medial patellar contact force showed no significant relationship with Insall-Salvati index in all the patients as well as in each prosthesis group.

The lateral patellar contact force at 120° and 135° of flexion in patients with PFC Sigma inversely correlated with postoperative flexion angle (120°: R = −0.43, P = 0.021; 135°: R = −0.46, P = 0.013) (Fig. 3a and b), while no correlation was found in patients with Attune as well as in all the patients. There was no significant correlation between the medial patellar contact force and the postoperative flexion angle.

Table 2
Medial and lateral patellar contact force.

	All (n = 55)	PFC sigma (n = 28)	Attune (n = 27)
Medial patellar contact force (kgf), mean (SEM)			
Knee flexion angle			
0°	0.0 (0.0) (range, 0.0–0.0)	0.0 (0.0) (range, 0.0–0.0)	0.0 (0.0) (range, 0.0–0.0)
10°	0.0 (0.0) (range, 0.0–1.5)	0.1 (0.1) (range, 0.0–1.5)	0.0 (0.0) (range, 0.0–0.0)
30°	0.0 (0.0) (range, 0.0–1.5)	0.1 (0.1) (range, 0.0–1.5)	0.0 (0.0) (range, 0.0–0.0)
60°	0.2 (0.1) (range, 0.0–2.3)	0.3 (0.1) (range, 0.0–2.3)	0.2 (0.0) (range, 0.0–0.7)
90°	0.5 (0.1) (range, 0.0–2.2)	0.5 (0.1) (range, 0.0–2.2)	0.4 (0.1) (range, 0.0–1.5)
120°	1.0 (0.2) (range, 0.0–6.2)	1.5 (0.3) (range, 0.0–6.2)	0.6 (0.1) (range, 0.0–1.9)
135°	1.9 (0.3) (range, 0.0–9.6)	2.3 (0.5) (range, 0.0–9.6)	1.4 (0.2) (range, 0.0–5.6)
Lateral patellar contact force (kgf), mean (SEM)			
Knee flexion angle			
0°	0.0 (0.0) (range, 0.0–0.4)	0.0 (0.0) (range, 0.0–0.4)	0.0 (0.0) (range, 0.0–0.0)
10°	0.0 (0.0) (range, 0.0–0.9)	0.0 (0.0) (range, 0.0–0.9)	0.0 (0.0) (range, 0.0–0.2)
30°	0.1 (0.0) (range, 0.0–1.0)	0.1 (0.0) (range, 0.0–1.0)	0.1 (0.0) (range, 0.0–0.6)
60°	0.9 (0.2) (range, 0.0–6.0)	1.1 (0.3) (range, 0.0–6.0)	0.6 (0.1) (range, 0.0–3.0)
90°	2.8 (0.4) (range, 0.0–13.7)	3.2 (0.6) (range, 0.0–13.7)	2.3 (0.6) (range, 0.1–6.0)
120°	5.0 (0.7) (range, 0.0–19.2)	7.2 (1.2) (range, 0.0–19.2)	3.3 (0.7) (range, 0.2–4.0)
135°	7.1 (0.7) (range, 0.0–19.2)	9.4 (1.3) (range, 0.0–19.2)	5.8 (1.0) (range, 0.2–8.0)

SEM: standard error of the mean.

4. Discussion

In this study, patients undergoing TKA using PFC Sigma and Attune were assessed and correlations between Insall-Salvati index and the patellar contact force at each flexion angle of between 0° and 135° in all the patients as well as in patients with each type of the prosthesis were analyzed using linear regression. Also, correlations between each patellar contact force and postoperative flexion angle were assessed.

The most important finding of the present study was that there was a positive correlation between Insall-Salvati index and the lateral patellar contact force at deep flexion of the knee regardless of the types of the

Table 1
Pre- and postoperative range of motion of the knee, hip-knee-ankle angle (HKA) and Insall-Salvati index.

