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Bony asymmetry in patellofemoral morphology and risk factors of instability are mostly clinically negligible

Louis Dagneaux¹  · Hamid Rahmatullah Bin Abd Razak² · Pierre Laumonerie³ · Ahmad Faizhan⁴ · Sally LiArno⁴ · Peter Wellings⁴ · Matthieu Ollivier⁵ · Christophe Jacquet⁵

Abstract

Purpose Previous investigations suggested that femoral side-to-side differences were located in the upper femur anatomy. However, little is known about the asymmetry between distal femur and patella. The degree of bony asymmetry in the patellofemoral joint was evaluated using pairs of CT-scans with emphasis on morphometric measurements and risk factors relevant to patellofemoral disorders.

Methods Patellofemoral morphometric parameters and anatomical risk factors were analyzed from 345 pairs of CT scans to evaluate side-to-side differences for each patient. All measurements were automatized using previously published algorithm-calculated bone landmarks. We analyzed asymmetry based on absolute differences (AD) and percentage asymmetry (AS%). Significant asymmetry was defined as AS% > 10%.

Results Patellar height was found to be highly symmetric (mean AD 0.1 for both Insall-Salvati and Caton-Deschamps methods, AS% 8% and 9%, respectively). Patellar and femoral morphometric parameters were found highly symmetric, except for the trochlear groove depth. Substantial asymmetry was reported in two patellofemoral risk factors: the lateral trochlear inclination (mean AD 2°, AS% 16%) and the tibial tuberosity-trochlear groove distance (1 mm, 116%). Patellar and femoral morphometric asymmetries were independent of demographics, including age, gender, height, weight and ethnicity.

Conclusion Patellar height was found to be highly symmetric and is, therefore, a reasonable index for contralateral templating. While very few patellofemoral morphometric parameters and anatomical risk factors were asymmetric, the mean differences were clinically negligible and independent of demographics.

Level of evidence III.

Keywords Side-to-side differences · Asymmetry · Femoral trochlea · Patellar height · CT-scan

Introduction

Studies evaluating bone anatomy and morphometry have focused more on inter-individual differences rather than intra-individual side-to-side differences [7]. An understanding of side-to-side differences is useful in the evaluation of bilateral musculoskeletal pathology. For example, differences in bone morphology and functional parameters between the knees of a patient may influence leg dominance which in turn may affect the risk of joint injury or degeneration [1]. There are studies that have reported substantial asymmetry and side-to-side differences in the proximal and distal femur [26, 33]. However, the literature is lacking with respect to side-to-side differences in the morphology of the femoral trochlea and patella.

✉ Louis Dagneaux
louisdagneaux@gmail.com

¹ Department of Orthopaedic Surgery, Lapeyronie University Hospital, Montpellier University, 371 Av du Doyen Gaston Giraud, 34295 Montpellier Cedex 5, France

² SingHealth Duke-NUS Musculoskeletal Sciences Academic Clinical Programme, 20 College Road, Academia Level 4, Singapore 169865, Singapore

³ Department of Orthopedic Surgery, Hôpital Pierre-Paul Riquet, Place du Docteur Baylac, 31059 Toulouse, France

⁴ Stryker, Mahwah, NJ, USA

⁵ Department of Orthopedics and Traumatology, St. Marguerite Hospital, Aix Marseille University, APHM, CNRS, ISM, Institute of Movement and Locomotion, 270 Boulevard Sainte Marguerite, BP 29, 13274 Marseille, France

The patellofemoral joint (PFJ), owing to its unique bone anatomy and the numerous capsuloligamentous structures and muscles that dynamically control the patella, is one of the most complex joints in the human body [34]. Patellofemoral disorders are commonly described bilaterally in individuals. However, the effect of side-to-side differences in bone anatomy and morphology on the risk of patellofemoral disorders has yet to be elucidated. Some of these parameters include trochlear morphology, patellar tilt and patellar height [6]. To date, there has only been a single study that has reported side-to-side differences in the human knee joint [7]. However, patellofemoral parameters were not analyzed in that study. Despite the challenges researchers face in analyzing the PFJ, data from modern computed tomography (CT) scans can be harnessed to reveal significant asymmetries [22, 27]. The natural question that the surgeon may have is “Is contralateral screening or templating of the PFJ appropriate in regards to these asymmetries?” Indeed, the contralateral knee is often used as reference in extensor mechanism reconstruction. In addition, to quantify asymmetries in the PFJ is crucial for the understanding of patellar and trochlear development. Substantial differences would help supporting the developmental versus genetic theory for trochlear and patellar shapes.

