Received: 7 April 2021 | Revised: 22 July 2021 | Accepted: 30 July 2021
DOI: 10.1002/ca.23773

REVIEW

CLINICAL ANATOMY WILEY

The intercondylar fossa—A narrative review

Lena Hirtler[1] | Franz Kainberger[2] | Sebastian Röhrich[2]

[1]Division of Anatomy, Center for Anatomy and Cell Biology, Medical University of Vienna, Vienna, Austria

[2]Department of Radiology and Image Guided Therapy, Medical University of Vienna, Vienna, Austria

Correspondence
Lena Hirtler, Division of Anatomy, Center for Anatomy and Cell Biology, Medical University of Vienna, Währinger Straße 13, 1090 Vienna, Austria.
Email: lena.hirtler@meduniwien.ac.at

Abstract

The intercondylar fossa ("intercondylar notch," IN) is a groove at the distal end of the femur, housing important stabilizing structures: cruciate ligaments and meniscofemoral ligaments. As the risk for injury to these structures correlates with changes to the IN, exact knowledge of its morphology, possible physiological and pathological changes and different approaches for evaluating it are important. The divergent ways of assessing the IN and the corresponding measurement methods have led to various descriptions of its possible shapes. Ridges at the medial and lateral wall are considered clinically important because they can help with orientation during arthroscopy, whereas ridges at the osteochondral border could affect the risk of ligament injury. Changes related to aging and sex differences have been documented, further emphasizing the importance of individual assessment of the knee joint. Overall, it is of the utmost importance to remember the interactions between the osseous housing and the structures within.

KEYWORDS
femur, intercondylar notch, variation

1 | INTRODUCTION

The intercondylar fossa ("intercondylar notch," IN), the region between the two femoral condyles, houses major stabilizing structures of the knee joint: the anterior (ACL) and posterior (PCL) cruciate ligaments, the anterior (aMFL) and posterior (pMFL) meniscofemoral ligaments, and pericruciate fat. Because of the intimate relationship between the included ligamentous structures and the osseous structures surrounding them, the term "intercondylar space" was defined to reflect the influences of all these structures on each other (Hirtler et al., 2016).

Several decades ago, the association between the shape and width of the IN and cruciate ligament injury or degeneration was shown to be clinically relevant (Al-Saeed et al., 2013; Anderson et al., 1987; Lund-Hanssen et al., 1994; Palmer, 2007). Additionally, the size of the notch width (NW) correlates with the occurrence of isolated tears in the menisci (Li et al., 2021). Early analysis of these correlations mostly involved measuring various morphological features of the IN on radiographs (Anderson et al., 2001; Herzog et al., 1994; Houseworth et al., 1987; Lund-Hanssen et al., 1994; Schickendantz & Weiker, 1993; Shelbourne et al., 1998; Souryal et al., 1988; Souryal & Freeman, 1993), but no conclusion was drawn. Risk factors for ACL rupture range from the size of the posterior arch of the IN (Houseworth et al., 1987; Kieffer et al., 1984) to its anterior outlet (Lund-Hanssen et al., 1994). Third parties even questioned this correlation (Herzog et al., 1994; Lombardo et al., 2005).

It was Souryal and Freeman (1993) and Souryal et al. (1988) who introduced the notch width index (NWI), the ratio of the notch width (NW) to the bicondylar width (BCW), as a new tool for risk assessment, a standardized method for comparison between sexes, and a way of minimizing bias due to interindividual size differences among patients and the magnification in radiographs (Kocher et al., 2004; LaPrade & Burnett, 1994; Souryal et al., 1988; Souryal & Freeman, 1993). However, this method is still not entirely reliable; the NWI is not standardized in relation to patient body height (Herzog et al., 1994; Lombardo et al., 2005; Schickendantz & Weiker, 1993; Shelbourne et al., 1998).

A summary of the widespread literature about the IN, with the multitude of conflicting arguments about risk assessment for ligament injury, would help to clarify its clinical relevance. Therefore, this review will summarize the major points about the anatomy of the IN, its aging and sex differences, how these affect the risk for injuries and pathological conditions of the knee, and methods for evaluating it.

2 | ANATOMY OF THE IN

Looking at the morphology of the IN (Figure 1A,B) and the corresponding literature, two topics dominate discussions, both with special focus on the ACL. First, there is the morphology of the IN and its influence on the development of ACL injury. Second, there are the ridges in the osseous walls of the notch, which are quite important for orientation during arthroscopy for ACL reconstruction.

2.1 | Shape of the IN

The literature defines its shape in several ways. Ireland et al. (2001) differentiated an A-shaped from a non-A-shaped notch: the former had a significantly larger notch base and a narrowed roof, whereas the latter was rounded, resembling an inverted horseshoe. No correlation with injury status was shown (Ireland et al., 2001; van Eck, Martins, Vyas, et al., 2010). Anderson et al. (1987) differentiated two extreme shapes of the IN: round (inverted U), and steep A-shaped or cresting wave-shaped notches (Figure 2A–E) (Anderson et al., 1987; Keays et al., 2016; Wada et al., 1999). Three additional shapes completed the description of the continuum between those two basic types, bringing the total number of shapes described by Anderson et al to five (Anderson et al., 1987). Tanzer and Lenczner (1990) differentiated among wide, square- and wave-shaped and between stenotic and non-stenotic notches. Van Eck, Martins, Lorenz, et al. (2010), van Eck, Martins, Vyas, et al. (2010), van Eck, Morse, Lesniak, et al. (2010), van Eck, Schreiber, Liu, and Fu (2010), and van Eck, Schreiber, Mejia, et al. (2010) distinguished an A-shaped notch with a narrow apex, a U-shaped notch with a wide apex, and a W-shaped notch that was rather a U-shaped with two apices rather than one (Figure 3A–C). The A-shaped notch was described as stenotic and therefore as a risk factor for ACL injury (Al-Saeed et al., 2013; Fahim et al., 2021; van Eck, Martins, Vyas, et al., 2010). More recently, Hirtler et al. (2016) introduced an age-related classification into A-shaped, Inverse-U and Ω-shaped (Figure 4A–C). As yet there is no clear consensus as to whether to use a shape classification for evaluating patients with knee joint pathologies, and if so, which shape classification to use. Further evaluations concerning the clinical applicability and reliability of such classifications would be warranted.

A changing shape of the IN does not always constitute a risk factor for ACL injury (Anderson et al., 1987; Tanzer & Lenczner, 1990; Tillman et al., 2002); it can also appear as a sign of aging and as an indicator of the development of osteoarthritis (OA) (Hirtler et al., 2016; Shepstone et al., 2001). This makes the evaluation of IN shape even more important for differentiating physiological and pathological conditions. In this differentiation, it is important to focus especially on the osteochondral border, where most of the changes in the IN take place (Hirtler et al., 2016). Here, so-called "ridges" were described by Everhart et al. (2014, 2012), most distinctively an anteromedial ridge, the thickness of which increases with age (Figure 5). This leads to narrowing of the anterior outlet of the IN (Everhart et al., 2012) and significantly increases the strain on the ACL (Durselen et al., 1995; Fleming et al., 2001; Krosshaug et al., 2007; Markolf et al., 1995; Nagano et al., 2007; Oh et al., 2011; Quatman et al., 2011; Shin et al., 2011), rendering it a likely risk factor for the development of ACL injury. Fung et al. (2007) described a similar ridge at the anterolateral osteochondral border of the IN, with the possible consequence of impingement on the ACL. These ridges can be identified in elderly persons as the previously-described Ω-shape (Hirtler et al., 2016).

The reason why this anteromedial ridge develops is not yet clear. It could be due to normal human variation or to biomechanical loading (Everhart et al., 2012). Also, it must be differentiated from osteophytes, which is possible histologically because its dense smooth cortical bone contrasts with the irregular and overhanging morphology of osteophytes (Everhart et al., 2014). However, especially when the IN morphology is examined by imaging techniques alone, it is difficult to distinguish between a "normal" ridge at the osteochondral

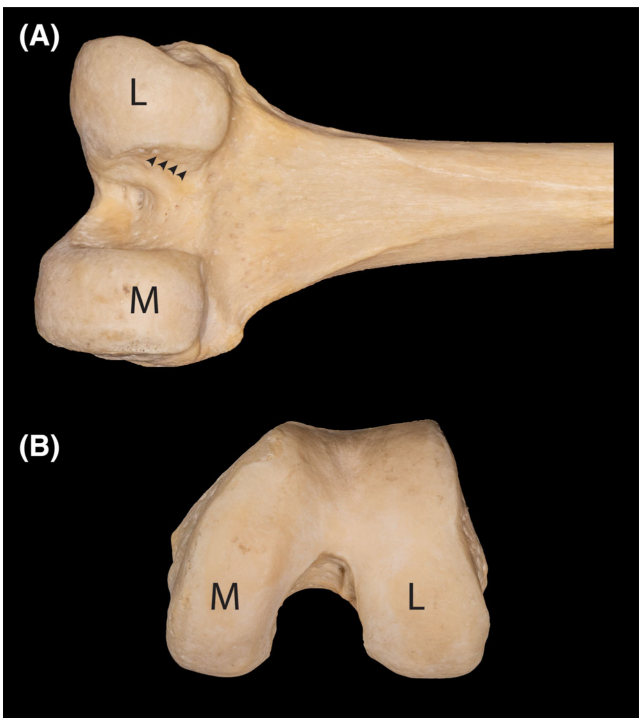

FIGURE 1 Skeletal morphology of the intercondylar fossa. (A) View of the distal femur from posterior, (B) view of the intercondylar fossa from distal. L, lateral femoral condyle; M, medial femoral condyle, arrowheads, lateral intercondylar ridge