	All (n = 55)	PFC Sigma (n = 28)	Attune (n = 27)
Extension (°), mean (SEM)			
Preoperative	−6.1 (0.8) (range, 0 to −20)	−6.3 (1.1) (range, 0 to −20)	−5.9 (1.3) (range, 0 to −20)
Postoperative	−0.9 (0.3) (range, 0 to −5)	−0.9 (0.4) (range, 0 to −5)	−0.9 (0.4) (range, 0 to −5)
Flexion (°), mean (SEM)			
Preoperative	124.6 (1.8) (range, 0 to 155)	125.7 (2.7) (range, 0 to 155)	123.5 (2.2) (range, 0 to 140)
Postoperative	122.5 (1.3) (range, 0 to 140)	123.4 (1.8) (range, 0 to 140)	121.5 (1.8) (range, 0 to 140)
HKA angle (°), mean (SEM)			
Preoperative	7.1 (0.8) (range, 0 to 27)	6.9 (1.3) (range, 0 to 27)	7.4 (1.1) (range, 0 to 18)
Postoperative	1.1 (0.3) (range, −4 to 7)	1.1 (0.4) (range, −3 to 7)	1.1 (0.4) (range, −4 to 5)
Insall-Salvati index, mean (SEM)	1.16 (0.013) (range, 1.00 to 1.41)	1.16 (0.015) (range, 1.00 to 1.34)	1.16 (0.022) (range, 1.01 to 1.41)

SEM: standard error of the mean.

Table 3
Correlation between the medial/lateral patellar contact force and Insall-Salvati index.

	All (n = 55)		PFC sigma (n = 28)		Attune (n = 27)	
Flexion angle (°)	Correlation coefficient (R)	*p* value	Correlation coefficient (R)	*p* value	Correlation coefficient (R)	*p* value
Medial						
0	0.042	0.76	0.073	0.71	1	–
10	0.042	0.76	0.073	0.71	1	–
30	0.004	0.98	0.0039	0.98	1	–
60	0.13	0.34	0.28	0.15	0.069	0.73
90	0.11	0.41	0.3	0.12	0.11	0.58
120	0.20	0.15	0.39	0.058	0.0016	0.99
135	0.28	0.056	0.41	0.058	0.24	0.22
Lateral						
0	0.07	0.61	0.12	0.53	1	–
10	0.024	0.86	0.12	0.53	0.17	0.4
30	0.043	0.75	0.089	0.65	0.23	0.25
60	0.21	0.12	0.3	0.12	0.19	0.35
90	0.12	0.38	0.32	0.1	0.022	0.91
120	0.28	0.056	0.53	0.0034[a]	0.19	0.34
135	0.42	0.0012[a]	0.55	0.0027[a]	0.72	<0.001[a]

[a] $p < 0.05$.

prosthesis used for TKA. Previous cadaver and clinical studies showed that the patellar contact forces on the medial and lateral sides were different [15,20]. Also, some other studies demonstrated a significant lateral pressure shift in the resurfaced knee compared with that in the native patella [21,22]. Therefore, patellar contact force was measured on both the medial and lateral sides in this study.

The results of the current study are in agreement with the experimental results of past studies. Luyckx et al. demonstrated that the maximal patellofemoral contact force increased significantly with increasing patellar height using a dynamic knee simulator system based on the Oxford rig and allowing six degrees of freedom [14]. They concluded that this is a consequence of the delay in the contact between