As such, the degree of bony asymmetry in PFJ was evaluated using pairs of CT-scans with emphasis on morphometric measurements and risk factors relevant to patellofemoral disorders. We hypothesized that substantial asymmetry would be present in association with demographic factors.

Materials and methods

After IRB approval (IRB 2019-015333-13, Aix-Marseille University, France), paired CT scans of the lower limbs from 389 individuals taken from the Stryker Orthopedic Modeling and Analytics (SOMA) database (Stryker, Mahwah, New Jersey, USA) were specifically analyzed for this investigation. SOMA is a database containing over 3500 CT scans which have been segmented to provide three-dimensional models of more than 15,000 individual bones. This outstanding dataset has already been utilized to study morphometric characteristics of the proximal femur and tibia [22, 27]. While the scans themselves are anonymized, patient data such as age, gender, height, weight, body mass index (BMI) and ethnicity were known for each scan. These scans were collected from several institutions globally and were included only if each slice was less than 1.5 mm thick with no motion artefact present.

Only patients with no clinical signs or symptoms in the knee were investigated. All participants underwent CT scans in the supine position, the knee in the fully extended with free natural rotation and complete extensor relaxation. Scans

were excluded if they showed any bone and joint anomalies such as significant arthritis, posttraumatic bony deformities or any evidence of previous surgery to investigate the constitutional morphology of the patellofemoral joint from this subset of individuals. Of the 389 paired CT scans (778 knees, left and right measurements pooled together), 198 were from men (51%) and 191 were from women. The mean age of included patients was 58 ± 16 years, and the mean BMI was 25 ± 4 kg/m². Demographic and functional parameters in the series can be seen in Table 1. The patients in our series had a diverse ethnicity including Caucasian (54%), Asian (39%), African-American and Middle Eastern (7%).

PFJ measurements

Anatomical measurements included patellar morphometric parameters, femoral trochlear morphometric parameters and PF anatomical risk factors usually considered of primary importance for the PFJ [4, 20]. All these measures were assessed for each pair of CT scans (Fig. 1). Automated landmarks were used to assess bone metrics (width and thickness) and articular angulation in an index bone using algorithm-calculated technology. Then, these measurements were mapped to each bone of the database by a previously validated software (Soma TM, Stryker, Mahwah, US), resulting in reproducible patient-specific bony landmarks extraction. The most proximal and distal points of the patella were selected to define the patellar width, the most anterior and posterior point of the patella defining the patellar thickness (Fig. 1). The same method was used for the medial and lateral facets of the patella, the medial and lateral femoral condyle and the femoral trochlea, resulting in the extraction of bony width, thickness, height and length. The intraclass correlation coefficient was found > 0.99 after two independent software extractions.

The trochlear length ratio was defined as the ratio between the lateral facet and medial facet of the trochlea.

Table 1 Demographic parameters in the overall series (left and right anatomical measurements are pooled together)

Parameters	% or Mean \pm SD (range)
Demographic	
Age, years	58 ± 16 (11–92)
Gender (female)	49%
Height, kg	166 ± 8 (140–189)
Weight, cm	70 ± 15 (39–110)
Body mass index, kg/m ²	25 ± 4 (15.6–41.6)
Ethnic background	
Caucasian	54% (211 individuals)
Asian	39% (151)
African American and middle eastern	7% (27)

Patellar Morphometric Parameters		Femoral Morphometric Parameters	
Width of patellar medial facet	MAFP, mm	Width of medial facet of femoral trochlea	MFFT, mm
Width of patellar lateral facet	LAFP, mm	Width of lateral facet of femoral trochlea	LFFT, mm
Patellar width (medial-lateral)	MWP, mm	Transepicondylar width	TEW, mm
Patellar width (proximal-distal)	MLFAP, mm	Trochlear length ratio (lateral-medial)	ETIT
Patellar thickness	MTP, mm	Trochlear groove depth	TGD, mm
Patellofemoral Anatomical Risk factors		Trochlear groove thickness	TGT, mm
Tibial tuberosity – trochlear groove distance	TTGT, mm	Trochlear groove thickness ratio	eTGT
Insall-Salvati index	IS	Lateral condylar height	LCH, mm
Caton-Deschamps index	CD	Medial condylar height	MCH, mm
Patella articular angle	AFAP, °	Central condylar height	CCH, mm
Sulcus angle	SA, °	Lateral epicondylar width ratio	eLCH
Lateral trochlear inclination	LCI, °	Medial epicondylar width ratio	eMCH
		Central epicondylar width ratio	eCCH