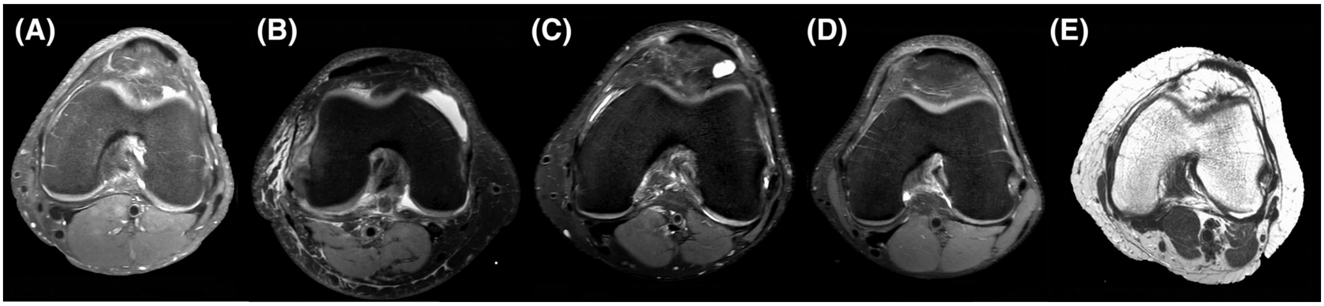

FIGURE 2 Shape types as described by Anderson et al. (1987). (A) Type 1—U-shape in the left knee of a 29-year-old male patient (3T, axial ePD SAIR), (B) Type 2 in the left knee of a 45-year-old male patient (3T, axial PD SPAIR), (C) Type 3 in the left knee of a 30-year-old male patient (3T, axial ePD SAIR), (D) Type 4 in the left knee of a 28-year-old male patient (3T, axial PD SPAIR), (E) Type 5—cresting wave-shape in the left knee of a 40-year-old female patient (3T, axial T2w TSE)

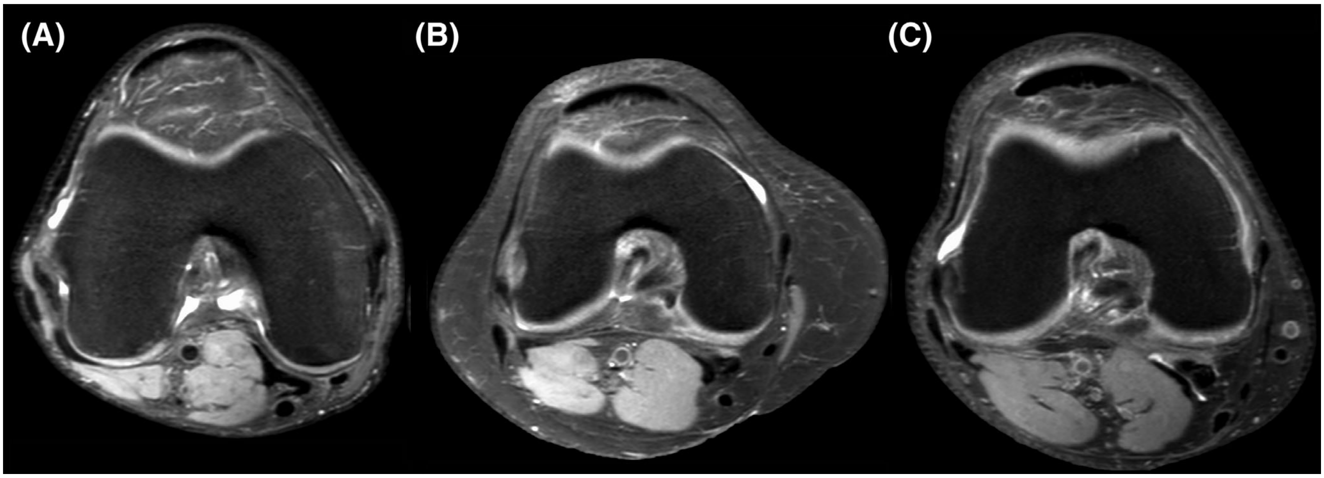

FIGURE 3 Shape types as described by van Eck, Martins, Vyas, et al. (2010). (A) A-shape in the right knee of a 26-year-old male patient (3T, axial PD SPAIR), (B) U-shape in the right knee of a 22-year-old female patient (3T, axial PD SPAIR), (C) W-shape in the right knee of a 55-year-old male patient (3T, axial PD SPAIR)

FIGURE 4 Shape types described by Hirtler et al. (2016). (A) A-shape in the right knee of a 15-year-old female patient (3T, coronal PD SPAIR), (B) Inverse-U-shape in the left knee of a 20-year-old male patient (3T, coronal PD SPAIR), (C) Ω-shape in the right knee of a 66-year-old male patient (3T, coronal PD SPAIR)

border and an osteophyte. Only histological examination can make this discrimination reliably, and ridge and osteophyte have approximately the same location.

The anteromedial and anterolateral ridges, as osseous formations at the osteochondral border directly influencing the shape of the IN, have to be differentiated from the ridges located at the insertions of

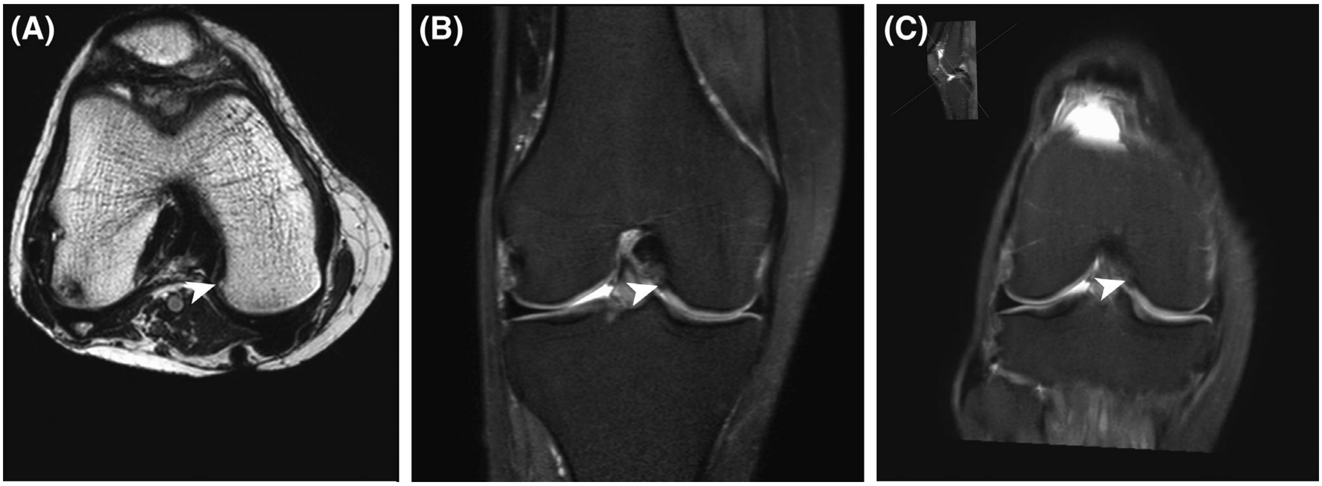

FIGURE 5 Anteromedial ridge (arrowhead) as described by Everhart et al. (2010, 2012) in the right knee of a 29-year-old female patient. (A) 3T, axial T2w TSE, (B) 3T, coronal PD SPAIR, (C) 3T, oblique coronal PD SPAIR with localizer

the cruciate ligaments and used as landmarks for tunnel placement in ligament reconstruction.

2.2 | Ridges as landmarks

The detailed morphology of the femoral condyles, the walls of which constitute the sites of origin of the cruciate ligaments, is especially important for reconstruction and for orientation before and during arthroscopic surgery.

On the medial wall of the lateral condyle, the lateral intercondylar ridge (LIR, Figure 1A) is referred to as the anterior border of the ACL in knee flexion. This ridge is also called "resident's ridge" because inexperienced surgeons can mistake it for the posterior edge of the lateral femoral condyle, leading to incorrect anterior tunnel placement and in consequence to premature failures of ACL reconstruction (Bicer et al., 2010; Ferretti et al., 2007; Hutchinson & Ash, 2003; Petersen & Zantop, 2007; Sasaki et al., 2012; Shino et al., 2010; Zauleck et al., 2014; Ziegler et al., 2011). The lateral bifurcate ridge (LBR) subdivides the footprint of the ACL into its two bundles (Forsythe et al., 2010; Fu & Jordan, 2007; Kopf et al., 2009; van Eck, Morse, Lesniak, et al., 2010; van Eck, Schreiber, Liu, & Fu, 2010; van Eck, Schreiber, Mejia, et al., 2010; Zauleck et al., 2014; Ziegler et al., 2011). Finally, the lateral posterior intercondylar ridge acts as the posterior border of the ACL insertion (Nawabi et al., 2016; Sasaki et al., 2012).

The lateral wall of the medial condyle shows a medial intercondylar ridge (Lopes et al., 2008; Raphael et al., 2011). This is the posterior border of the attachment of the PCL in knee flexion, its anterior border being the osteochondral junction. Here, a medial bifurcate ridge subdivides the attachments of the two bundles of the ligament (Lopes et al., 2008).

3 | EVALUATION OF THE IN

Depending on imaging modalities and specific investigational interests, there are several methods for evaluating the IN. The following paragraphs survey the influence of imaging modalities on the results of measurements, the different measurement parameters, and their reliability in comparison with direct measurements obtained from studies of anatomical specimens or during arthroscopy.

3.1 | Imaging modalities

In plain radiography, the knee is positioned in a tunnel view position (Holmblad 70°, Rosenberg view at 45° knee flexion, at 30° knee flexion, at 20° knee flexion, >80° knee flexion) to reveal the lateral and medial condyles without superposition of other structures and for reliable evaluation of the IN (Ballinger et al., 2003; Boegard et al., 1997; Hernigou & Garabedian, 2002; Herzog et al., 1994; Holmblad, 1937; Keays et al., 2016; LaPrade & Burnett, 1994; Lombardo et al., 2005; Lund-Hanssen et al., 1994; Palmer, 2007; Rosenberg et al., 1988; Schickendantz & Weiker, 1993; Shelbourne et al., 1997; Shelbourne et al., 1998; Shelbourne et al., 2007; Souryal et al., 1988; Souryal & Freeman, 1993; van Kuijk et al., 2021; Vaswani et al., 2020). Nowadays, CT or MRI are most often used for evaluating the IN (Al-Saeed et al., 2013; Anderson et al., 2001; Chen et al., 2016; Davis et al., 1999; Dienst et al., 2007; Domzalski et al., 2010, 2015; Fujii et al., 2015; Hernigou & Garabedian, 2002; Herzog et al., 1994; Hoteya et al., 2011; Sonnery-Cottet et al., 2011; Staubli et al., 1999; Stein et al., 2010; Swami et al., 2013; van Eck, Martins, Lorenz, et al., 2010; Vrooijink et al., 2011; Whitney et al., 2014). These modalities make it possible to reformat the image orientation for better evaluation of the structures and to allow 3D reconstruction. MRI has been used most often in recent IN evaluations, although this is not the technique of choice for examining bones; and these images are in any case available because of the patient's indications, so no additional radiation exposure is required.

