



Lateral femoral impaction fractures during an ACL tear extend posteriorly on the weight-bearing area of the tibiofemoral joint

Konrad Malinowski^{1,2}  | Marcin Mostowy^{1,3}  | Kacper Ruzik⁴ |
 Krzysztof Starszak⁵ | Grzegorz Maciąg^{6,7} | Paweł Skowronek⁸ |
 Michael T. Hirschmann⁹ | Przemysław A. Pękala² | Robert F. LaPrade¹⁰ |
 Dong Woon Kim²

¹Artromedical Orthopedic Clinic, Bełchatów, Poland

²Department of Anatomy, Jagiellonian University Medical College, Kraków, Poland

³Orthopedic and Trauma Department, Veteran's Memorial Teaching Hospital in Łódź, Medical University of Łódź, Łódź, Poland

⁴Department of Anatomical Dissection and Donation, Medical University of Łódź, Łódź, Poland

⁵Department of Human Anatomy, Medical University of Silesia in Katowice, Katowice, Poland

⁶Department of Descriptive and Clinical Anatomy, Center for Biostructure Research, Medical University of Warsaw, Warsaw, Poland

⁷Department of Orthopedics and Rehabilitation, Medical University of Warsaw, Warsaw, Poland

⁸Department of Orthopaedic and Trauma Surgery, S. Żeromski Hospital, Kraków, Poland

⁹Department of Orthopaedic Surgery and Traumatology, Kantonsspital Baselland (Bruderholz, Liestal, Laufen), Switzerland University of Basel, Basel, Switzerland

¹⁰Twin Cities Orthopedics, Edina, Minnesota, USA

Correspondence

Konrad Malinowski, Artromedical Orthopaedic Clinic, Chrobrego 24, 97-400 Bełchatów, Poland.
 Email: malwin8@wp.pl

Funding information

None

Abstract

Purpose: Posterior elongation of the physiological terminal sulcus (TS) due to lateral femoral condyle impaction fracture (LFC-IF) after an anterior cruciate ligament (ACL) tear could potentially decrease the weight-bearing area of the tibiofemoral joint, decrease the tension on lateral meniscus and cause flattening of the LFC which would influence rotational knee motion and cause anisometry of the lateral and anterolateral stabilizers. Therefore, the purpose of the study was to assess if the LFC-IF elongates the physiological TS posteriorly.

Methods: One hundred patients magnetic resonance images (MRIs) (75 males, 25 females, mean age 32.2 years, SD = 8.2) were included with a 1:1 ratio between the full-thickness ACL tear group and the control group (patients with knee MRI performed due to other reasons, with no tear of ACL on MRI and negative clinical tests). Two independent raters evaluated the sagittal T1-weighted preselected MRI scans. The principal measurement of interest was the distance from the intersection of the Blumensaat line with subchondral bone to the posterior border of the TS/LFC-IF.

Results: The median distance from the Blumensaat line to the posterior border of the TS/LFC-IF was significantly higher in the ACL tear group: 14.3 mm, interquartile range (IQR) = 11.6–16.4 mm versus control group: 12.8 mm, IQR = 9.0–15.0 mm, $p = 0.038$. Intrarater and inter-rater reliabilities were >0.90.

Conclusion: LFC-IF after full-thickness ACL tear significantly elongates the physiological TS in the posterior direction.

Level of Evidence: Level III.

KEYWORDS

anterior cruciate ligament, impaction fracture, lateral femoral condyle, terminal sulcus

Abbreviations: ACL, anterior cruciate ligament; ICC, intraclass correlation coefficient; IQR, interquartile range; LFC-IF, lateral femoral condyle impaction fracture; LTP-IF, lateral tibial plateau impaction fracture; MPR, multiplanar reconstruction technique; MRI, magnetic resonance imaging; PTS, posterior tibial slope; SD, standard deviation; TS, terminal sulcus.

NCT05682820.

© 2024 European Society of Sports Traumatology, Knee Surgery and Arthroscopy.

INTRODUCTION

Anterior cruciate ligament (ACL) injuries commonly occur in the 'pivot-shift' mechanism with impaction of the lateral tibial plateau against the lateral femoral condyle (LFC) [2, 12, 34, 36, 47], which may result in a LFC impaction fracture (LFC-IF) [21, 30, 34]. An LFC-IF has been reported to be located within the physiological depression of the bony surface of the LFC—terminal sulcus (TS)—increasing its anatomical depth [2–4]. Numerous authors reported that a deep LFC-IF is associated with an increased risk of persistent instability and graft rerupture rate after an ACL reconstruction [12], increased preoperative rotational instability [30], concomitant meniscus injury [4, 21, 29] and osteoarthritis development [1, 10, 44]. On the contrary, the elongation of the TS due to an LFC-IF has only been investigated in a few studies, mostly using plain radiographs [1, 4, 19, 22, 29]. In the study of Herbst et al., who assessed the LFC-IF length on magnetic resonance imaging (MRI), the specific values were not reported [21]. In addition, only a single study assessed whether this elongation occurs anteriorly or posteriorly [21].

Influence of abnormal depression anterior to the TS would be potentially limited to the patellofemoral joint surface at terminal angles of knee flexion [11, 20, 22]. Conversely, abnormal depression posterior to the TS would decrease the weight-bearing area of the tibiofemoral joint (Figure 1) [11, 20, 22, 39]. Negative consequences of such a decrease of weight-bearing area due to an LFC-IF could be further aggravated by residual anterolateral subluxation of the tibia after ACL reconstruction [23, 27, 47]. Therefore, it remains to be assessed if posterior elongation of the TS by a LFC-IF may be one of factors associated with a high risk of not returning to play at the preinjury level after an ACL reconstruction. Identification of this group of patients may be especially important in athletes with high functional demands. However, before assessing the

clinical importance of posterior elongation of TS by LFC-IF, first it has to be confirmed that such posterior elongation exists, to justify further research in the topic. Therefore, the purpose of this proof-of-concept study was to define whether LFC-IF tended to elongate the physiological TS posteriorly in the full-thickness ACL tear group in comparison with controls. The study hypothesis was that the LFC-IF elongates the physiological TS posteriorly in the full-thickness ACL tear group in comparison with controls.

METHODS

The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the district medical chamber (No. K.B.–12/2020), and individual consent for this MRI diagnostic analysis was waived.