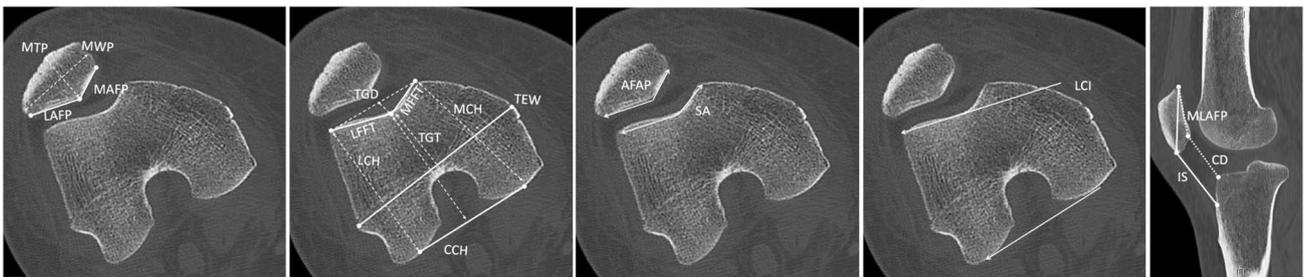


Fig. 1 CT scan measurements of the patellofemoral joint from axial and sagittal segmentations using automatized software

The trochlear groove thickness ratio was defined as the ratio between the trochlear groove thickness (Line 1 is drawn across the posterior margins of the medial and lateral condyles. Two lines parallel to line 1 are drawn crossing the centers of the trochlear groove and the posterior femoral condylar groove, respectively. Trochlear groove thickness is the perpendicular distance between these 2 lines) and the central condylar height (line 1 is drawn across the posterior margins of the medial and lateral condyles. The central condylar height is the perpendicular distance from line 1 to the deepest part of the trochlear groove). The epicondylar width ratio was defined using the lateral or medial condylar height expressed as a percentage of the transepicondylar width.

Patellar height was assessed using the Caton-Deschamps index [5] and Insall-Salvati ratio [15]. Anatomical risk factors were conventional measurements associated with patellofemoral pathology, including the alignment of the extensor mechanism (defined by the tibial tuberosity-trochlear groove (TT-TG) distance) [9], the patella articular angle (defined as the angulation between the two patellar facets, AFAP) [17], the sulcus angle (defined as the angulation between the two trochlear facets, SA) [18] and the lateral trochlear inclination (defined as the angulation between the trochlear lateral facet and the femoral posterior condyles, LCI) [12]. Algorithm-based mesh-morphing and measurements from CT scans

of human femurs have been reported to be greatly accurate [13], and in-house accuracy and reproducibility analysis estimated that algorithms from CT scans allows automated bony measurements for the patella with the same margin of error < 2 mm and $< 1^\circ$.

Assessment of asymmetry

Side-to-side absolute differences (AD) were calculated simply by subtracting right and left values for each individual and expressed by mean and range in the entire cohort (Tables 2 and 3). As such, the maximum of individual AD reflected the magnitude of asymmetry.

The percentage of absolute asymmetry (AS%) was determined for each individual as the absolute difference divided by (the mean of the right and left values), and expressed by the mean of AS% in the entire cohort [33]. As such, this value reflected the significance of asymmetry and we defined a percentage of $> 10\%$ as significant.

Statistical analysis

Mean and standard deviations (SD) were determined for each of the measurements made for the population as a whole and for various subgroups, based on gender and

Table 2 Side to side differences in morphological parameters of the patellofemoral joint with percentage of asymmetry and absolute difference