3.2 | Measurements performed for IN evaluation

In radiographs, a line is drawn tangential to the femoral condyles. Parallel to it, the line for measuring the widths of the IN is positioned according to the investigator's choice (Table 1). Two notch widths (NW) can be measured in radiographs: the anterior NW and the posterior NW (Lund-Hanssen et al., 1994).

In MRI and CT, most measurements previously obtained from radiographs were adapted for this sectional imaging method, although here too, in addition of choosing either a coronal or an axial oriented slice, the exact positioning of the line of measurement depends on the investigator's choice (Table 1). The baseline as a tangential line to the femoral condyles is the same as in radiography, irrespective of the orientation of the slice.

In axial images, the image chosen for IN measurements shows the beginning of the roof of the IN in relation to the anterior end of Blumensaat's line (Anderson et al., 2001; Chen et al., 2016; Stein et al., 2010), the best view of the outline of the entire notch entrance (Vaswani et al., 2019, 2020), or the level of the groove for the popliteus tendon, as in coronal image measurements (Al-Saeed et al., 2013).

In coronal images, the image chosen for IN measurements shows the decussation of the cruciate ligaments, which is most often at the midsubstance of the ACL (Chen et al., 2016; Davis et al., 1999; Domzalski et al., 2010; Swami et al., 2013). The ligaments are said to be at their narrowest here, so they are most vulnerable to rupture at this location (Davis et al., 1999).

Specially reconstructed images are used for measurements at level of the groove for the popliteus tendon (Dienst et al., 2007; Staubli et al., 1999). Also, coronal oblique reconstructions parallel to the anterior border of the ACL and axial oblique reconstructions transverse to the ACL have been described (Whitney et al., 2014).

Recently, Hirtler et al. (2016) showed the importance of the correct choice of measuring level for evaluating the IN. Osseous changes were significantly more frequent at the level of the joint line than at the level of the groove of the popliteal tendon. In particular, Everhart et al. reported that there are ridges at the osteochondral border of the condyles and correlated them positively with the incidence of ACL injury (Everhart et al., 2014). Therefore, the width of the IN at the level of the joint line should be monitored most closely when risk factors for ACL injury are assessed.

Apart from measurements by different imaging techniques, direct measurements in anatomical specimens or during arthroscopy are described (Table 1).

Besides NW measurements, there are several other descriptions of morphometrical parameters including the notch height, the IN angle, the lateral wall angle, the widths of the femoral condyles, the medial to lateral condyle size ratio, the area of the notch, the cross-sectional area of the IN, the width of the cruciate ligaments, the width of the fat between the cruciate ligaments, the volume of the IN, the ridge at the outlet of the IN, notch depth and notch depth index, the width of the notch entrance, the ACL insertion site, etc. (Anderson et al., 2001; Charlton et al., 2002; Davis et al., 1999; Domzalski et al., 2015; Fujii et al., 2015; Hernigou & Garabedian, 2002; Herzog et al., 1994; Jha & Pandit, 2021; Stijak, Radonjic, et al., 2009; Swami et al., 2013; van Eck et al., 2011; Vaswani et al., 2020; Vrooijink et al., 2011; Wada et al., 1999; Wang et al., 2021; Whitney et al., 2014; Wolters et al., 2011).

Using the widths of the IN and the distal femur (bicondylar width), the notch width index (NWI) can be calculated as the NW to bicondylar width ratio (Al-Saeed et al., 2013; Chen et al., 2016; Dienst et al., 2007; Domzalski et al., 2010; Herzog et al., 1994; Hoteya et al., 2011; Ireland et al., 2001; Lund-Hanssen et al., 1994; Sonnery-Cottet et al., 2011; Souryal & Freeman, 1993; Souryal et al., 1988; Stein et al., 2010; Swami et al., 2013; Vrooijink et al., 2011; Wada et al., 1999; Whitney et al., 2014). The NWI as an absolute parameter can be used for comparing between sexes as it is thought to be standardized for patient size (Charlton et al., 2002). However, the NW does not increase directly with height, in contrast to the bicondylar width, which could replace this parameter as a standardizing tool (Anderson et al., 2001; Shelbourne et al., 1998; Shelbourne & Kerr, 2001). Additionally, Lombardo et al. (2005) reported that the absolute size of the IN did not correlate with an increased risk for ACL injury, questioning the validity of the NWI as a predictor of such injury (Lombardo et al., 2005). Also, Whitney et al. (2014) pointed out that the use of index ratios did not strengthen any of the associations observed using unstandardized measurements. The NWI provides no information about the configuration of the notch (Souryal & Freeman, 1993) and does not correlate with notch volume (van Eck, Martins, Lorenz, et al., 2010).

4 | PHYSIOLOGICAL AND PATHOLOGICAL VARIABILITY OF THE IN

As the IN houses the major central stabilizing structures of the knee joint, changes to these osseous borders influence the health of those ligaments. These changes range from "physiological," that is, differences associated with sex and age, to "pathological," that is, alterations in notch stenosis and due to osteoarthritis.

4.1 | Influence of sex

Sex is a major influence on IN morphology, so it is a risk factor for ACL injury. Overall, women sustain ACL injuries 2–8 times more often than males (Arendt et al., 1999; Harmon & Ireland, 2000; Henry & Kaeding, 2001). One reason could be the up to 40%–50% smaller cross-sectional area and mass of the ACL, resulting in a higher stress load during movement in females (Chandrashekar et al., 2005;

TABLE 1 Summary of imaging modality and reported measurement location of the NW

Modality	Measurement of NW	References
Plain radiography	In the middle of a line perpendicular to the baseline	Lund-Hanssen et al. (1994), Hernigou and Garabedian (2002), Shelbourne et al. (2007)
	At the groove of the popliteal tendon	Souryal et al. (1988), Souryal and Freeman (1993), Herzog et al. (1994), LaPrade and Burnett (1994), Shelbourne et al. (1997), Ireland et al. (2001), Lombardo et al. (2005), Hoteya et al. (2011)
	At two thirds of the depth of the IN	Herzog et al. (1994)
	At the level of the articular margins	Herzog et al. (1994)
MRI and CT		
Axial	At the level of the groove of the popliteal tendon	Herzog et al. (1994), Al-Saeed et al. (2013), Lima et al. (2020)
	At site with minimum NW	Hoteya et al. (2011)
	At one third of the depth of the IN	Alentorn-Geli et al. (2015), Vaswani et al. (2020), Jha and Pandit (2021)
	At two thirds of the depth of the IN	Herzog et al. (1994), Anderson et al. (2001), Stein et al. (2010), Chen et al. (2016), Vaswani et al. (2020)
	At the level of the articular margins	Herzog et al. (1994), Hernigou and Garabedian (2002), Vaswani et al. (2019, 2020)
	At half the depth of the IN	Al-Saeed et al. (2013)
Coronal	At the region near the ACL attachment site	Hoteya et al. (2011), Whitney et al. (2014), Chen et al. (2016)
	Posterior to the ACL attachment site	Hoteya et al. (2011), Whitney et al. (2014)
	At the groove of the popliteal tendon	Herzog et al. (1994), Davis et al. (1999), Domzalski et al. (2010), Sonnery-Cottet et al. (2011), Vrooijink et al. (2011), Swami et al. (2013), Domzalski et al. (2015), Fujii et al. (2015), Chen et al. (2016), Hirtler et al. (2016), Pekala et al. (2019)
	At one third of the depth of the IN	Alentorn-Geli et al. (2015), Jha and Pandit (2021)
	At two thirds of the depth of the IN	Herzog et al. (1994)
	At the level of the articular margins	Herzog et al. (1994), Hirtler et al. (2016)
	At the inlet of the notch	Whitney et al. (2014)
	At the outlet of the notch	Whitney et al. (2014)
Direct measurements in anatomical specimens	At the anterior outlet	Wada et al. (1999)
	At width of the IN at two-thirds of the notch depth	Wada et al. (1999)
	At width of the IN at the midpoint of each third	Tanzer and Lenczner (1990)
	At the width of the IN at the level of the groove for the popliteus tendon	Stijak, Radonjic, et al. (2009)
Direct arthroscopic measurements	Entrance at the base, the middle and the top of the IN	Wolters et al. (2011), Vaswani et al. (2019, 2020), Wang et al. (2021)

Charlton et al., 2002; Davis et al., 1999; Dienst et al., 2007; Staeubli et al., 1999). Additionally, differences in knee flexion angles between males and females have been reported during sports requiring cutting, landing or jumping movements. Anterior tibial translation in the knee joint is maximal at flexion angles below 30°, so the ACL is most often injured at low flexion angles; control of anterior tibial translation in those movements has been shown to be of major importance. In combination with the reported significant neuromuscular imbalance between the quadriceps femoris and the hamstring muscles, this indicates an inherent difficulty in decelerating from a landing, and controlling the anterior tibial translation has been identified as a further pathophysiological factor in women (Quatman et al., 2010).

These sex differences entail a major problem: the correct use and interpretation of metric parameters and indices during comparisons. No statistically significant difference between men and women in the NWI or other ratios has been reported (Anderson et al., 1987, 2001; Chandrashekar et al., 2005; Charlton et al., 2002; Domzalski et al., 2010; Gormeli et al., 2015; Hirtler et al., 2016; LaPrade & Burnett, 1994; Tillman et al., 2002), whereas metric values (notch width, bicondylar width, width of the femoral condyles, notch volume) are significantly greater in males than females (Anderson et al., 1987; 2001; Davis et al., 1999; Everhart et al., 2012; Hirtler et al., 2016; Ireland et al., 2001; Shelbourne et al., 1997; Souryal & Freeman, 1993; Staeubli et al., 1999; Stijak, Nikolic, et al., 2009; Swami et al., 2013; van Diek et al., 2014; van Eck, Martins, Lorenz, et al., 2010; Vrooijink et al., 2011; Wolters et al., 2011). This sex difference in the size of the NW is rather easily explained, as it is positively associated with height and weight (Anderson et al., 2001; Charlton et al., 2002; Dienst et al., 2007; Everhart et al., 2014; Shelbourne et al., 1998; Whitney et al., 2014).