Study design and participants

MRI scans of consecutive patients who had presented to our clinic with knee complaints between June 2020 and July 2021 were prospectively collected. The patients included in the study were assigned to the ACL tear group or the control group (no ACL tear). The inclusion criteria were (1) age between 18 and 45 years, (2) available MRI scans and (3) *only for ACL tear group*: (3a) clear full-thickness tear of ACL visible on MRI, accompanied with (3b) ACL-related instability confirmed by a positive Lachman, anterior drawer and pivot-shift tests. The mentioned tests were performed by two orthopaedic surgeons with >10 years of experience in knee instability treatment, and stability was compared to the contralateral limb. Inconclusive cases were excluded. The exclusion criteria were as follows: (1) previous ACL reconstruction, (2) presence of other instabilities in clinical examination, (3) injuries to the



FIGURE 1 Decrease of the weight-bearing area of tibiofemoral joint due to a lateral femoral condyle impaction fracture elongating the native terminal sulcus posteriorly, from the mild case (a), through the intermediate case (b) and to the severe case (c).

other ligaments of the knee visible on MRI, (4) absence of distinct bony depression of the LFC visualized on MRI, (5) partial-thickness tear of the ACL with questionable instability on clinical exam, (6) presence of osteophytes in the intercondylar notch and/or other morphological disturbances impeding measurements on MRI and (7) low MRI quality and a < 1.5 T magnetic field. In order to minimize selection bias, all patients (consecutive series) were considered for inclusion into the study if they met the eligibility criteria. The study was preregistered at <https://www.clinicaltrials.gov> (NCT 05682820) and conducted in accordance with the STROBE (STrengthening the Reporting of OBservational studies in Epidemiology) reporting checklist for observational studies in epidemiology [8].

Quantitative measurements

After fulfilling the designed number of patients according to the study protocol, all MRIs were evaluated for the location, depth and length of the TS/LFC-IF independently by two authors. All measurements were performed on T1-weighted MRI scans in the sagittal view. Two independent authors selected the MRI slices for each measurement. In cases of disagreement, the senior author was consulted. To calculate intrarater reliability, each author independently assessed all variables twice, with a 2-month interval between measurements to avoid recall bias.

The Blumensaat line was drawn through the roof of the intercondylar notch of the femur as seen in Figure 2a [16, 28]. The Blumensaat line was then copy-pasted to the preselected slices with a visible LFC bony surface contour depression (TS/LFC-IF). Then, the distance from the

Blumensaat line to the posterior and anterior border of the LFC depression was measured. The principal measurement of interest was the distance from the intersection of the Blumensaat line with the subchondral bone to the posterior border of the TS/LFC-IF (Figure 2b). The posterior border was defined as the location where the concave surface of the LFC depression transitioned into the convex surface of the healthy LFC. The Blumensaat line was chosen as a reference point due to the fact that it is located on the femur, and therefore, knee flexion does not influence the measurements.

Secondary measurements included the TS/LFC-IF length (Figure 3a), distance from the intersection of Blumensaat line with subchondral bone to the anterior border of the TS/LFC-IF (Figure 3b) and to the deepest point of the TS/LFC-IF (Figure 3c) and depth of the TS/LFC-IF (Figure 3d). Due to the necessity of Blumensaat line drawing, which corresponds to the sagittal slices on which the ACL tear is visible, it was not possible to blind the reviewers.

Statistical analysis

Statistical analysis was performed using SPSS software, version 29.0.1 (IBM), and G*Power 3.1.9.7 [13]. A minimum number of 34 patients in each group was calculated in the a priori sample size analysis with the distance from the Blumensaat line to the posterior border of the TS/LFC-IF as a primary outcome, based on Lodewijks et al. results from plain radiographs ($\alpha = 0.05$, power $[1 - \beta] = 0.95$, calculated effect size = 1.28) [29]. However, it was decided to include 50 patients in each group, in accordance with the published general recommendations for evaluating

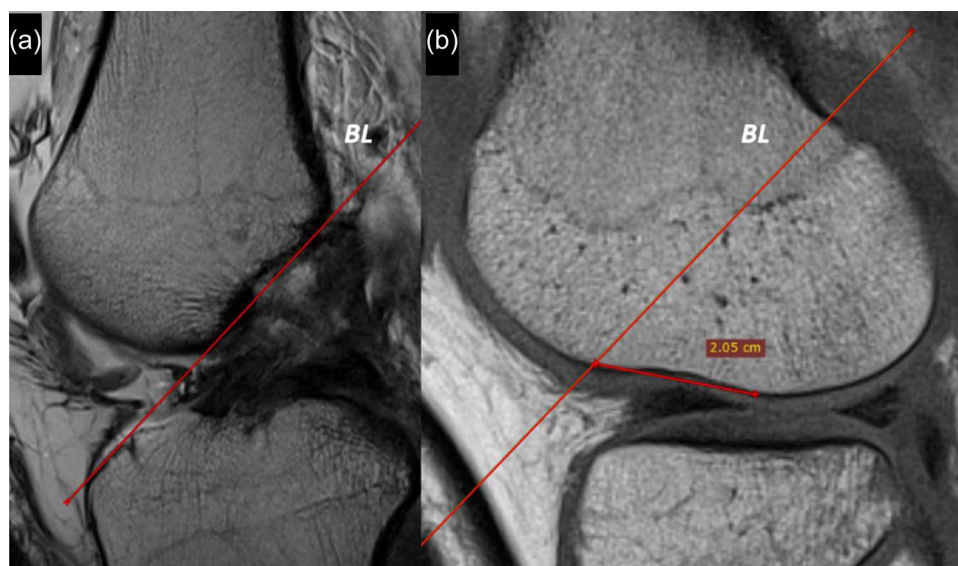


FIGURE 2 Primary measurement—posterior elongation of terminal sulcus (TS) due to lateral femoral condyle impaction fracture (LFC-IF). (a) Drawing the Blumensaat line (BL) through the roof of the intercondylar notch of the femur. (b) Distance from the intersection of copy-pasted Blumensaat line with subchondral bone to the posterior border of the TS/LFC-IF (b).

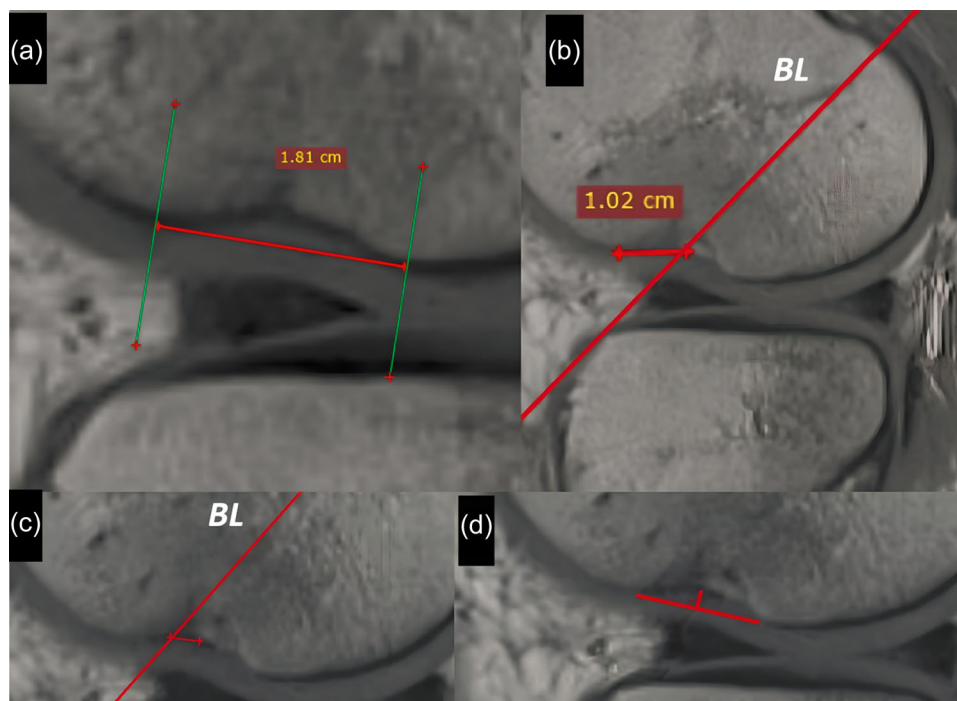


FIGURE 3 Secondary measurements of terminal sulcus (TS)/lateral femoral condyle impact fracture (LFC-IF) morphology. (a) TS/LFC-IF length; (b) distance from the intersection of copy-pasted Blumensaat line (BL) with subchondral bone to the anterior border of the TS/LFC-IF. (c) Distance from the intersection of copy-pasted Blumensaat line with subchondral bone to the deepest point of the TS/LFC-IF. (d) TS/LFC-IF depth.