		Right side		Left side		AS%	AD	<i>p</i>
		Mean (SD)	Range	Mean (SD)	Range			
Width of patellar medial facet	MAFP, mm	21.1 (2.9)	12.2–29.7	20.7 (3)	8.6–28.9	8%	1.4 (0–8)	<0.00001
Width of patellar lateral facet	LAFP, mm	23.1 (2.8)	15.3–32.3	22.9 (2.9)	14.1–30.8	6%	1.3 (0–9)	<0.00001
Patellar Width (medial–lateral)	MWP, mm	37.3 (4.7)	21.8–50.3	36.8 (4.9)	17.3–49.6	6%	2.0 (0–12)	<0.00001
Patellar Width (proximal–distal)	MLFAP, mm	29.9 (3)	18.6–40.8	30.1 (3)	16.3–37.2	4%	1.2 (0–7)	<0.00001
Patellar thickness	MTP, mm	20.4 (2.3)	14.9–30.6	20.3 (2.3)	13.6–32.2	4%	0.7 (0–6)	<0.00001
Width of medial face of femoral trochlea	MFFT, mm	12.5 (1.4)	8.8–16.7	12.4 (1.3)	8.5–16.6	5%	0.6 (0–3)	<0.00001
Width of lateral face of femoral trochlea	LFFT, mm	22.3 (1.8)	18.1–27.6	22.4 (1.9)	17.4–30.2	3%	0.6 (0–3)	<0.00001
Transepicondylar width	TEW, mm	79.4 (6.1)	65.8–93.5	79.7 (6.1)	65.3–94.2	1%	0.7 (0–3)	n.s
Trochlear Length ratio (lat/med)	ETIT	1.7 (0.2)	1.5–2.8	1.8 (0.2)	1.3–2.6	7%	0.1 (0–2)	<0.00001
Trochlear groove depth	TGD, mm	3.5 (1.3)	0.1–8.0	3.4 (1.4)	0.1–7.1	39%	0.6 (0–4)	<0.00001
Trochlear groove thickness	TGT, mm	35.8 (3.1)	27.8–47.9	35.9 (3.1)	28.3–45.5	2%	0.7 (0–4)	0.0014
Trochlear groove thickness ratio	eTGT	45.1 (2.3)	38.9–52.5	45.1 (2.3)	39.1–51.9	2%	0.9 (0–4)	<0.00001
Lateral condylar height	LCH, mm	63.2 (4.4)	48.1–75.5	63.4 (4.5)	48.0–75.9	1.3%	0.8 (0–9)	0.009
Medial condylar height	MCH, mm	61.1 (4.5)	50.5–73.7	61.2 (4.4)	50.6–73.6	1.3%	0.8 (0–4)	0.016
Central condylar height	CCH, mm	57.1 (4.1)	45.8–68.7	57.2 (4.1)	47.4–68.3	1.2%	0.7 (0–4)	0.018
Lateral epicondylar width ratio	eLCH	79.7 (3)	72.5–90.8	79.6 (3)	72.3–89.9	1.3%	1.0 (0–4)	<0.00001
Medial epicondylar width ratio	eMCH	77.1 (3.1)	69.4–87.7	76.9 (3.1)	67.5–89.2	1.4%	1.0 (0–4)	<0.00001
Central epicondylar width ratio	eCCH	72 (3)	63.7–81.4	71.9 (3)	63.7–82.6	1.3%	0.9 (0–10)	0.00003

p values indicated with an absolute difference were calculated using Student's *t* test, upon smaller versus larger global means comparison. Substantially asymmetry is defined as a side-to-side difference %AS > 10%

SD standard deviation, %AS percentage of asymmetry, AD absolute difference, n.s. non-significant

Table 3 Side to side differences in patellofemoral anatomical risk factors with the percentage of asymmetry and absolute difference

		Right side		Left side		AS%	AD	<i>p</i>
		Mean (SD)	Range	Mean (SD)	Range			
Tibial tuberosity-trochlear groove distance	TTTG (mm)	11.3 (1)	0–16.7	11.3 (1)	0–15.3	116%	0.6 (0–3)	<0.00001
Insall-Salvati ratio	IS	1.2 (0.4)	0.7–5.4	1.2 (0.4)	0.8–6.8	8.6%	0.1 (0–1)	0.0004
Caton-Deschamps index	CD	1 (0.4)	0.6–6.1	1 (0.5)	0.7–7.2	8%	0.1 (0–1)	0.013
Patella articular angle	AFAP,	115.8 (8.3)	83.9–137.8	114.8 (8.6)	82.9–155.7	4.4%	4.8 (0–44)	<0.00001
Sulcus angle	SA, °	155.2 (8.7)	126.7–179.3	155.5 (9.1)	131.8–179.3	2.6%	3.9 (0–17)	<0.00001
Lateral trochlear inclination	LTI, °	15.6 (4.2)	0–26.1	15.8 (4.3)	1.3–25.9	16%	1.9 (0–10)	<0.00001

p values indicated with an absolute difference were calculated using Student's *t* test, upon smaller versus larger global means comparison. Substantially asymmetry is defined as a side-to-side difference AS% > 10%