4.2 | Influence of age

Aging alters the morphology of the knee joint (Figure 6A–D). From the age of three to 17 years the NWI grows smaller, from 0.326 in the youngest to 0.25 in the eldest (Anderson et al., 2001; Domzalski et al., 2015; Herzog et al., 1994; Lima et al., 2020; Pekala et al., 2019). Everhart et al. (2014) also described a positive age-related change in the size of the anteromedial ridge at the osteochondral border of the notch. Specimens under the age of 15 showed no ridge; it grew ever more discernible in the older age groups; and over age 35 the ridges were at least

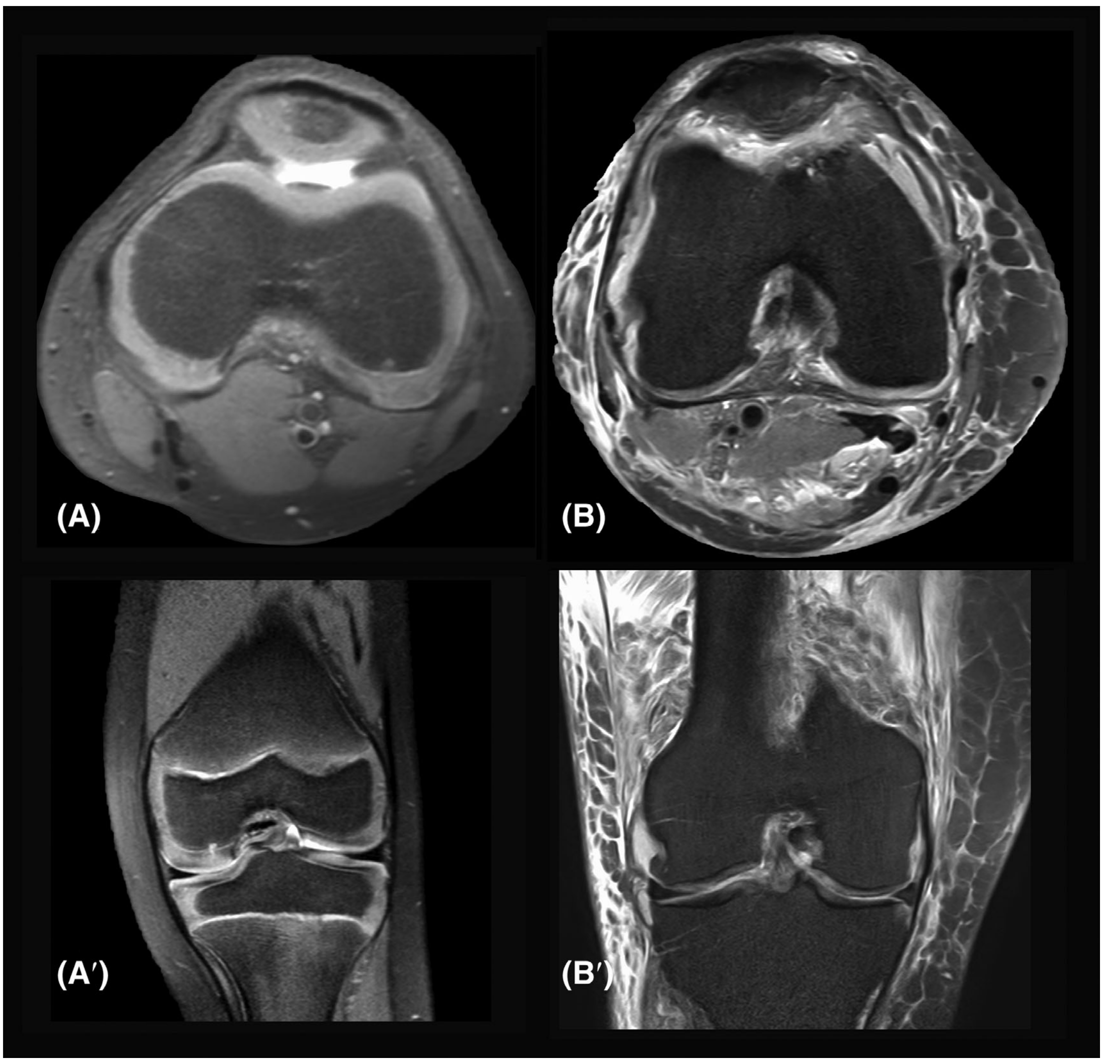

FIGURE 6 Examples showing age differences in the morphology of the IN. (A, A′) left knee of a 7-year-old male patient. (B) and (B′) right knee of a 75-year-old female patient. (A) 3T, axial PD SPAIR, (A′) 3T, coronal PD SPAIR, (B) 3T, axial ePD SAIR, (B′) 3T, coronal ePD SPAIR

1.0 mm thick (Everhart et al., 2014). Hirtler et al. (2016) described a retrospective cross-sectional study of the IN. They showed that these changes do not stop after completion of growth but continue into great age and are more marked at the level of the joint line than at the level of the groove for the popliteus tendon, which is the measurement level most often used in the literature. Through their subclassification of the shape of the IN, these authors assigned three specific shapes to different stages of life: A-shape in children, Ω-shape in elderly persons, and inverse-U-shape in between. This opens a totally new field of investigation: age-specific evaluation of risk factors for knee joint injury when healthy and injured probands of the same age group are compared.

4.3 | Notch stenosis

Notch stenosis is the main osseous cause for ACL injury. This is relevant not only to the initial development of ACL injury, but also to rerupturing of the reconstructed graft and degenerative changes to it (Ahn et al., 2007; Fujii et al., 2015; Herbst et al., 2017; Mayr et al., 2017; Muellner et al., 1999; Tuca et al., 2021). However, there is currently no overall agreement about a cut-off value for IN measurements. The recommended benchmarks for identifying IN stenosis range between 15 mm and 17 mm for the notch width (Lombardo et al., 2005; Lund-Hanssen et al., 1994; Shelbourne et al., 1997; Souryal & Freeman, 1993; Stein et al., 2010) and between 0.18 and 0.27 for the NWI (Al-Saeed et al., 2013; Domzalski et al., 2010; Gormeli et al., 2015; Hoteya et al., 2011; Keays et al., 2016; LaPrade & Burnett, 1994; Lombardo et al., 2005; Shelbourne et al., 1997; Sonnery-Cottet et al., 2011; Souryal & Freeman, 1993; Stein et al., 2010; Uhorchak et al., 2003).

Everhart et al. (2014) showed that the aforementioned anteromedial ridge is age-dependent and is involved in the development of notch stenosis. Even during its early development it was responsible for a certain percentage of notch stenosis cases (Everhart et al., 2014).

Leon et al. (2005) classified four types of intercondylar stenosis on the basis of the arthroscopic correlation of osseous changes with ACL injury, without relying on specific measurements or osseous parameters. Type I (anterior type) was detected in 29% of patients who showed injury on the anterior-distal area of the ACL due to an ACL-notch mismatch. Type II (lateral type) was identified in 20% of patients with injuries in the midlateral area of the ACL. Type III (mixed type) injured the anterior-distal and midlateral portions of the ACL in 48% of patients; and type IV (massive type), found in 3% of patients, is defined as severe intercondylar stenosis with complex injury to the ACL that is not covered by the other three types.

In ACL reconstruction, some authors therefore suggest performing a notchplasty in combination with reconstruction of the ligament itself in order to minimize the rerupture and failure rates and the postoperative development of a so-called cyclops formation (Ahn et al., 2007; Asahina et al., 2000; Dienst et al., 2007; Fujii et al., 2015; Herbst et al., 2017; Iriuchishima et al., 2013; Keklikci et al., 2013; Mayr et al., 2017; Muellner et al., 1999; Orsi et al., 2017; Tuca et al., 2021).

This summary of the literature shows the wide range of possible open questions concerning IN morphology and the border between healthy and pathological INs. Existing data provide no basis for clear instructions.

4.4 | Influence of osteoarthritis

Osteoarthritis is diagnosed in up to 30% of the population over the age of 65 in the western world (van Saase et al., 1989). The knee joint is affected early in 6% of adults aged 30 years or more and in at least 13% of adults aged 60 or more, leading to morphological changes and ligament destruction (Chan et al., 1991; Dunlop et al., 2001; Felson et al., 2000; Hill et al., 2005; Link et al., 2003; Stein et al., 2010).

Owing to the complexity and socioeconomic importance of OA there is a large body of literature concerning different risk factors, several of them being anatomical variations and age-related changes, the IN constituting one of them. A general widening and flattening of the condyles on the medial side ("elephant's foot," Figure 7) in combination with osteophytic growth in the vicinity of the osteochondral and osteosynovial border and a narrower notch are identifiers for OA in the distal part of the femur (Chen et al., 2016; Marshall, 1969; Neogi et al., 2013). These osteophytes are most frequent at the lateral and superior margins of the IN (Good et al., 1991) and narrow the IN as the OA progresses (Wada et al., 1999).

FIGURE 7 Elephant's foot at the lateral femoral condyle; osteoarthritis in a 73-year-old male patient. 3T, coronal eT1w TSE

These osteophytic changes in OA not only change the osseous morphology of the IN but also influence the ACL, leading to progressive impingement of this ligament during joint movement and ultimately to disruption of it and its proprioceptive feedback (Leon et al., 2005; Sharma & Pai, 1997; Staeubli et al., 1999). Combined with a certain inhibition of the quadriceps femoris muscle (Snyder-Mackler et al., 1994) and altered joint kinematics, this leads to the further progression of degeneration (Dye & Cannon, 1988; Shepstone et al., 2001).

Wada et al. (1999) compared the influence of an injured ACL on the dimensions and morphology of the IN in patients with OA. NW and NWI were significantly smaller in patients with ACL problems than in those with a healthy ACL, and also correlated positively with the severity of the OA (Kellgren and Lawrence grades 3 and 4 vs. grades 1 and 2: Kellgren & Lawrence, 1952, 1957). Ruptures were most often complete in patients with Kellgren and Lawrence grade 4. It also seemed that osseous growth of the femoral condyles proceeded anteroposteriorly, widening the femoro-tibial contact area and thus increasing the stability of the knee joint in this direction. This helps to explain the increasing joint stiffness in more severe OA (Brage et al., 1994; Marshall & Olsson, 1971; Sharma et al., 1999; Wada et al., 1996, 1999). This anteroposterior and vertical growth of osteophytes in OA therefore contributes to the development of an ACL tear (Wada et al., 1999). Also, deterioration of the ACL during the progression of OA further promotes joint degeneration, especially as the development of ligament laxity in the knee precedes the formation of osteophytes (Quasnichka et al., 2005), constituting a vicious circle.