measurement properties [41]. Intrarater and inter-rater reliabilities were calculated using the intraclass correlation coefficient (ICC) with a two-way random effects model, single measurements and absolute agreement. ICC values <0.40 , between 0.41 and 0.60 , between 0.61 and 0.80 and >0.81 were considered weak, moderate, substantial and in almost perfect agreement, respectively [29, 42]. The normality of the measured variables was assessed using the Shapiro–Wilk test, and the homogeneity of the variances was assessed using Levene's test.

Continuous data for parametrically distributed variables were expressed as the mean \pm standard deviation (SD) and for nonparametrically distributed variables as the median and interquartile range (IQR). The student t test or the Mann–Whitney U test was used to compare the differences between the measured variables in the ACL injury and the control groups for parametrically and nonparametrically distributed variables, respectively. Youden index was used for optimal cut-off calculation. Statistical significance was set to $p < 0.05$ (two-tailed) for all statistical tests.

RESULTS

A total of 141 consecutive patients were considered for eligibility into the study. After excluding patients based on study criteria (Figure 4), 100 patients were included in the study with a 1:1 ratio between the ACL tear group

and the control group. Demographics were presented in Table 1.

Posterior elongation of the TS due to an LFC-IF occurred in the ACL tear group, with the median distance from the Blumensaat line to the posterior border of the TS/LFC-IF significantly longer in ACL tear group: 14.3 mm, IQR = 11.6 – 16.4 mm versus control group: 12.8 mm, IQR = 9.0 – 15.0 mm, $p = 0.038$. Secondary outcomes are presented in Table 1.

ICC values for intrarater and inter-rater reliabilities were all >0.90 (almost perfect agreement) [29, 42], Table 2).

The optimal cut-off value between ACL and control group for the distance between the Blumensaat line and the posterior border of the TS/LFC-IF was 14.0 mm with a sensitivity of 58.0% , specificity of 66.0% , positive predictive value of 63.0% and negative predictive value of 61.1% .

DISCUSSION

The main finding of this study was that the lateral femoral condyle impact fracture (LFC-IF) after full-thickness ACL tear significantly elongates the physiological TS in the posterior direction. Three potential mechanisms of its negative impact are discussed based on the current literature: decrease of the weight-bearing area of the tibiofemoral joint, decrease of the tension on lateral meniscus and flattening of the LFC.

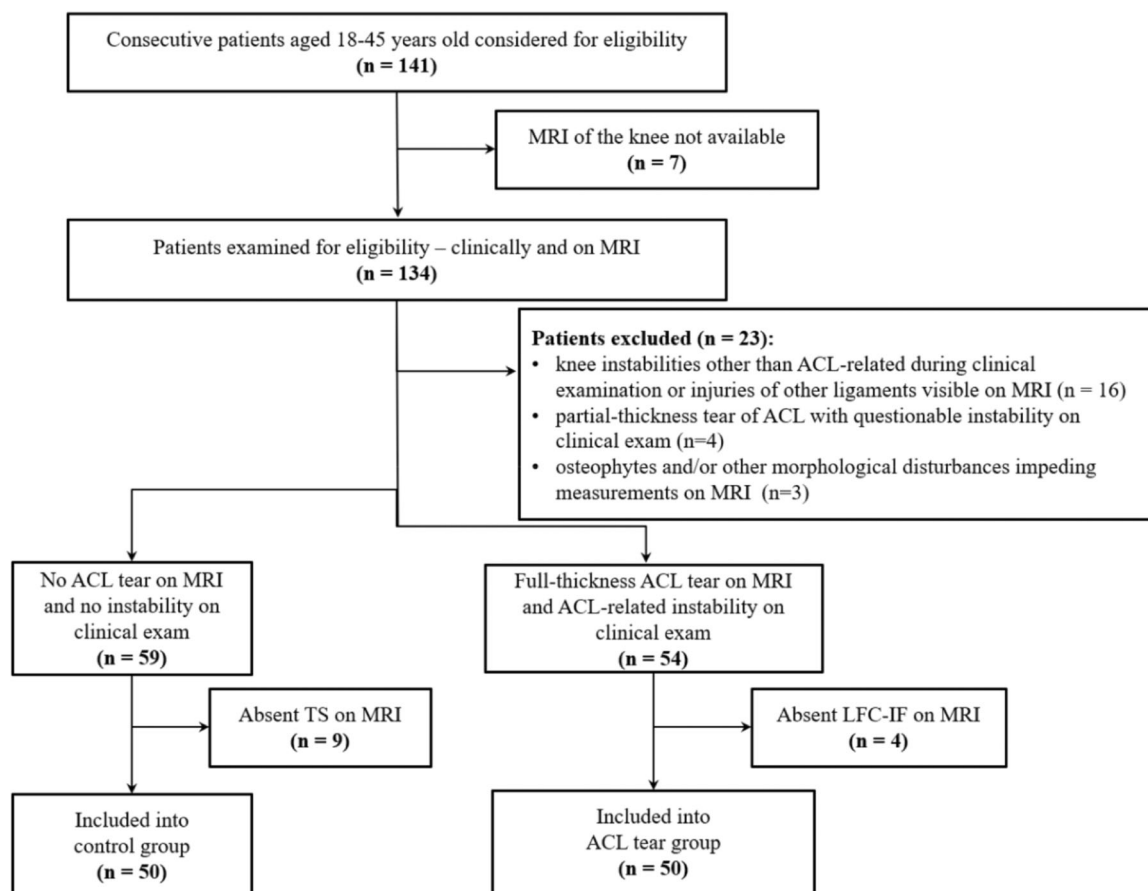


FIGURE 4 Flowchart of patients' inclusion and exclusion. ACL, anterior cruciate ligament; IF, impaction fracture; LFC, lateral femoral condyle; MRI, magnetic resonance imaging; TS, terminal sulcus.