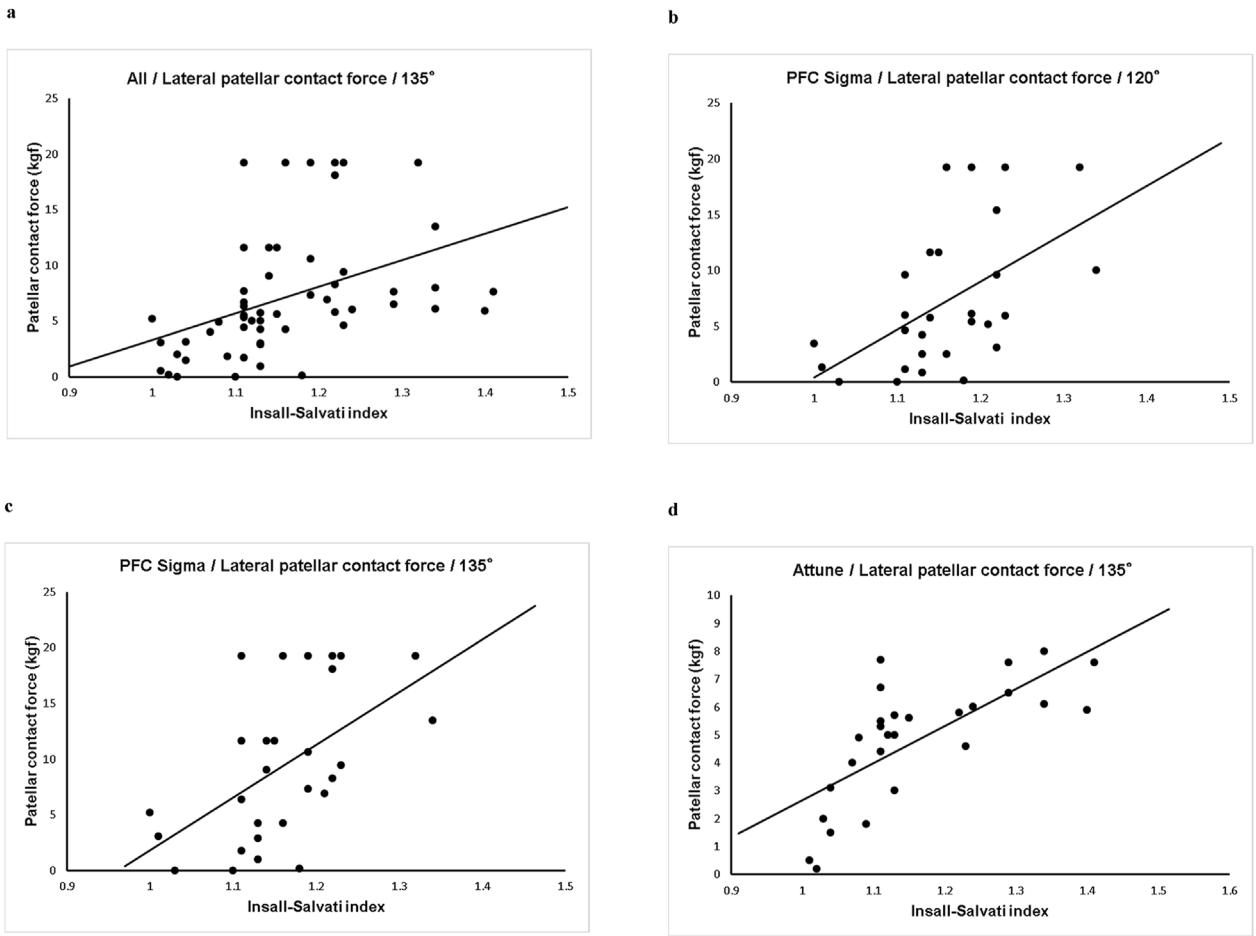

Fig. 2. Correlations between Insall-Salvati index and the lateral patellar contact force. **a**: At 135° of knee flexion in all the patients. R = 0.42, P = 0.0012. **b**: At 120° of knee flexion in patients using PFC Sigma. R = 0.53, P = 0.0034. **c**: At 135° of knee flexion in patients using PFC Sigma. R = 0.55, P = 0.0027. **d**: At 135° of knee flexion in patients using Attune. R = 0.72, P < 0.001.