5 | SUMMARY

Changes to the intercondylar fossa, either physiological or pathological, influence the structures within, that is, the cruciate ligaments and the meniscofemoral ligaments. To interpret this part of the distal femur as static would be unwise, as the literature shows changes not only during growth but throughout life. These changes can sometimes have consequences for the stabilizing ligaments within. Correct assessment of the risk involved requires in-depth knowledge of the osseous anatomy and its changes throughout life in combination with a strategic and clinically applicable evaluation system. In particular, the combination of measurements of the notch width and determinations of the shape of the intercondylar fossa could delineate the risk for ACL injury and thus influence further treatment of the patient.

ACKNOWLEDGMENT

The authors sincerely thank those who donated their bodies to science so that anatomical research could be performed. Results from such research can potentially increase mankind's overall knowledge that can then improve patient care. Therefore, these donors and their families deserve our highest gratitude (Iwanaga et al., 2021).

ORCID

Lena Hirtler https://orcid.org/0000-0001-5194-9118

REFERENCES

Ahn, J. H., Yoo, J. C., Yang, H. S., Kim, J. H., & Wang, J. H. (2007). Second-look arthroscopic findings of 208 patients after ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *15*(3), 242–248. https://doi.org/10.1007/s00167-006-0177-8

Al-Saeed, O., Brown, M., Athyal, R., & Sheikh, M. (2013). Association of femoral intercondylar notch morphology, width index and the risk of anterior cruciate ligament injury. *Knee Surgery, Sports Traumatology, Arthroscopy*, *21*(3), 678–682. https://doi.org/10.1007/s00167-012-2038-y

Anderson, A. F., Dome, D. C., Gautam, S., Awh, M. H., & Rennirt, G. W. (2001). Correlation of anthropometric measurements, strength, anterior cruciate ligament size, and intercondylar notch characteristics to sex differences in anterior cruciate ligament tear rates. *The American Journal of Sports Medicine*, *29*(1), 58–66. https://doi.org/10.1177/03635465010290011501

Alentorn-Geli, E., Pelfort, X., Mingo, F., Lizano-Díez, X., Leal-Blanquet, J., Torres-Claramunt, R., Hinarejos, P., Puig-Verdié, L., & Monllau, J. C. (2015). An evaluation of the association between radiographic intercondylar notch narrowing and anterior cruciate ligament injury in men: the notch angle is a better parameter than notch width. *Arthroscopy*, *31*(10), 2004–2017. https://doi.org/10.1016/j.arthro.2015.04.088.

Anderson, A. F., Lipscomb, A. B., Liudahl, K. J., & Addlestone, R. B. (1987). Analysis of the intercondylar notch by computed tomography. *The American Journal of Sports Medicine*, *15*(6), 547–552. https://doi.org/10.1177/036354658701500605

Arendt, E. A., Agel, J., & Dick, R. (1999). Anterior cruciate ligament injury patterns among collegiate men and women. *Journal of Athletic Training*, *34*(2), 86–92.

Asahina, S., Muneta, T., & Ezura, Y. (2000). Notchplasty in anterior cruciate ligament reconstruction: An experimental animal study. *Arthroscopy*, *16*(2), 165–172.

Ballinger, P. W., Frank, E. D., & Merrill, V. (2003). *Merrill's atlas of radiographic positions & radiologic procedures* (10th ed.). Mosby.

Bicer, E. K., Lustig, S., Servien, E., Selmi, T. A., & Neyret, P. (2010). Current knowledge in the anatomy of the human anterior cruciate ligament. *Knee Surgery, Sports Traumatology, Arthroscopy*, *18*(8), 1075–1084. https://doi.org/10.1007/s00167-009-0993-8

Boegard, T., Rudling, O., Petersson, I. F., Sanfridsson, J., Saxne, T., Svensson, B., & Jonsson, K. (1997). Postero-anterior radiogram of the knee in weight-bearing and semiflexion. Comparison with MR imaging. *Acta Radiologica*, *38*(6), 1063–1070.

Brage, M. E., Draganich, L. F., Pottenger, L. A., & Curran, J. J. (1994). Knee laxity in symptomatic osteoarthritis. *Clinical Orthopaedics and Related Research*, *304*, 184–189.

Chan, W. P., Lang, P., Stevens, M. P., Sack, K., Majumdar, S., Stoller, D. W., Basch, C., & Genant, H. K. (1991). Osteoarthritis of the knee: Comparison of radiography, CT, and MR imaging to assess extent and severity. *American Journal of Roentgenology*, *157*(4), 799–806. https://doi.org/10.2214/ajr.157.4.1892040

Chandrashekar, N., Slauterbeck, J., & Hashemi, J. (2005). Sex-based differences in the anthropometric characteristics of the anterior cruciate ligament and its relation to intercondylar notch geometry: A cadaveric study. *The American Journal of Sports Medicine*, *33*(10), 1492–1498. https://doi.org/10.1177/0363546504274149

Charlton, W. P., St John, T. A., Ciccotti, M. G., Harrison, N., & Schweitzer, M. (2002). Differences in femoral notch anatomy between men and women: A magnetic resonance imaging study. *The American Journal of Sports Medicine*, *30*(3), 329–333. https://doi.org/10.1177/03635465020300030501

Chen, C., Ma, Y., Geng, B., Tan, X., Zhang, B., Jayswal, C. K., Khan, M. S., Meng, H., Ding, N., Jiang, J., Wu, M., Wang, J., & Xia, Y. (2016). Intercondylar notch stenosis of knee osteoarthritis and relationship between stenosis and osteoarthritis complicated with anterior cruciate ligament injury: A study in MRI. *Medicine*, *95*(17), e3439. https://doi.org/10.1097/MD.0000000000003439

Davis, T. J., Shelbourne, K. D., & Klootwyk, T. E. (1999). Correlation of the intercondylar notch width of the femur to the width of the anterior and posterior cruciate ligaments. *Knee Surgery, Sports Traumatology, Arthroscopy*, *7*(4), 209–214. https://doi.org/10.1007/s001670050150

Dienst, M., Schneider, G., Altmeyer, K., Voelkering, K., Georg, T., Kramann, B., & Kohn, D. (2007). Correlation of intercondylar notch cross sections to the ACL size: A high resolution MR tomographic in vivo analysis. *Archives of Orthopaedic and Trauma Surgery*, *127*(4), 253–260. https://doi.org/10.1007/s00402-006-0177-7

Domzalski, M., Grzelak, P., & Gabos, P. (2010). Risk factors for anterior cruciate ligament injury in skeletally immature patients: Analysis of intercondylar notch width using magnetic resonance imaging. *International Orthopaedics*, *34*(5), 703–707. https://doi.org/10.1007/s00264-010-0987-7

Domzalski, M. E., Keller, M. S., Grzelak, P., & Gabos, P. (2015). MRI evaluation of the development of intercondylar notch width in children. *Surgical and Radiologic Anatomy*, *37*(6), 609–615. https://doi.org/10.1007/s00276-015-1433-8

Dunlop, D. D., Manheim, L. M., Song, J., & Chang, R. W. (2001). Arthritis prevalence and activity limitations in older adults. *Arthritis and Rheumatism*, *44*(1), 212–221. https://doi.org/10.1002/1529-0131(200101)44:1<212::AID-ANR28>3.0.CO;2-Q

Durselen, L., Claes, L., & Kiefer, H. (1995). The influence of muscle forces and external loads on cruciate ligament strain. *The American Journal of Sports Medicine*, *23*(1), 129–136. https://doi.org/10.1177/036354659502300122

Dye, S. F., & Cannon, W. D., Jr. (1988). Anatomy and biomechanics of the anterior cruciate ligament. *Clinics in Sports Medicine*, *7*(4), 715–725.

Everhart, J. S., Flanigan, D. C., & Chaudhari, A. M. (2014). Anteromedial ridging of the femoral intercondylar notch: An anatomic study of 170 archival skeletal specimens. *Knee Surgery, Sports Traumatology, Arthroscopy*, *22*(1), 80–87. https://doi.org/10.1007/s00167-012-2282-1

Everhart, J. S., Flanigan, D. C., Simon, R. A., & Chaudhari, A. M. (2010). Association of noncontact anterior cruciate ligament injury with presence and thickness of a bony ridge on the anteromedial aspect of the femoral intercondylar notch. *The American Journal of Sports Medicine*, *38*(8), 1667–1673. https://doi.org/10.1177/0363546510367424

Fahim, S. M., Dhawan, T., Jagadeesh, N., & Ashwathnarayan, Y. P. (2021). The relationship of anterior cruciate ligament injuries with MRI based calculation of femoral notch width, notch width index, notch shape-A randomized control study. *Journal of Clinical Orthopaedics and Trauma*, *17*, 5–10. https://doi.org/10.1016/j.jcot.2021.01.006

Felson, D. T., Lawrence, R. C., Dieppe, P. A., Hirsch, R., Helmick, C. G., Jordan, J. M., Kington, R. S., Lane, N. E., Nevitt, M. C., Zhang, Y., Sowers, M., McAlindon, T., Spector, T. D., Poole, A. R., Yanovski, S. Z., Ateshian, G., Sharma, L., Buckwalter, J. A., Brandt, K. D., & Fries, J. F. (2000). Osteoarthritis: new insights. Part 1: The disease and its risk factors. *Annals of Internal Medicine*, *133*(8), 635–646.

Ferretti, M., Ekdahl, M., Shen, W., & Fu, F. H. (2007). Osseous landmarks of the femoral attachment of the anterior cruciate ligament: An anatomic study. *Arthroscopy*, *23*(11), 1218–1225. https://doi.org/10.1016/j.arthro.2007.09.008

Fleming, B. C., Renstrom, P. A., Beynnon, B. D., Engstrom, B., Peura, G. D., Badger, G. J., & Johnson, R. J. (2001). The effect of weightbearing and external loading on anterior cruciate ligament strain. *Journal of Biomechanics*, *34*(2), 163–170.