The first mechanism in which posterior elongation of TS due to an LFC-IF could increase the risk of ACL reconstruction failure and the risk of not returning to play at the preinjury level is the decrease of the weight-bearing area of the tibiofemoral joint. This bony deficiency may result in increased forces on the reconstructed ACL graft [12]. What is more, due to the mechanism of injury, a LFC-IF in more than 13% of cases is associated with a lateral tibial plateau impaction fracture (LTP-IF) [2]. The accumulation of negative effects of bony deficiency on both sides may be compared to the Hill-Sachs and Bankart bony lesions in shoulder instability. A LFC-IF has been compared to a Hill-Sachs lesion by numerous authors [21, 24, 31], and a LTP-IF has been compared to a bony Bankart lesion as well [9, 31, 32]. The recent biomechanical study by Milinkovic et al. proved that the 'Bankart knee' (LTP-IF) resulted in significantly increased translational and anterolateral rotational instability in the ACL-deficient knees [32]. The authors of this study are not aware of such biomechanical study for LFC-IF. Speculatively, a 'Hill-Sachs of the knee' that reaches posteriorly enough on the LFC may decrease overall bony congruence and subsequently increase forces on the reconstructed

ACL graft due to partial loss of bony and soft tissue support. In a recent study of Flury et al., 'Bankart knee' was associated with increased rate of anterolateral complex injury and worse functional outcomes after ACL reconstruction [15]. On the other hand, similarly to the Hill-Sachs and Bankart lesions, even deep impaction fracture of the LFC would theoretically not influence the stability [1, 10, 44] if it was anterior enough, analogously to the 'nonengaging' Hill-Sachs lesion [5]. However, this assumption has to be verified by future studies.

The second potential negative impact of posterior elongation of the TS due to an LFC-IF is reduced tension on the lateral meniscus (LM) [22, 34]. The TS is an anatomical impression of the anterior horn of the LM in full knee extension [22, 34]. Thus, the speculative assumption can be drawn that posterior elongation of the TS due to a LFC-IF may lead to disturbance of cartilaginous-meniscal congruence, leading to a 'slack' LM and abnormal axial load distribution [22, 34], as well as disturbance of rotational stability, which LM itself was proven to provide [33, 45].

The third mechanism in which posterior elongation of the TS due to an LFC-IF could increase the risk of

TABLE 1 Patient characteristics and quantitative measurements of the TS/LFC-IF in cases and controls.

Measured variables	ACL injury	Controls	p Value ^c
Demographics			
Age (year)	30.9 ± 8.5	33.4 ± 7.8	n.s.
Sex (%)			
Male	44 (88.0)	31 (62.0)	<0.001
Female	6 (12.0)	19 (38.0)	<0.001
Primary outcome			
BL to posterior border of TS/LFC-IF ^a	−14.3 (−11.6, −16.4)	−12.8 (−9.0, −15.0)	0.038
Secondary outcomes			
Depth of TS/LFC-IF ^a	1.4 (1.1, 1.8)	1.0 (0.8, 1.2)	<0.001
Length of TS/LFC-IF ^b	15.7 ± 3.6	12.6 ± 3.2	<0.001
BL to anterior border of TS/LFC-IF ^b	1.8 ± 4.5	0.8 ± 5.8	n.s.
BL to deepest part of TS/LFC-IF ^a	−6.7 (−3.1, −9.3)	−6.7 (−2.1, −9.5)	n.s.

Abbreviations: ACL, anterior cruciate ligament; BL, Blumensaat line; IF, impaction fracture; LFC, lateral femoral condyle; n.s., not significant; TS, terminal sulcus.

^aNonparametrically distributed variables are reported as the median and quartiles (lower quartile, upper quartile).

^bParametrically distributed variables are reported as the mean ± standard deviation.

^cp Values for nonparametrically distributed variables were calculated using the Mann–Whitney *U* test and for parametrically distributed variables using the Student's *t* test.

ACL reconstruction failure and increase the risk of not returning to play at the preinjury level is flattening of the LFC (Figure 5a). Numerous studies have reported that anatomically flat LFCs are associated with increased ACL reconstruction failure rates [18, 26]. Anatomical flatness of the LFC was most commonly assessed by the height to the anteroposterior diameter ratio (HAPR) [18, 26]. The study of Li et al. reported that a decreased HAPR was a more important risk factor for ACL failure than increased posterior tibial slope (PTS) [26]. Posterior elongation of the TS due to an LFC-IF may speculatively flatten the LFC, affecting knee biomechanics in slight knee flexion (Figure 5b–c).

The exact reason why a flatter LFC increases the risk of rotational instability is not fully understood. Li et al. suggested that as the LFC rolls from the anterior circular bending radius to its flatter part, the knee joint experiences physiologic rotational motion. Therefore, changing the radius of curvature of the LFC by elongation of its 'flatter part' would influence rotational knee motion [26]. The second possible reason may be due to anisometry of the lateral and anterolateral stabilizers. Pfeiffer et al. suggested that such anisometry may occur in knees with higher ratio of posterior condylar distance to the total anteroposterior condylar distance due to different distance between attachments in given knee flexion angles [35]. While posterior elongation of LFC-IF due to TS does not influence the ratio described

by Pfeiffer et al., it may influence the modified HAPR (Figure 5), speculatively changing distance between lateral and anterolateral ligamentous attachments in the given knee flexion angles. What is more, the deepest part of LFC-IF is usually seen far laterally. Importance of anterolateral complex, which acts through bony shape of lateral knee compartment, is getting more and more appreciated, as expressed by increasing ratio of concomitant reconstruction [7]. Loss of LFC volume in the far lateral portion could potentially impact bony support and negatively influence soft tissue stabilizer function. Therefore, flattening of the LFC due to posterior elongation of the TS by an LFC-IF may result in dysfunction of the anterolateral complex, which is a well-known risk factor for ACL injury and ACL reconstruction failure [6, 14].

In the three above-proposed mechanisms, even slight posterior elongation of TS due to LFC-IF may prove its clinical importance. In the study of Lindanger et al., less than 3 mm of side-to-side difference of anterior tibial translation after ACL reconstruction were reported to significantly affect outcomes at 2 and 25 years postoperatively [27]. In the study of Leite et al., as little as 2.8° of significant difference in tibiofemoral rotation angle were reported between successful and failed ACL reconstructions [25]. Also, outliers with an increased posterior elongation of the TS due to an LFC-IF may be the most susceptible to

TABLE 2 ICC values of intrarater and inter-rater reliability.

Variables	Intra-rater reliability [95% CI] ^a		Inter-rater reliability [95% CI] ^a
	Observer 1	Observer 2	
BL to posterior border of TS/LFC-IF	0.934 [0.904–0.955]	0.993 [0.990–0.995]	0.980 [0.970–0.986]
Length of TS/LFC-IF	0.944 [0.917–0.962]	0.996 [0.994–0.997]	0.978 [0.965–0.986]
BL to anterior border of TS/LFC-IF	0.952 [0.930–0.968]	0.998 [0.997–0.998]	0.985 [0.978–0.990]
BL to deepest part of TS/LFC-IF	0.940 [0.912–0.959]	0.993 [0.990–0.996]	0.908 [0.866–0.937]
Depth of TS/LFC-IF	0.947 [0.922–0.964]	0.993 [0.989–0.995]	0.983 [0.974–0.988]

Abbreviations: BL, Blumensaat line; CI, confidence interval; ICC, intraclass correlation coefficient; IF, impaction fracture; LFC, lateral femoral condyle; TS, terminal sulcus.