SD standard deviation, %AS percentage of asymmetry, AD absolute difference

°degrees

ethnicity. Normal (Gaussian) distributions of the absolute differences and percentage asymmetry between pairs of PFJ parameters were determined. Univariate analysis was performed using Student's paired *t* tests to compare side-to-side mean values as well as Student's *t* test to compare smaller versus larger mean values. Pearson's coefficients were calculated to examine correlations among absolute differences, specimen demographic data and PFJ measurements. Multiple linear regression models were developed

to establish the determinants for each of the variables that defined a difference between left and right measurements. For each model, variables with a *p* value < 0.1 in the univariate analysis were kept in the final model. A trained statistician (MO) performed all the statistical analyses using SPSS (Version 22; IBM Corp, Armonk, New York, USA). All calculations assumed two-tailed tests. Results were considered statistically significant at *p* value < 0.05. Sample size was calculated based on the estimated patellar inclination angle

difference with a α of 0.05, and a power ($1-\beta$) of 0.80. Using G*power, a minimum of 81 paired CT scans was calculated to detect 10% asymmetry [11].

Results

Side-to-side differences in morphological parameters, percentages of asymmetry and absolute differences are summarized in Table 2. Patellar morphometric measurements including patellar width, patellar facet width and patellar thickness were found to have side-to-side differences under the 10% threshold (i.e. non-significant). As such, patellar asymmetries were found negligible. Femoral morphometric measurements were highly symmetric, including the width of the trochlear facets, transepicondylar width, condylar heights and ratio (Table 2). The only significant asymmetry was found in the trochlear groove depth (TGD, mean AD 1 mm, AS% 39%) with a maximum asymmetry of 4 mm.

Patellar height was highly symmetric from one patient to another with a mean AD of 0.1 mm for both Insall-Salvatti and Caton-Deschamps methods (AS% 8% and 9%, respectively). We found significant side-to-side differences in two patellofemoral anatomical risk factors (Table 3): lateral trochlear inclination (LTI, mean AD 2°, AS% 16%) and TTTG distance (mean AD 1 mm, AS% 116%). The maximum asymmetry for LTI and TTTG were 10° and 3 mm, respectively.

While significantly asymmetric, mean absolute differences showed in this study were not clinically relevant for the trochlear groove depth (mean absolute difference of 1 mm), LTI (2°) TT-GT (1 mm). The few asymmetries that we found above was independent of demographic factors, including age, gender, BMI and ethnicity (Table 4).

Discussion

The most important finding of the present study was very few patellofemoral morphometric parameters and anatomical risk factors were asymmetric. To our knowledge, this is the first study reporting side-to-side differences and asymmetry of the PFJ. Reconstruction of the extensor apparatus

often required contralateral planning of the patella height or morphology, including quadriceps and patellar tendon reconstruction or sizing for allograft in chronic failure. Our main result suggests that templating patellar morphology from the contralateral side is a good option in cases that require patellar reconstruction, allograft sizing and patellar implantation [19]. Similarly, templating patellar height from the contralateral side can be a valuable target for the reconstruction of the extensor mechanism.

The main asymmetry in the femoral morphometric parameters was found in the trochlear groove depth (TGD, AS% 39%) with a maximum of 4 mm. This parameter is directly related to trochlear dysplasia and patellar maltracking [28]. Previously reported side-to-side differences in the femur include neck-shaft angle, femoral offset, femoral neck version, femoral neck thickness, femoral shaft dimension, femoral canal flare index and coronal alignment of the distal femur [7, 33]. In our study, asymmetry in the distal femur was limited to the femoral trochlea, as the patella morphometric parameters were found highly symmetric.

Besides the asymmetry of the trochlear groove depth, we also found asymmetry in the lateral trochlear inclination (LTI, AS% 16%) with a maximum of 10°. While no asymmetry of the femoral condyle dimensions was found in this investigation, lateral trochlear inclination has been found to correlate with femoral neck anteversion angle, neck-shaft angle and mediolateral offset of the proximal femur [32]. In light of known asymmetry of the proximal femur and the correlation between the morphology of the proximal femur and the trochlea, asymmetry of trochlear parameters was expected using modern measurement methods.