Forsythe, B., Kopf, S., Wong, A. K., Martins, C. A., Anderst, W., Tashman, S., & Fu, F. H. (2010). The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. *The Journal of Bone and Joint Surgery. American Volume*, *92*(6), 1418–1426. https://doi.org/10.2106/JBJS.I.00654

Fu, F. H., & Jordan, S. S. (2007). The lateral intercondylar ridge-a key to anatomic anterior cruciate ligament reconstruction. *The Journal of Bone and Joint Surgery. American Volume*, *89*(10), 2103–2104. https://doi.org/10.2106/JBJS.G.00851

Fujii, M., Furumatsu, T., Miyazawa, S., Okada, Y., Tanaka, T., Ozaki, T., & Abe, N. (2015). Intercondylar notch size influences cyclops formation after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *23*(4), 1092–1099. https://doi.org/10.1007/s00167-014-2891-y

Fung, D. T., Hendrix, R. W., Koh, J. L., & Zhang, L. Q. (2007). ACL impingement prediction based on MRI scans of individual knees. *Clinical Orthopaedics and Related Research*, *460*, 210–218. https://doi.org/10.1097/BLO.0b013e31804d2339

Good, L., Odensten, M., & Gillquist, J. (1991). Intercondylar notch measurements with special reference to anterior cruciate ligament surgery. *Clinical Orthopaedics and Related Research*, *263*, 185–189.

Gormeli, C. A., Gormeli, G., Ozturk, B. Y., Ozdemir, Z., Kahraman, A. S., Yildirim, O., & Gozukarab, H. (2015). The effect of the intercondylar notch width index on anterior cruciate ligament injuries: A study on groups with unilateral and bilateral ACL injury. *Acta Orthopaedica Belgica*, *81*(2), 240–244.

Harmon, K. G., & Ireland, M. L. (2000). Gender differences in noncontact anterior cruciate ligament injuries. *Clinics in Sports Medicine*, *19*(2), 287–302.

Henry, J. C., & Kaeding, C. (2001). Neuromuscular differences between male and female athletes. *Current Women's Health Reports*, *1*(3), 241–244.

Herbst, E., Hoser, C., Gfoller, P., Hepperger, C., Abermann, E., Neumayer, K., Musahl, V., & Fink, C. (2017). Impact of surgical timing on the outcome of anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *25*(2), 569–577. https://doi.org/10.1007/s00167-016-4291-y

Hernigou, P., & Garabedian, J. M. (2002). Intercondylar notch width and the risk for anterior cruciate ligament rupture in the osteoarthritic knee: Evaluation by plain radiography and CT scan. *The Knee*, *9*(4), 313–316.

Herzog, R. J., Silliman, J. F., Hutton, K., Rodkey, W. G., & Steadman, J. R. (1994). Measurements of the intercondylar notch by plain film radiography and magnetic resonance imaging. *The American Journal of Sports Medicine*, *22*(2), 204–210. https://doi.org/10.1177/036354659402200209

Hill, C. L., Seo, G. S., Gale, D., Totterman, S., Gale, M. E., & Felson, D. T. (2005). Cruciate ligament integrity in osteoarthritis of the knee. *Arthritis and Rheumatism*, *52*(3), 794–799. https://doi.org/10.1002/art.20943

Hirtler, L., Rohrich, S., & Kainberger, F. (2016). The femoral intercondylar notch during life: An anatomic redefinition with patterns predisposing to cruciate ligament impingement. *American Journal of Roentgenology*, *207*, 1–10. https://doi.org/10.2214/AJR.16.16015

Holmblad, E. C. (1937). Postero-anterior x-ray view of the knee in flexion. *JAMA*, *109*, 1196–1197.

Hoteya, K., Kato, Y., Motojima, S., Ingham, S. J., Horaguchi, T., Saito, A., & Tokuhashi, Y. (2011). Association between intercondylar notch narrowing and bilateral anterior cruciate ligament injuries in athletes. *Archives of Orthopaedic and Trauma Surgery*, *131*(3), 371–376. https://doi.org/10.1007/s00402-010-1254-5

Houseworth, S. W., Mauro, V. J., Mellon, B. A., & Kieffer, D. A. (1987). The intercondylar notch in acute tears of the anterior cruciate ligament: A computer graphics study. *The American Journal of Sports Medicine*, *15*(3), 221–224. https://doi.org/10.1177/036354658701500305

Hutchinson, M. R., & Ash, S. A. (2003). Resident's ridge: Assessing the cortical thickness of the lateral wall and roof of the intercondylar notch. *Arthroscopy*, *19*(9), 931–935.

Ireland, M. L., Ballantyne, B. T., Little, K., & McClay, I. S. (2001). A radiographic analysis of the relationship between the size and shape of the intercondylar notch and anterior cruciate ligament injury. *Knee Surgery, Sports Traumatology, Arthroscopy*, *9*(4), 200–205. https://doi.org/10.1007/s001670100197

Iriuchishima, T., Shirakura, K., & Fu, F. H. (2013). Graft impingement in anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *21*(3), 664–670. https://doi.org/10.1007/s00167-012-2014-6

Iwanaga, J., Singh, V., Ohtsuka, A., Hwang, Y., Kim, H. J., Moryś, J., Ravi, K. S., Ribatti, D., Trainor, P. A., Sañudo, J. R., Apaydin, N., Şengül, G., Albertine, K. H., Walocha, J. A., Loukas, M., Duparc, F., Paulsen, F., del Sol, M., Adds, P., … Tubbs, R. S. (2021). Acknowledging the use of human cadaveric tissues in research papers: Recommendations from anatomical journal editors. *Clinical Anatomy*, *34*(1), 2–4. https://doi.org/10.1002/ca.23671

Jha, V., & Pandit, A. (2021). Notch volume measured on magnetic resonance imaging is better than 2-dimensional notch parameters for predicting noncontact anterior cruciate ligament injury in males. *Arthroscopy*, *37*(5), 1534–1543.e1531. https://doi.org/10.1016/j.arthro.2020.11.050

Keays, S. L., Keays, R., & Newcombe, P. A. (2016). Femoral intercondylar notch width size: A comparison between siblings with and without anterior cruciate ligament injuries. *Knee Surgery, Sports Traumatology, Arthroscopy*, *24*(3), 672–679. https://doi.org/10.1007/s00167-014-3491-6

Keklikci, K., Yapici, C., Kim, D., Linde-Rosen, M., Smolinski, P., & Fu, F. H. (2013). The effect of notchplasty in anterior cruciate ligament reconstruction: A biomechanical study in the porcine knee. *Knee Surgery, Sports Traumatology, Arthroscopy*, *21*(8), 1915–1921. https://doi.org/10.1007/s00167-012-2343-5

Kellgren, J. H., & Lawrence, J. S. (1952). Rheumatism in miners. II. X-ray study. *British Journal of Industrial Medicine*, *9*(3), 197–207.

Kellgren, J. H., & Lawrence, J. S. (1957). Radiological assessment of osteoarthrosis. *Annals of the Rheumatic Diseases*, *16*(4), 494–502.

Kieffer, D. A., Curnow, R. J., Southwell, R. B., Tucker, W. F., & Kendrick, K. K. (1984). Anterior cruciate ligament arthroplasty. *The American Journal of Sports Medicine*, *12*(4), 301–312. https://doi.org/10.1177/036354658401200411

Kocher, M. S., Mandiga, R., Klingele, K., Bley, L., & Micheli, L. J. (2004). Anterior cruciate ligament injury versus tibial spine fracture in the skeletally immature knee: A comparison of skeletal maturation and notch width index. *Journal of Pediatric Orthopedics*, *24*(2), 185–188.

Kopf, S., Musahl, V., Tashman, S., Szczodry, M., Shen, W., & Fu, F. H. (2009). A systematic review of the femoral origin and tibial insertion morphology of the ACL. *Knee Surgery, Sports Traumatology, Arthroscopy*, *17*(3), 213–219. https://doi.org/10.1007/s00167-008-0709-5

Krosshaug, T., Slauterbeck, J. R., Engebretsen, L., & Bahr, R. (2007). Biomechanical analysis of anterior cruciate ligament injury mechanisms: Three-dimensional motion reconstruction from video sequences. *Scandinavian Journal of Medicine & Science in Sports*, *17*(5), 508–519. https://doi.org/10.1111/j.1600-0838.2006.00558.x

LaPrade, R. F., & Burnett, Q. M., 2nd. (1994). Femoral intercondylar notch stenosis and correlation to anterior cruciate ligament injuries. A prospective study. *The American Journal of Sports Medicine*, *22*(2), 198–202. https://doi.org/10.1177/036354659402200208

Leon, H. O., Blanco, C. E., Guthrie, T. B., & Martinez, O. J. (2005). Intercondylar notch stenosis in degenerative arthritis of the knee. *Arthroscopy*, *21*(3), 294–302. https://doi.org/10.1016/j.arthro.2004.11.019

Li, W., Liang, J., Zeng, F., Lin, B., Liu, C., Huang, S., & Liu, Q. (2021). Anatomic characteristics of the knee influence the risk of suffering an isolated meniscal injury and the risk factors differ between women and men. *Knee Surgery, Sports Traumatology, Arthroscopy*. Epub ahead of print. https://doi.org/10.1007/s00167-020-06396-5

Lima, F. M., Debieux, P., Aihara, A. Y., Cardoso, F. N., Franciozi, C. E., Grimberg, A., & Fernandes, A. R. C. (2020). The development of the intercondylar notch in the pediatric population. *The Knee*, *27*(3), 747–754. https://doi.org/10.1016/j.knee.2020.04.020

Link, T. M., Steinbach, L. S., Ghosh, S., Ries, M., Lu, Y., Lane, N., & Majumdar, S. (2003). Osteoarthritis: MR imaging findings in different stages of disease and correlation with clinical findings. *Radiology*, *226*(2), 373–381. https://doi.org/10.1148/radiol.2262012190

Lombardo, S., Sethi, P. M., & Starkey, C. (2005). Intercondylar notch stenosis is not a risk factor for anterior cruciate ligament tears in professional male basketball players: An 11-year prospective study. *The American Journal of Sports Medicine*, *33*(1), 29–34. https://doi.org/10.1177/0363546504266482

Lopes, O. V., Jr., Ferretti, M., Shen, W., Ekdahl, M., Smolinski, P., & Fu, F. H. (2008). Topography of the femoral attachment of the posterior cruciate ligament. *The Journal of Bone and Joint Surgery. American Volume*, *90*(2), 249–255. https://doi.org/10.2106/JBJS.G.00448

Lund-Hanssen, H., Gannon, J., Engebretsen, L., Holen, K. J., Anda, S., & Vatten, L. (1994). Intercondylar notch width and the risk for anterior cruciate ligament rupture. A case-control study in 46 female handball players. *Acta Orthopaedica Scandinavica*, *65*(5), 529–532.

Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A., & Slauterbeck, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research*, *13*(6), 930–935. https://doi.org/10.1002/jor.1100130618

Marshall, J. L. (1969). Periarticular osteophytes. Initiation and formation in the knee of the dog. *Clinical Orthopaedics and Related Research*, *62*, 37–47.

Marshall, J. L., & Olsson, S. E. (1971). Instability of the knee. A long-term experimental study in dogs. *The Journal of Bone and Joint Surgery. American Volume*, *53*(8), 1561–1570.

Mayr, H. O., Brandt, C. M., Weig, T., Koehne, M., Bernstein, A., Suedkamp, N. P., Hube, R., & Stoehr, A. (2017). Long-term results of arthroscopic arthrolysis for arthrofibrosis after anterior cruciate ligament reconstruction. *Arthroscopy*, *33*(2), 408–414. https://doi.org/10.1016/j.arthro.2016.07.029

Muellner, T., Kdolsky, R., Grossschmidt, K., Schabus, R., Kwasny, O., & Plenk, H., Jr. (1999). Cyclops and cyclopoid formation after anterior cruciate ligament reconstruction: Clinical and histomorphological differences. *Knee Surgery, Sports Traumatology, Arthroscopy*, *7*(5), 284–289. https://doi.org/10.1007/s001670050165

Nagano, Y., Ida, H., Akai, M., & Fukubayashi, T. (2007). Gender differences in knee kinematics and muscle activity during single limb drop landing. *The Knee*, *14*(3), 218–223. https://doi.org/10.1016/j.knee.2006.11.008

Nawabi, D. H., Tucker, S., Schafer, K. A., Zuiderbaan, H. A., Nguyen, J. T., Wickiewicz, T. L., Imhauser, C. W., & Pearle, A. D. (2016). ACL fibers near the lateral intercondylar ridge are the most load bearing during stability examinations and isometric through passive flexion. *The American Journal of Sports Medicine*, *44*(10), 2563–2571. https://doi.org/10.1177/0363546516652876

Neogi, T., Bowes, M. A., Niu, J., De Souza, K. M., Vincent, G. R., Goggins, J., Zhang, Y., & Felson, D. T. (2013). Magnetic resonance imaging-based three-dimensional bone shape of the knee predicts onset of knee osteoarthritis: Data from the osteoarthritis initiative. *Arthritis and Rheumatism*, *65*(8), 2048–2058. https://doi.org/10.1002/art.37987

Oh, Y. K., Kreinbrink, J. L., Ashton-Miller, J. A., & Wojtys, E. M. (2011). Effect of ACL transection on internal tibial rotation in an in vitro simulated pivot landing. *The Journal of Bone and Joint Surgery. American Volume*, *93*(4), 372–380. https://doi.org/10.2106/JBJS.J.00262

Orsi, A. D., Canavan, P. K., Vaziri, A., Goebel, R., Kapasi, O. A., & Nayeb-Hashemi, H. (2017). The effects of graft size and insertion site location during anterior cruciate ligament reconstruction on intercondylar notch impingement. *The Knee*, *24*(3), 525–535. https://doi.org/10.1016/j.knee.2017.02.010

Palmer, I. (2007). On the injuries to the ligaments of the knee joint: A clinical study. 1938. *Clinical Orthopaedics and Related Research*, *454*, 17–22. https://doi.org/10.1097/BLO.0b013e31802c7915

Pekala, L., Podgorski, M., Shukla, A., Winnicka, M., Biernacka, K., & Grzelak, P. (2019). Do variants of the intercondylar notch predispose children to the injury of the anterior cruciate ligament? *Clinical Anatomy*, *32*(5), 706–709. https://doi.org/10.1002/ca.23382

Petersen, W., & Zantop, T. (2007). Anatomy of the anterior cruciate ligament with regard to its two bundles. *Clinical Orthopaedics and Related Research*, *454*, 35–47. https://doi.org/10.1097/BLO.0b013e31802b4a59

Quasnichka, H. L., Anderson-MacKenzie, J. M., Tarlton, J. F., Sims, T. J., Billingham, M. E., & Bailey, A. J. (2005). Cruciate ligament laxity and femoral intercondylar notch narrowing in early-stage knee osteoarthritis. *Arthritis and Rheumatism*, *52*(10), 3100–3109. https://doi.org/10.1002/art.21340

Quatman, C. E., Kiapour, A., Myer, G. D., Ford, K. R., Demetropoulos, C. K., Goel, V. K., & Hewett, T. E. (2011). Cartilage pressure distributions provide a footprint to define female anterior cruciate ligament injury mechanisms. *The American Journal of Sports Medicine*, *39*(8), 1706–1713. https://doi.org/10.1177/0363546511400980

Quatman, C. E., Quatman-Yates, C. C., & Hewett, T. E. (2010). A 'plane' explanation of anterior cruciate ligament injury mechanisms: A systematic review. *Sports Medicine*, *40*(9), 729–746. https://doi.org/10.2165/11534950-000000000-00000

Raphael, B. S., Maak, T., Cross, M. B., Plaskos, C., Wickiewicz, T., Amis, A., & Pearle, A. (2011). From wall graft to roof graft: Reassessment of femoral posterior cruciate ligament positioning. *American Journal of Orthopedics*, *40*(9), 479–484.

Rosenberg, T. D., Paulos, L. E., Parker, R. D., Coward, D. B., & Scott, S. M. (1988). The forty-five-degree posteroanterior flexion weight-bearing radiograph of the knee. *The Journal of Bone and Joint Surgery. American Volume*, *70*(10), 1479–1483.

Sasaki, N., Ishibashi, Y., Tsuda, E., Yamamoto, Y., Maeda, S., Mizukami, H., Toh, S., Yagihashi, S., & Tonosaki, Y. (2012). The femoral insertion of the anterior cruciate ligament: Discrepancy between macroscopic and histological observations. *Arthroscopy*, *28*(8), 1135–1146. https://doi.org/10.1016/j.arthro.2011.12.021

Schickendantz, M. S., & Weiker, G. G. (1993). The predictive value of radiographs in the evaluation of unilateral and bilateral anterior cruciate ligament injuries. *The American Journal of Sports Medicine*, *21*(1), 110–113. https://doi.org/10.1177/036354659302100118

Sharma, L., Lou, C., Felson, D. T., Dunlop, D. D., Kirwan-Mellis, G., Hayes, K. W., Weinrach, D., & Buchanan, T. S. (1999). Laxity in healthy and osteoarthritic knees. *Arthritis and Rheumatism*, *42*(5), 861–870. https://doi.org/10.1002/1529-0131(199905)42:5<861::AID-ANR4>3.0.CO;2-N

Sharma, L., & Pai, Y. C. (1997). Impaired proprioception and osteoarthritis. *Current Opinion in Rheumatology*, *9*(3), 253–258.

Shelbourne, K. D., Davis, T. J., & Klootwyk, T. E. (1998). The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears. A prospective study. *The American Journal of Sports Medicine*, *26*(3), 402–408.

Shelbourne, K. D., Facibene, W. A., & Hunt, J. J. (1997). Radiographic and intraoperative intercondylar notch width measurements in men and women with unilateral and bilateral anterior cruciate ligament tears. *Knee Surgery, Sports Traumatology, Arthroscopy*, *5*(4), 229–233. https://doi.org/10.1007/s001670050055

Shelbourne, K. D., Gray, T., & Benner, R. W. (2007). Intercondylar notch width measurement differences between African American and white men and women with intact anterior cruciate ligament knees. *The American Journal of Sports Medicine*, *35*(8), 1304–1307. https://doi.org/10.1177/0363546507300060

Shelbourne, K. D., & Kerr, B. (2001). The relationship of femoral intercondylar notch width to height, weight, and sex in patients with intact anterior cruciate ligaments. *The American Journal of Knee Surgery*, *14*(2), 92–96.

Shepstone, L., Rogers, J., Kirwan, J. R., & Silverman, B. W. (2001). Shape of the intercondylar notch of the human femur: A comparison of osteoarthritic and non-osteoarthritic bones from a skeletal sample. *Annals of the Rheumatic Diseases*, *60*(10), 968–973. https://doi.org/10.1136/ard.60.10.968

Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2011). Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Medicine and Science in Sports and Exercise*, *43*(8), 1484–1491. https://doi.org/10.1249/MSS.0b013e31820f8395

Shino, K., Suzuki, T., Iwahashi, T., Mae, T., Nakamura, N., Nakata, K., & Nakagawa, S. (2010). The resident's ridge as an arthroscopic landmark for anatomical femoral tunnel drilling in ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *18*(9), 1164–1168. https://doi.org/10.1007/s00167-009-0979-6

Snyder-Mackler, L., De Luca, P. F., Williams, P. R., Eastlack, M. E., & Bartolozzi, A. R., 3rd. (1994). Reflex inhibition of the quadriceps femoris muscle after injury or reconstruction of the anterior cruciate ligament. *The Journal of Bone and Joint Surgery. American Volume*, *76*(4), 555–560.

Sonnery-Cottet, B., Archbold, P., Cucurulo, T., Fayard, J. M., Bortolletto, J., Thaunat, M., Prost, T., & Chambat, P. (2011). The influence of the tibial slope and the size of the intercondylar notch on rupture of the anterior cruciate ligament. *Journal of Bone and Joint Surgery. British Volume*, *93*(11), 1475–1478. https://doi.org/10.1302/0301-620X.93B11.26905

Souryal, T. O., & Freeman, T. R. (1993). Intercondylar notch size and anterior cruciate ligament injuries in athletes. A prospective study. *The American Journal of Sports Medicine*, *21*(4), 535–539. https://doi.org/10.1177/036354659302100410

Souryal, T. O., Moore, H. A., & Evans, J. P. (1988). Bilaterality in anterior cruciate ligament injuries: Associated intercondylar notch stenosis. *The American Journal of Sports Medicine*, *16*(5), 449–454. https://doi.org/10.1177/036354658801600504

Staeubli, H. U., Adam, O., Becker, W., & Burgkart, R. (1999). Anterior cruciate ligament and intercondylar notch in the coronal oblique plane: Anatomy complemented by magnetic resonance imaging in cruciate ligament-intact knees. *Arthroscopy*, *15*(4), 349–359.