^a*p* Values for all intra- and inter-rater reliability ICC values were <0.001.

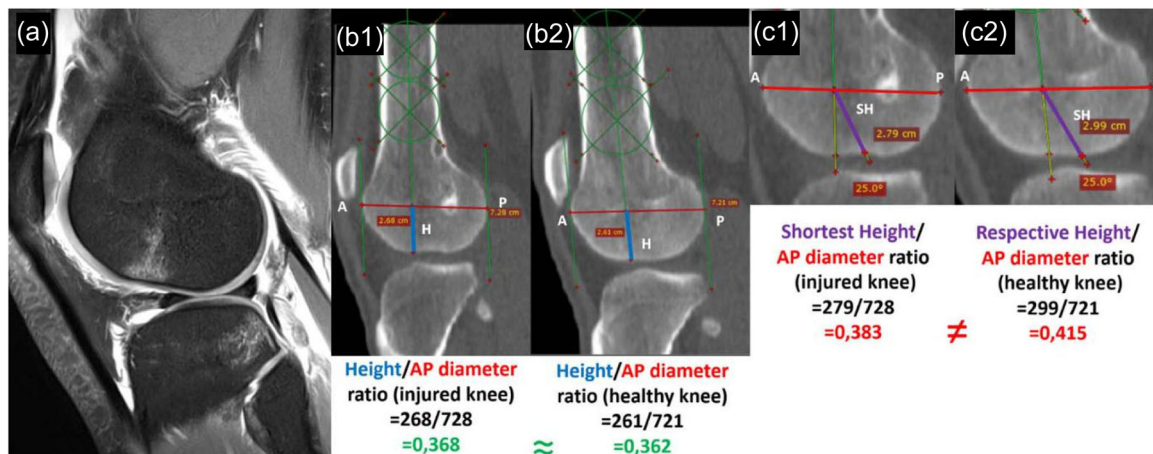


FIGURE 5 Flattening of lateral femoral condyle (LFC) due to posterior elongation of terminal sulcus (TS) by LFC impaction fracture visible on magnetic resonance imaging (a) and computed tomography (b, c). (b1, c1) Anterior cruciate ligament (ACL)-injured knees; (b2, c2) healthy contralateral knees. (b) Posterior elongation of TS due to LFC-IF did not decrease the height to the anteroposterior diameter ratio (HAPR). (c) The modified HAPR, with shortest height of LFC instead of the regular height was much lower in the ACL-injured knee than the respective ratio in the healthy contralateral knee (0.383 vs. 0.415, respectively). A, anterior; AP, anteroposterior; H, height; P, posterior.

diminished outcomes of treatment, similarly as in other morphological risk factors [43]. While the risk/benefit ratio or cut-offs for reduction of an LFC-IF are not defined yet [17, 31, 38, 40], the three above-proposed mechanisms provide a theoretical framework for consideration of anterolateral complex procedures by the means of anterolateral ligament reconstruction or lateral extraarticular tenodesis in the cases of posterior elongation of TS due to LFC-IF. While due to the authors knowledge there is no study to confirm the effectiveness of LFC-IF as an indication for extra-articular procedure, many authors are using deep LFC-IF as an indication, mostly due to the mechanism of the injury [6, 14, 45].

While MRI is a gold standard in cartilage, meniscus, ligaments and soft tissue diagnostics, posterior elongation of the TS due to an LFC-IF may potentially be easily overlooked on routine MRI scans. The first proposed reason is that routine MRI scans are usually performed in slight knee flexion due to the post-traumatic haematoma, effusion, differences in MRI

procedure and different knee coil models. As the knee is flexed, the LM translates posteriorly, while the LFC rolls and rotates, with the more posterior parts of the LFC coming into contact with the tibia [37, 46]. On MRI performed in standard settings (slight knee flexion), the disturbance of the cartilaginous-meniscal congruence is potentially not obvious (Figure 6b), while on MRI performed in full knee extension, the disturbance of the cartilaginous-meniscal congruence can be clearly seen (Figure 6c). Therefore, in this study, the elongation of the TS was assessed with the femur-based Blumensaat line as reference point to eliminate the potential impact of knee flexion angle during MRI scans.

The second reason why posterior elongation of the TS due to an LFC-IF and subsequent cartilaginous-meniscal incongruence can be missed on routine MRI scan is that an LFC-IF is usually the deepest very near to the lateral border of the LFC. Therefore, on standard MRI with predefined orientation of sagittal slices, its visualization can be hampered. Using multiplanar

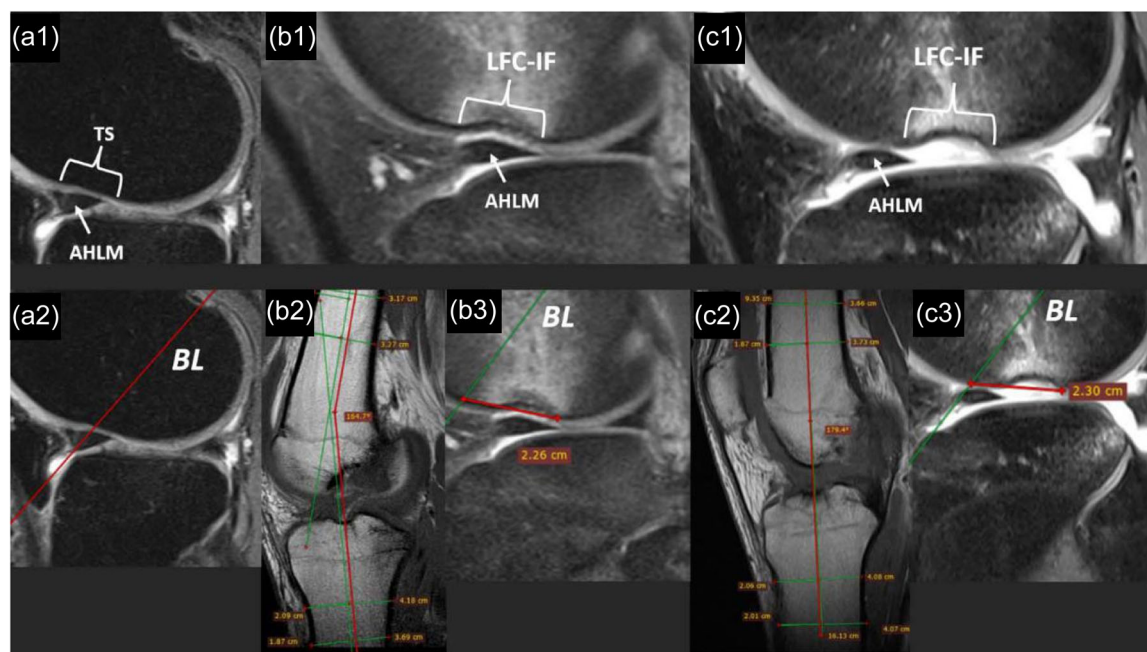


FIGURE 6 Impact of knee flexion on position of lateral femoral condyle impaction fracture (LFC-IF) relative to the anterior horn of lateral meniscus (AHLM). (a) Healthy knee magnetic resonance imaging (MRI). (b) MRI scan with about 15° of knee flexion; (c) MRI scan of the same patient with full knee extension. Notice that while the position of LFC-IF relative to the AHLM changed a lot, the distance from the intersection of copy-pasted Blumensaat line (BL) with subchondral bone to the posterior border of the TS/LFC-IF did not change.