The clinical significance of these asymmetries is debatable although abnormalities in trochlear inclination, depth and orientation have been known to induce patellofemoral disorders [30]. Mehl et al. reported that cartilage defects of the patella are associated with the geometry of the PFJ especially with flat and shallow trochlea [25]. However, they did not perform side-to-side comparisons in their study. Deep femoral sulcus depth and increased sulcus angle have been found to correlate with the incidence of PFJ osteoarthritis [8, 18]. Moreover, we know that for every 1° increase in the femoral sulcus angle, there is an associated 9.1 mm³ (95% CI 3.1–15.0) increase in medial patella cartilage volume

Table 4 Multivariate analysis regarding asymmetrical factors

Parameters	Gender	Age	BMI	Height	Weight	Ethnicity
TGD	(n.s)	(n.s)	(n.s)	(n.s)	(n.s)	(n.s)
TTTG	(n.s)	(n.s)	(n.s)	(n.s)	(n.s)	(n.s)
LCI	(n.s)	(n.s)	(n.s)	(n.s)	(n.s)	(n.s)

All *p* values calculated using multiple analysis of variance testing (MANOVA)

TGD trochlear groove depth, TTTG tibial tuberosity-trochlear groove distance, LCI lateral trochlear inclination, BMI body mass index, n.s non-significant

[8]. However, the asymmetries found in our study cannot be strongly related to factors of early PF degeneration found by others [14] in regards to the small absolute differences.

In evaluating patellofemoral risk factors, we found side-to-side differences in LTI and TTTG distance. This asymmetries could explain side-dominance in the occurrence of patellofemoral pain syndrome, patellar instability and recurrent dislocation [10]. As a strong predictor of patellofemoral tracking disorders, LTI correlated strongly with lateral tilt and bisect offset index with an adjusted R^2 of 0.70 and 0.46, respectively, in a study by Biyani et al. [2] and was the best predictor of patellar lateral displacement and tilt at 20°, 40° and 60° of knee flexion [31]. Interestingly, lateral tilt and bisect offset index are linked to other relevant parameters for the PFJ (lateral patellar displacement, patellar inclination angle and trochlear congruence angle). However, the methodology used in our study was not published to quantify asymmetries in functional measures (i.e. not anatomical).

Demographics (including age, gender, height, weight, and ethnicity) were not related to patellofemoral asymmetries from the multivariate analyses. In contrast, it has been reported that a higher risk of developing patellofemoral pain syndrome [16] and patellar instability [3, 23] were found with females. This predisposition cannot be related to asymmetries found in our study, although some authors have postulated that females may have risk factors associated with asymmetry, predisposing them to patellofemoral disorders [21, 24, 31].

This study does have its limitations. First, measurements of the proximal femur were not considered. The automated measurements focused on patellofemoral landmarks with no integration of rotational abnormalities of the femur and at the ankle [26, 33]. Next, CT-scans were utilized to investigate bony morphology in determining joint orientation, neglecting the geometry of articular cartilage. Finally, in assessing absolute side-to-side differences for individual patients, the number of paired femurs required to assess significant changes can range from 3 to 165 pairs depending on the desired effect size or sensitivity, as reported by Pierre et al. [29]. A small risk of overestimation of the effect size needs to be acknowledged in regards to the high number of CT-scans included.

In regards to the magnitude of asymmetries located in the patellofemoral joint, we highlight the need for careful contralateral screening as these asymmetrical risk factors involve the occurrence of recurrent dislocations or contribute to adverse outcomes. These findings help to understand the underlying reasons for asymmetry in patellar positions, patellofemoral symptoms and adverse results. Potential side-to-side differences outcomes after isolated medial patellofemoral ligament reconstruction should be noted in the patient's information. The label of "healthy" contralateral knee should be considered with caution when addressing

recurrent patellofemoral instability or patellofemoral pain syndrome.

Conclusions

Patellar height was found to be highly symmetric and is, therefore, a reasonable index for contralateral templating. While very few patellofemoral morphometric parameters and anatomical risk factors were asymmetric, the mean differences were clinically negligible and independent of demographics.

Author contributions LD, AF, SL, PW, MO the conception and design of the study, or acquisition of data, or analysis and interpretation of data. LD, HR, P-L, CJ drafting the article or revising it critically for important intellectual content. LD, HR, P-L, AF, SL, PW, MO, CJ final approval of the version to be submitted. AF, SL, PW, MO statistics. CJ experimentation or surgery performance.

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Compliance with ethical standards

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Ethical approval Each author certifies that his institution has approved the reporting of these cases, that all investigations were conducted in conformity with ethical principles of research. This manuscript contains a study with human participants, which has been approved by our institutional ethics committee (2019-A00912533).

Informed consent Not applicable.

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