Staubli, H. U., Durrenmatt, U., Porcellini, B., & Rauschning, W. (1999). Anatomy and surface geometry of the patellofemoral joint in the axial plane. *Journal of Bone and Joint Surgery. British Volume*, *81*(3), 452–458.

Stein, V., Li, L., Guermazi, A., Zhang, Y., Kent Kwoh, C., Eaton, C. B., Hunter, D. J., & OAI Investigators. (2010). The relation of femoral notch stenosis to ACL tears in persons with knee osteoarthritis. *Osteoarthritis and Cartilage*, *18*(2), 192–199. https://doi.org/10.1016/j.joca.2009.09.006

Stijak, L., Nikolic, V., Blagojevic, Z., Radonjic, V., & Malobabic, S. (2009). Morphometric parameters of the intercondylar notch, gender and age differences. *Acta Chirurgica Iugoslavica*, *56*(1), 53–59.

Stijak, L., Radonjic, V., Nikolic, V., Blagojevic, Z., Aksic, M., & Filipovic, B. (2009). Correlation between the morphometric parameters of the anterior cruciate ligament and the intercondylar width: Gender and age differences. *Knee Surgery, Sports Traumatology, Arthroscopy*, *17*(7), 812–817. https://doi.org/10.1007/s00167-009-0807-z

Swami, V. G., Mabee, M., Hui, C., & Jaremko, J. L. (2013). Three-dimensional intercondylar notch volumes in a skeletally immature pediatric population: A magnetic resonance imaging-based anatomic comparison of knees with torn and intact anterior cruciate ligaments. *Arthroscopy*, *29*(12), 1954–1962. https://doi.org/10.1016/j.arthro.2013.08.031

Tanzer, M., & Lenczner, E. (1990). The relationship of intercondylar notch size and content to notchplasty requirement in anterior cruciate ligament surgery. *Arthroscopy*, *6*(2), 89–93.

Tillman, M. D., Smith, K. R., Bauer, J. A., Cauraugh, J. H., Falsetti, A. B., & Pattishall, J. L. (2002). Differences in three intercondylar notch geometry indices between males and females: A cadaver study. *The Knee*, *9*(1), 41–46.

Tuca, M., Gausden, E., Luderowski, E., Valderrama, I., Pineda, T., Potter, H., Cordasco, F., & Green, D. (2021). Stenotic intercondylar notch as a risk factor for physeal-sparing ACL reconstruction failure: A case-control study. *Journal of the American Academy of Orthopaedic Surgeons. Global Research & Reviews*, *5*(7), e21.00143. https://doi.org/10.5435/JAAOSGlobal-D-21-00143

Uhorchak, J. M., Scoville, C. R., Williams, G. N., Arciero, R. A., St Pierre, P., & Taylor, D. C. (2003). Risk factors associated with noncontact injury of the anterior cruciate ligament: A prospective four-year evaluation of 859 West Point cadets. *The American Journal of Sports Medicine*, *31*(6), 831–842. https://doi.org/10.1177/03635465030310061801

van Diek, F. M., Wolf, M. R., Murawski, C. D., van Eck, C. F., & Fu, F. H. (2014). Knee morphology and risk factors for developing an anterior cruciate ligament rupture: An MRI comparison between ACL-ruptured and non-injured knees. *Knee Surgery, Sports Traumatology, Arthroscopy*, *22*(5), 987–994. https://doi.org/10.1007/s00167-013-2588-7

van Eck, C. F., Martins, C. A., Kopf, S., Lertwanich, P., Fu, F. H., & Tashman, S. (2011). Correlation between the 2-dimensional notch width and the 3-dimensional notch volume: A cadaveric study. *Arthroscopy*, *27*(2), 207–212. https://doi.org/10.1016/j.arthro.2010.06.027

van Eck, C. F., Martins, C. A., Lorenz, S. G., Fu, F. H., & Smolinski, P. (2010). Assessment of correlation between knee notch width index and the three-dimensional notch volume. *Knee Surgery, Sports Traumatology, Arthroscopy*, *18*(9), 1239–1244. https://doi.org/10.1007/s00167-010-1131-3

van Eck, C. F., Martins, C. A., Vyas, S. M., Celentano, U., van Dijk, C. N., & Fu, F. H. (2010). Femoral intercondylar notch shape and dimensions in ACL-injured patients. *Knee Surgery, Sports Traumatology, Arthroscopy*, *18*(9), 1257–1262. https://doi.org/10.1007/s00167-010-1135-z

van Eck, C. F., Morse, K. R., Lesniak, B. P., Kropf, E. J., Tranovich, M. J., van Dijk, C. N., & Fu, F. H. (2010). Does the lateral intercondylar ridge disappear in ACL deficient patients? *Knee Surgery, Sports Traumatology, Arthroscopy*, *18*(9), 1184–1188. https://doi.org/10.1007/s00167-009-1038-z

van Eck, C. F., Schreiber, V. M., Liu, T. T., & Fu, F. H. (2010). The anatomic approach to primary, revision and augmentation anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *18*(9), 1154–1163. https://doi.org/10.1007/s00167-010-1191-4

van Eck, C. F., Schreiber, V. M., Mejia, H. A., Samuelsson, K., van Dijk, C. N., Karlsson, J., & Fu, F. H. (2010). "Anatomic" anterior cruciate ligament reconstruction: A systematic review of surgical techniques and reporting of surgical data. *Arthroscopy*, *26*(9 Suppl), S2–S12. https://doi.org/10.1016/j.arthro.2010.03.005

van Kuijk, K. S. R., Eggerding, V., Reijman, M., van Meer, B. L., Bierma-Zeinstra, S. M. A., van Arkel, E., Waarsing, J. H., & Meuffels, D. E. (2021). Differences in knee shape between ACL injured and non-injured: A matched case-control study of 168 patients. *Journal of Clinical Medicine*, *10*(5), 968. https://doi.org/10.3390/jcm10050968

van Saase, J. L., van Romunde, L. K., Cats, A., Vandenbroucke, J. P., & Valkenburg, H. A. (1989). Epidemiology of osteoarthritis: Zoetermeer survey. Comparison of radiological osteoarthritis in a Dutch population with that in 10 other populations. *Annals of the Rheumatic Diseases*, *48*(4), 271–280.

Vaswani, R., Meredith, S. J., Lian, J., Li, R., Nickoli, M., Fu, F. H., & Musahl, V. (2019). Intercondylar notch measurement during arthroscopy and on preoperative magnetic resonance imaging. *Arthroscopy Techniques*, *8*(10), e1263–e1267. https://doi.org/10.1016/j.eats.2019.06.017

Vaswani, R., Meredith, S. J., Lian, J., Li, R., Nickoli, M., Fu, F. H., & Musahl, V. (2020). Intercondylar notch size can be predicted on preoperative magnetic resonance imaging. *Arthroscopy, Sports Medicine, and Rehabilitation*, *2*(1), e17–e22. https://doi.org/10.1016/j.asmr.2019.10.004

Vrooijink, S. H., Wolters, F., van Eck, C. F., & Fu, F. H. (2011). Measurements of knee morphometrics using MRI and arthroscopy: A comparative study between ACL-injured and non-injured subjects. *Knee Surgery, Sports Traumatology, Arthroscopy*, *19*(Suppl 1), S12–S16. https://doi.org/10.1007/s00167-011-1502-4

Wada, M., Imura, S., Baba, H., & Shimada, S. (1996). Knee laxity in patients with osteoarthritis and rheumatoid arthritis. *British Journal of Rheumatology*, *35*(6), 560–563.

Wada, M., Tatsuo, H., Baba, H., Asamoto, K., & Nojyo, Y. (1999). Femoral intercondylar notch measurements in osteoarthritic knees. *Rheumatology*, *38*(6), 554–558.

Wang, C., Gong, X., Hu, X. Q., Jiang, Y. F., & Ao, Y. F. (2021). Association between time from anterior cruciate ligament injury to reconstruction and morphological changes of the intercondylar notch using MRI and arthroscopy. *The Knee*, *31*, 127–135. https://doi.org/10.1016/j.knee.2021.05.012

Whitney, D. C., Sturnick, D. R., Vacek, P. M., DeSarno, M. J., Gardner-Morse, M., Tourville, T. W., Smith, H. C., Slauterbeck, J. R., Johnson, R. J., Shultz, S. J., Hashemi, J., & Beynnon, B. D. (2014). Relationship between the risk of suffering a first-time noncontact ACL injury and geometry of the femoral notch and ACL: A prospective cohort study with a nested case-control analysis. *The American Journal of Sports Medicine*, *42*(8), 1796–1805. https://doi.org/10.1177/0363546514534182

Wolters, F., Vrooijink, S. H., van Eck, C. F., & Fu, F. H. (2011). Does notch size predict ACL insertion site size? *Knee Surgery, Sports Traumatology, Arthroscopy*, *19*(Suppl 1), S17–S21. https://doi.org/10.1007/s00167-011-1503-3

Zauleck, M. K., Gabriel, S., Fischmeister, M. F., & Hirtler, L. (2014). Origin of the anterior cruciate ligament and the surrounding osseous landmarks of the femur. *Clinical Anatomy*, *27*(7), 1103–1110. https://doi.org/10.1002/ca.22440

Ziegler, C. G., Pietrini, S. D., Westerhaus, B. D., Anderson, C. J., Wijdicks, C. A., Johansen, S., Engebretsen, L., & LaPrade, R. F. (2011). Arthroscopically pertinent landmarks for tunnel positioning in single-bundle and double-bundle anterior cruciate ligament reconstructions. *The American Journal of Sports Medicine*, *39*(4), 743–752. https://doi.org/10.1177/0363546510387511

How to cite this article: Hirtler, L., Kainberger, F., & Röhrich, S. (2022). The intercondylar fossa—A narrative review. *Clinical Anatomy*, *35*(1), 2–14. https://doi.org/10.1002/ca.23773