reconstruction techniques for creation of sagittal slices more tangent to the lateral LFC border may potentially allow for better visualization, while Blumensaat line is an objective landmark, the distance to the posterior border of the TS/LFC-IF reached relatively low sensitivity/specificity in this study. Therefore, it probably may not serve as a secondary sign for ACL tear. The first limitation of this study is that there was a significantly higher proportion of male patients in the ACL tear group; however, those were consecutive patients presenting to the clinic. This is also similar to the study of Garth et al. [16], Berthold et al. [4] and Lodewijks et al. [29]. The second limitation was that it was impossible to blind the authors performing the measurements because drawing of the Blumensaat line required opening the sagittal scans with visible cruciate ligaments. However, the measurements were performed independently by two authors, each of whom assessed all variables twice, with a 2-month interval between the measurements to avoid recall bias, and high intrarater and inter-rater reliabilities were achieved. The third limitation is that we did not assess medial-lateral extension of the LFC-IF. It was due to the differences in the MRI protocols and orientation of planes between exams performed in different facilities. Usage of multiplanar reconstruction technique was trialed; however, the results as to the quality and repeatability of reconstruction were not satisfactory.

CONCLUSIONS

LFC-IF after full-thickness ACL tear significantly elongates the physiological TS in the posterior direction.

AUTHOR CONTRIBUTIONS

Konrad Malinowski: Conceptualization; methodology; resources; data curation; writing—review and editing; supervision; project administration. **Marcin Mostowy:** Conceptualization; methodology; formal analysis; investigation; data curation; writing—original draft preparation; visualization; project administration. **Kacper Ruzik:** Methodology; investigation; writing—original draft preparation. **Krzysztof Starszak:** Methodology; investigation; writing—original draft preparation. **Grzegorz Maciąg:** Formal analysis; data curation; visualization. **Paweł Skowronek:** Data Curation; writing—review and editing; supervision. **Michael T. Hirschmann:** Data Curation; writing—review and editing; supervision. **Przemysław A. Pękala:** Conceptualization; methodology; writing—review and editing; supervision. **Robert F. LaPrade:** Conceptualization, methodology, writing—review and editing, supervision. **Dong Woon Kim:** Formal analysis; data curation; writing—review and editing; visualization.

ACKNOWLEDGEMENTS

The authors have no funding to report.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data of this study are available upon request.

ETHICS STATEMENT

The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the district medical chamber (No. K.B.–12/2020). Individual consent for this MRI diagnostic analysis was waived by the district medical chamber. No individual data of participants were included.

ORCID

Konrad Malinowski  <http://orcid.org/0000-0001-7573-7937>

Marcin Mostowy  <http://orcid.org/0000-0002-8301-164X>

REFERENCES

- Behzadi, C., Welsch, G.H., Petersen, J.P., Schoennagel, B.P., Bannas, P., Kaul, M.G. et al. (2018) T2 relaxation times of the anterolateral femoral cartilage in patients after ACL-reconstruction with and without a deep lateral femoral notch sign. *European Journal of Radiology*, 106(July), 85–91. Available from: <https://doi.org/10.1016/j.ejrad.2018.07.007>
- Bernholt, D.L., DePhillipo, N.N., Crawford, M.D., Aman, Z.S., Grantham, W.J. & LaPrade, R.F. (2020) Incidence of displaced posterolateral tibial plateau and lateral femoral condyle impaction fractures in the setting of primary anterior cruciate ligament tear. *The American Journal of Sports Medicine*, 48(3), 545–553. Available from: <https://doi.org/10.1177/0363546519895239>
- Bernholt, D.L., Dornan, G.J., Dephillipo, N.N., Aman, Z.S., Kennedy, M.I. & LaPrade, R.F. (2020) High-grade posterolateral tibial plateau impaction fractures in the setting of a primary anterior cruciate ligament tear are correlated with an increased preoperative pivot shift and inferior postoperative outcomes after anterior cruciate ligament reconst. *The American Journal of Sports Medicine*, 48(9), 2185–2194. Available from: <https://doi.org/10.1177/0363546520932912>
- Berthold, D.P., Muench, L.N., Herbst, E., Mayr, F., Chadayammuri, V., Imhoff, A.B. et al. (2021) High prevalence of a deep lateral femoral notch sign in patients with anterior cruciate ligament (ACL) and concomitant posterior root tears of the lateral meniscus. *Knee Surgery, Sports Traumatology, Arthroscopy*, 29(0123456789), 1018–1024. Available from: <https://doi.org/10.1007/s00167-020-06071-9>
- Boden, S.A., Charles, S., Hughes, J.D., Miller, L., Rodosky, M., Popchak, A. et al. (2023) Recurrent instability after arthroscopic bankart repair in patients with hyperlaxity and near-track lesions. *Orthopaedic Journal of Sports Medicine*, 11(9), 1–9. Available from: <https://doi.org/10.1177/23259671231200231>
- Boksh, K., Sheikh, N., Chong, H.H., Ghosh, A. & Aujla, R. (2023) The role of anterolateral ligament reconstruction or lateral extra-articular tenodesis for revision anterior cruciate ligament reconstruction: a systematic review and meta-analysis of comparative clinical studies. *American Journal of Sports Medicine*, 52(1), 269–285. Available from: <https://doi.org/10.1177/03635465231157377>
- Cerciello, S., Ollivier, M., Kocaoglu, B., Khakha, R. & Seil, R. (2022) ACL surgical trends evolve in the last five years for young European surgeons: results of the survey among the U45 ESSKA members. *Knee Surgery, Sports Traumatology, Arthroscopy*, 31, 1–7. Available from: <https://doi.org/10.1007/s00167-022-07005-3>
- Cevallos, M. & Egger, M. (2014) STROBE (STrengthening the reporting of OBservational studies in epidemiology). In: Moher, D., Altman, D.G., Schulz, K.F., Simera, I., Wager, E. (Eds.) *Guidelines for reporting health research: a user's Manual*. 1st edition, Bern: John Wiley & Sons, Ltd. pp. 169–179.
- Ciszkowska-Lysoń, B., Dominik, B., Zdanowicz, U. & Śmigielski, R. (2018) Proposing an MRI-Based classification system allowing proper assessment of the damage to the posteriori edge of the tibia. (Poster). Vienna, Austria: European Congress of Radiology. Available from: <https://doi.org/10.1594/ecr2018/C-3210>
- Costa-Paz, M., Muscolo, D.L., Ayerza, M., Makino, A. & Aponte-Tinao, L. (2001) Magnetic resonance imaging follow-up study of bone bruises associated with anterior cruciate ligament ruptures. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 17(5), 445–449. Available from: <https://doi.org/10.1053/jars.2001.23581>
- Dadoo, S., Ozbek, E.A., Nukuto, K., Runer, A., Keeling, L.E., Grandberg, C. et al. (2023) What it takes to have a high-grade pivot shift—focus on bony morphology. *Knee Surgery, Sports Traumatology, Arthroscopy*, 31, 4080–4089. Available from: <https://doi.org/10.1007/s00167-023-07472-2>
- Dimitriou, D., Reimond, M., Foessel, A., Baumgaertner, B., Zou, D., Tsai, T.Y. et al. (2020) The deep lateral femoral notch sign: a reliable diagnostic tool in identifying a concomitant anterior cruciate and anterolateral ligament injury. *Knee Surgery, Sports Traumatology, Arthroscopy*, 29(6), 1968–1976. Available from: <https://doi.org/10.1007/s00167-020-06278-w>
- Faul, F., Erdfelder, E., Buchner, A. & Lang, A.G. (2009) Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. *Behavior Research Methods*, 41(4), 1149–1160. Available from: <https://doi.org/10.3758/BRM.41.4.1149>
- Firth, A.D., Bryant, D.M., Litchfield, R., McCormack, R.G., Heard, M., MacDonald, P.B. et al. (2022) Predictors of graft failure in young active patients undergoing hamstring autograft anterior cruciate ligament reconstruction with or without a lateral extra-articular tenodesis: the stability experience. *The American Journal of Sports Medicine*, 50(2), 384–395. Available from: <https://doi.org/10.1177/03635465211061150>
- Flury, A., Hodel, S., Andronic, O., Kaiser, D., Fritz, B., Imhoff, F.B. et al. (2023) Extent of posterolateral tibial plateau impaction fracture correlates with anterolateral complex injury and has an impact on functional outcome after ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, 31(6), 2266–2273. Available from: <https://doi.org/10.1007/s00167-022-07282-y>
- Garth, W.P., Greco, J. & House, M.A. (2000) The lateral notch sign associated with acute anterior cruciate ligament disruption. *The American Journal of Sports Medicine*, 28(1), 68–73. Available from: <https://doi.org/10.1177/03635465000280012301>
- Garth, W.P. & Wilson, T. (2001) Open reduction of a lateral femoral notch associated with an acute anterior cruciate ligament tear. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 17(8), 874–877. Available from: [https://doi.org/10.1016/S0749-8063\(01\)90012-X](https://doi.org/10.1016/S0749-8063(01)90012-X)
- Grassi, A., Macchiarola, L., Urrizola Barrientos, F., Zicaro, J.P., Costa Paz, M., Adravanti, P. et al. (2019) Steep posterior tibial slope, anterior tibial subluxation, deep posterior lateral femoral condyle, and meniscal deficiency are common findings in multiple anterior cruciate ligament failures: an MRI case-control study. *The American Journal of Sports Medicine*, 47(2), 285–295. Available from: <https://doi.org/10.1177/0363546518823544>
- Grimberg, A., Shirazian, H., Torshizy, H., Smitaman, E., Chang, E.Y. & Resnick, D.L. (2014) Deep lateral notch sign and