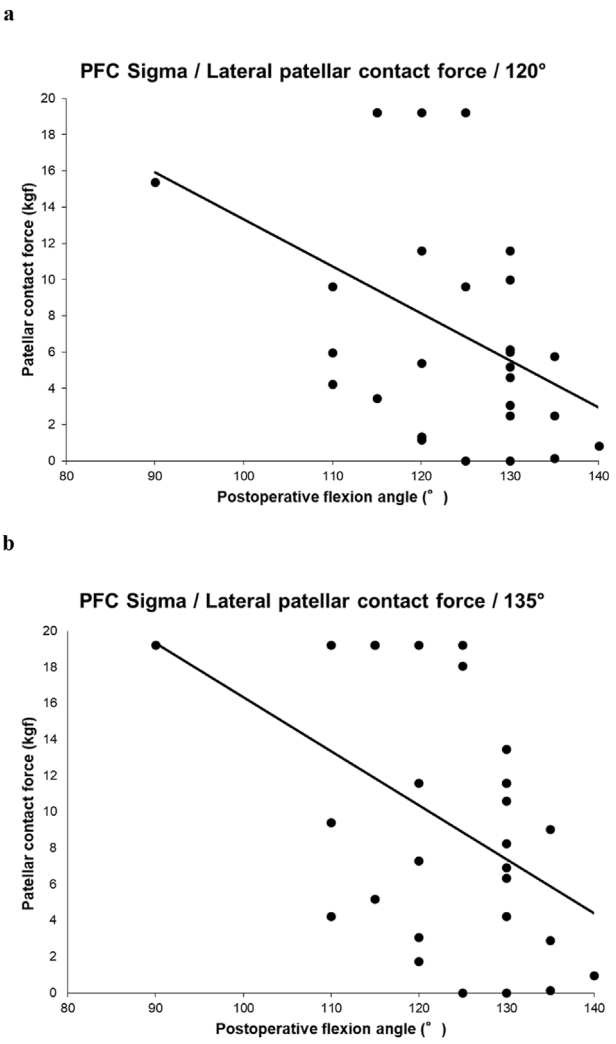

Fig. 3. a: Lateral patellar contact force in patients with PFC Sigma at 120° of flexion showed inverse correlation to postoperative flexion angle. R = −0.43, P = 0.021. **b:** Lateral patellar contact force in patients with PFC Sigma at 135° of flexion showed inverse correlation to postoperative flexion angle. R = −0.46, P = 0.013.

the quadriceps tendon and the femoral trochlea, which occurs beyond a certain degree of flexion because this contact leads to load sharing by the quadriceps tendon and a reduction in contact force on the patellofemoral joint during deep flexion. Singerman et al. reported on the direct *in vitro* measurement of the patellofemoral contact force by a specially designed six-degree-of-freedom force transducer under loading simulating rising from a chair. They demonstrated that when patellar height was experimentally increased (decreased) the magnitude of the patellofemoral contact force increased (decreased). For a knee with patella alta, the onset of contact between the quadriceps tendon and the femoral trochlea was delayed and the patellofemoral contact force continued to increase with increasing flexion angle [11]. Our current data are consistent with these previous *in vitro* findings and confirm these results by direct *in vivo* measurement of the patellofemoral contact force. We suppose this is because the contact between the quadriceps tendon and the femoral condyle is delayed above a certain degree of flexion, and this contact results in load sharing by the quadriceps tendon, reducing the patellofemoral contact force during deep flexion, as with the past studies showed.

As for the relationships between the patellar contact force and the postoperative flexion angle, the lateral patellar contact force at 120° and 135° of flexion in patients with PFC Sigma inversely correlated with postoperative flexion angle, while no correlation was found in patients with Attune as well as in all the patients. Matsumoto et al. previously showed that high lateral patellar contact force at deep flexion reduced postoperative flexion angle in patients undergoing TKA with the use of PFC Sigma [15]. They thought that lateral laxity at flexion arc resulting in reduced lateral patellar pressure, which might contribute to the acquisition of postoperative high flexion angle. The results of the current study are in agreement with their results.