- double notch sign in complete tears of the anterior cruciate ligament: MR imaging evaluation. *Skeletal Radiology*, 44(3), 385–391. Available from: <https://doi.org/10.1007/s00256-014-2056-6>
20. He, M. & Li, J. (2022) Increased lateral femoral condyle ratio measured by MRI is associated with higher risk of noncontact anterior cruciate ligament injury. *BMC Musculoskeletal Disorders*, 23(1), 190. Available from: <https://doi.org/10.1186/s12891-022-05134-x>
 21. Herbst, E., Hoser, C., Tecklenburg, K., Filipovic, M., Dallapozza, C., Herbolt, M. et al. (2015) The lateral femoral notch sign following ACL injury: frequency, morphology and relation to meniscal injury and sports activity. *Knee Surgery, Sports Traumatology, Arthroscopy*, 23(8), 2250–2258. Available from: <https://doi.org/10.1007/s00167-014-3022-5>
 22. Hoffelner, T., Pichler, I., Moroder, P., Osti, M., Hudelmaier, M., Wirth, W. et al. (2015) Segmentation of the lateral femoral notch sign with MRI using a new measurement technique. *BMC Musculoskeletal Disorders*, 16(1), 217. Available from: <https://doi.org/10.1186/s12891-015-0677-0>
 23. Kamada, K., Matsushita, T., Nagai, K., Hoshino, Y., Araki, D., Kanzaki, N. et al. (2023) Risk factors of residual pivot-shift after anatomic double-bundle anterior cruciate ligament reconstruction. *Archives of Orthopaedic and Trauma Surgery*, 143(2), 977–985. Available from: <https://doi.org/10.1007/s00402-022-04428-y>
 24. Kanakamedala, A.C., Burnham, J.M., Pfeiffer, T.R., Herbst, E., Kowalczyk, M., Popchak, A. et al. (2018) Lateral femoral notch depth is not associated with increased rotatory instability in ACL-injured knees: a quantitative pivot shift analysis. *Knee Surgery, Sports Traumatology, Arthroscopy*, 26(5), 1399–1405. Available from: <https://doi.org/10.1007/s00167-017-4770-9>
 25. Leite, C.B.G., Merkely, G., Farina, E.M., Smith, R., Görtz, S., Hazzard, S. et al. (2023) Effect of tibiofemoral rotation angle on graft failure after anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine*, 51(9), 2291–2299. Available from: <https://doi.org/10.1177/03635465231163856>
 26. Li, R., Yuan, X., Fang, Z., Liu, Y., Chen, X. & Zhang, J. (2020) A decreased ratio of height of lateral femoral condyle to anteroposterior diameter is a risk factor for anterior cruciate ligament rupture. *BMC Musculoskeletal Disorders*, 21(1), 1–6. Available from: <https://doi.org/10.1186/s12891-020-03440-w>
 27. Lindanger, L., Strand, T., Mølster, A.O., Solheim, E. & Inderhaug, E. (2021) Effect of early residual laxity after anterior cruciate ligament reconstruction on long-term laxity, graft failure, return to sports, and subjective outcome at 25 years. *The American Journal of Sports Medicine*, 49(5), 1227–1235. Available from: <https://doi.org/10.1177/0363546521990801>
 28. Liu, F., Zhang, S., Xiao, Y., Feng, X., Liang, Z., Leung, F. et al. (2022) Stenotic intercondylar notch is not a risk factor for posterior cruciate ligament rupture: a morphological analyses using magnetic resonance imaging. *Knee Surgery, Sports Traumatology, Arthroscopy*, 30(5), 1711–1717. Available from: <https://doi.org/10.1007/s00167-021-06724-3>
 29. Lodewijks, P.C.A.M., Delawi, D., Bollen, T.L., Dijkhuis, G.R., Wolterbeek, N. & Zijl, J.A.C. (2019) The lateral femoral notch sign: a reliable diagnostic measurement in acute anterior cruciate ligament injury. *Knee Surgery, Sports Traumatology, Arthroscopy*, 27(2), 659–664. Available from: <https://doi.org/10.1007/s00167-018-5214-x>
 30. Lucidi, G.A., Grassi, A., Di Paolo, S., Agostinone, P., Neri, M.P., Macchiarola, L. et al. (2021) The lateral femoral notch sign is correlated with increased rotatory laxity after anterior cruciate ligament injury: pivot shift quantification with a surgical navigation system. *The American Journal of Sports Medicine*, 49(3), 649–655. Available from: <https://doi.org/10.1177/0363546520982002>
 31. Malinowski, K., Mostowy, M., Góralczyk, A., LaPrade, R.F. & Hermanowicz, K. (2020) Technique for treatment of subchondral compression fracture of the lateral femoral condyle associated with ACL tear. *Arthroscopy Techniques*, 9(6), e823–e828. Available from: <https://doi.org/10.1016/j.eats.2020.02.016>
 32. Milinkovic, D.D., Kittl, C., Herbst, E., Fink, C., Greis, F., Raschke, M.J. et al. (2023) The “Bankart knee”: high-grade impression fractures of the posterolateral tibial plateau lead to increased translational and anterolateral rotational instability of the ACL-deficient knee. *Knee Surgery, Sports Traumatology, Arthroscopy*, 31(10), 4151–4161. Available from: <https://doi.org/10.1007/s00167-023-07432-w>
 33. Minami, T., Muneta, T., Sekiya, I., Watanabe, T., Mochizuki, T., Horie, M. et al. (2018) Lateral meniscus posterior root tear contributes to anterolateral rotational instability and meniscus extrusion in anterior cruciate ligament-injured patients. *Knee Surgery, Sports Traumatology, Arthroscopy*, 26(4), 1174–1181. Available from: <https://doi.org/10.1007/s00167-017-4569-8>
 34. Mostowy, M., Ruzik, K., Ebisz, M., Laprade, R.F. & Malinowski, K. (2023) Impaction fractures of the lateral femoral condyle related to anterior cruciate ligament injury: a scoping review concerning diagnosis, prevalence, clinical importance, and management. *Clinics in Orthopaedic Surgery*, 15, 781. Available from: <https://doi.org/10.4055/cios22278>
 35. Pfeiffer, T.R., Burnham, J.M., Kanakamedala, A.C., Hughes, J.D., Zlotnicki, J., Popchak, A. et al. (2019) Distal femur morphology affects rotatory knee instability in patients with anterior cruciate ligament ruptures. *Knee Surgery, Sports Traumatology, Arthroscopy*, 27(5), 1514–1519. Available from: <https://doi.org/10.1007/s00167-018-5269-8>
 36. Pinheiro, V.H., Borque, K.A., Laughlin, M.S., Jones, M., Balendra, G., Kent, M.R. et al. (2023) Determinants of performance in professional soccer players at 2 and 5 years after ACL reconstruction. *The American Journal of Sports Medicine*, 51(14), 3649–3657. Available from: <https://doi.org/10.1177/03635465231207832>
 37. Pinskerova, V., Samuelson, K.M., Stammers, J., Maruthinar, K., Sosna, A. & Freeman, M.A.R. (2009) The knee in full flexion: an anatomical study. *The Journal of Bone and Joint Surgery. British Volume*, 91(6), 830–834. Available from: <https://doi.org/10.1302/0301-620X.91B6.22319>
 38. Sadlo, P.A. & Nebelung, W. (2006) Arthroscopically assisted reduction of a lateral femoral notch in acute tear of the anterior cruciate ligament. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 22(5), 574.e1–574.e3. Available from: <https://doi.org/10.1016/j.arthro.2005.11.006>
 39. Speer, K.P., Spritzer, C.E., Bassett, F.H., Feagin, J.A. & Garrett, W.E. (1992) Osseous injury associated with acute tears of the anterior cruciate ligament. *The American Journal of Sports Medicine*, 20(4), 382–389. Available from: <https://doi.org/10.1177/036354659202000403>
 40. Tauber, M., Fox, M., Koller, H., Klampfer, H. & Resch, H. (2008) Arthroscopic treatment of a large lateral femoral notch in acute anterior cruciate ligament tear. *Archives of Orthopaedic and Trauma Surgery*, 128(11), 1313–1316. Available from: <https://doi.org/10.1007/s00402-007-0535-0>
 41. Terwee, C.B., Bot, S.D.M., de Boer, M.R., van der Windt, D.A.W.M., Knol, D.L., Dekker, J. et al. (2007) Quality criteria were proposed for measurement properties of health status questionnaires. *Journal of Clinical Epidemiology*, 60(1), 34–42. Available from: <https://doi.org/10.1016/j.jclinepi.2006.03.012>
 42. Viera, A.J. & Garrett, J.M. (2005) Understanding interobserver agreement: the kappa statistic. *Family Medicine*, 37(5), 360–363. Available from: <https://pubmed.ncbi.nlm.nih.gov/15883903/>