As AKP after TKA has been reported in as many as 45% of patients [23,24] and was reported to be partially related to high patellofemoral contact force [25,26], surgeons should pay attention to some points when treating patients with patella alta to avoid postoperative AKP. Firstly, appropriate soft tissue balance may be important for appropriate patellar tracking. Matsumoto et al. reported that lateral laxity in flexion resulted in reduced lateral patellar contact force. Surgeons should take medial-lateral laxity into account when considering patellofemoral joint kinematics [15]. Secondly, using the mobile-bearing insert might be a good option for patients with high-riding patella to prevent high patellar contact force during TKA. Kuroda et al. demonstrated that patellar contact force was significantly lower, especially on the lateral side with mobile-than with fixed-bearing TKA at mid-to deep knee flexion on the same patients [27]. Thirdly, using a specific type of implant may be of help to lower the patellar contact force. Recently, Nakano et al. reported that the patellar contact force was significantly lower, especially on the lateral side in patients using the Attune than in patients using the PFC Sigma at deep knee flexion [16]. Reduced thickness and width of the anterior flange of the femoral component in the Attune may play a role in low patellar contact force and partially explain the current results that only the knees with PFC Sigma showed a positive correlation between Insall-Salvati index and the lateral patellar contact force at 120° of flexion. Fourthly, reduced anterior condylar height, i.e., reduction in the distal femoral anterior condyle after TKA, may be helpful to decrease patellofemoral contact force. Nishitani et al. described that the cases with reduced medial anterior condylar height after TKA showed decreased patellofemoral contact forces on computer simulation in 101 knees [28]. Fifthly, patella thickness can be the factor on patellofemoral contact force in TKA. Tanikawa et al. showed that in cadaveric study, a 2 mm increase or decrease in patellar thickness resulted in an approximately 20% increase or decrease in the patellofemoral contact force and they recommended not to increase the thickness during patellar replacement since increased patellofemoral contact force may reduce knee joint function [29].

Our study had several limitations. Firstly, we have not measured subjective outcomes including AKP and patient satisfaction in this series. Secondly, patella tendon strain was not measured while the influence of patella height includes mainly two factors, patella tendon strain and patellar length. Therefore, the relationship between patella tendon strain and patella length was unclear. Thirdly, the patellar contact force was only assessed in mobile-bearing PS TKA. Fourthly, the postoperative rotation angles of the femoral and tibial components were not assessed in this study. Fifthly, the patellar height can be changed after surgery because of the bone resection, which may affect the results. Sixthly, only linear analysis was done in this series and results may differ by using other analysis methods. Seventhly, as the knee flexion angle shown in this study is the value at one year postoperatively, Insall-Salvati index at that time differs from the preoperative Insall-Salvati index measured in this study, thus the relationship between postoperative knee flexion angle and Insall-Salvati index was not be directly examined. Lastly, the patellar contact force and the kinematics were measured under anesthesia in this study. Future studies should be conducted to compare these values between under anesthesia and during daily living activities.

5. Conclusions

Patients with superior patellar position tended to demonstrate high lateral patellar contact force in deep knee flexion after TKA, and the lateral patellar contact force at deep flexion inversely correlated with

postoperative flexion angle. The possibility that AKP caused by high patellar contact force may have contributed to this cannot be ruled out, therefore, interventions aimed at decreasing patellofemoral contact force may be efficacious in this patient population.

Author contribution

N Nakano was the chief investigator and responsible for the data analysis. T Matsumoto was responsible for the organization and coordination of the study. Y Kuroda, M Tsubosaka, T Kamenaga, K Ishida, S Hayashi, T Matsushita and Y Hoshino developed the study design. R Kuroda supervised the study and edited the manuscript. All authors contributed to the writing of the final manuscript.

Declaration of competing interest

The authors declare no competing interests.

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