43. Weiler, A., Berndt, R., Wagner, M., Scheffler, S., Schatka, I. & Gwinner, C. (2023) Tibial slope on conventional lateral radiographs in anterior cruciate ligament-injured and intact knees: mean value and outliers. *The American Journal of Sports Medicine*, 51(9), 2285–2290. Available from: <https://doi.org/10.1177/03635465231178292>
44. Wierer, G., Simetinger, T., Hudelmaier, M., Moroder, P. & Hoffelner, T. (2020) Fate of the lateral femoral notch following early anterior cruciate ligament reconstruction. *The Knee*, 27(2), 414–419. Available from: <https://doi.org/10.1016/j.knee.2020.01.009>
45. Willinger, L., Athwal, K.K., Holthof, S., Imhoff, A.B., Williams, A. & Amis, A.A. (2023) Role of the anterior cruciate ligament, anterolateral complex, and lateral meniscus posterior root in anterolateral rotatory knee instability: a biomechanical study. *The American Journal of Sports Medicine*, 51(5), 1136–1145. Available from: <https://doi.org/10.1177/03635465231161071>
46. Yao, J., Lancianese, S.L., Hovinga, K.R., Lee, J. & Lerner, A.L. (2008) Magnetic resonance image analysis of meniscal translation and tibio-menisco-femoral contact in deep knee flexion. *Journal of Orthopaedic Research*, 26(5), 673–684. Available from: <https://doi.org/10.1002/jor.20553>
47. Ye, Z., Zhang, T., Wu, C., Qiao, Y., Su, W., Chen, J., et al. (2022) Predicting the objective and subjective clinical outcomes of anterior cruciate ligament reconstruction: a machine learning analysis of 432 patients. *The American Journal of Sports Medicine*, 50(14), 3786–3795. Available from: <https://doi.org/10.1177/03635465221129870>

How to cite this article: Malinowski, K., Mostowy, M., Ruzik, K., Starszak, K., Maciąg, G., Skowronek, P. et al. (2024) Lateral femoral impaction fractures during an ACL tear extend posteriorly on the weight-bearing area of the tibiofemoral joint. *Knee Surgery, Sports Traumatology, Arthroscopy*, 1–11. <https://doi.org/10.1002/ksa.12438>