Paediatric reference anatomy for ACL reconstruction and secondary anterolateral ligament or lateral extra-articular tenodesis procedures

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ARTICLE INFO

Keywords:
Anterior cruciate ligament (ACL) reconstruction
Lateral extra-articular tenodesis
Anterolateral ligament (ALL) reconstruction
Lateral collateral ligament
Popliteus
Physis

ABSTRACT

Objectives: For iliotibial band (ITB) lateral extra-articular tenodesis or anterolateral ligamentous/capsular reconstruction with anterior cruciate ligament reconstruction, a clear understanding of the referenced anterolateral knee anatomy is critical—especially given the risk of injury to the physis or key anterolateral structures in the paediatric population, which is at high-risk for primary and secondary anterior cruciate ligament injury. The purpose of this study was to quantitatively assess the anatomy of the knee physes, paediatric lateral collateral ligament (LCL) origin, popliteus origin and ITB tibial insertion.

Methods: Nine paediatric cadaveric knee specimens with average age 4.2 years (range 2 months–10 years) underwent dissection to identify the LCL’s and popliteus’ femoral origins and the ITB’s tibial insertion. Metallic marking pins demarcated precise anatomic attachment sites, and subsequent computerised tomography scans enabled quantified measurements among them.

Results: LCL & Popliteus: On the femur, the popliteus origin lay consistently deep to the LCL and inserted both distally and anteriorly to the LCL, a mean distance of 4.6 mm (range 1.9–7.6; standard deviation 2.0). From the joint line, the LCL lay a mean distance of 12.5 mm proximally while the popliteus measured a mean of 8.2 mm. Both were consistently distal to the physis. The LCL was a mean distance of 4.4 mm (range 1.0–9.5) and the popliteus was a mean distance of 8.2 (range 1.7–12.5) from the physis. ITB insertion: The ITB insertion at Gerdy’s tubercle had an average footprint measuring 28.2 mm² (range 10.3–58.4) and the ITB centre lay proximal to the physis in 6 specimens (mean age 4.2 years, median 2.5 years) and distal in 3 specimens (mean age 1.5 years, median 4 months). Mean distance from the footprint centre to the physis was 1.6 mm proximal (range 7.1 proximal – 2.2 distal).

Conclusion: This study describes relative and quantitative positions of the femoral LCL and popliteus origins and tibial ITB insertion and their respective physeal relationships. Knowledge of paediatric anterolateral knee anatomy will help guide essential future research and procedures providing extra-articular anterolateral rotatory stabilisation and may help reduce iatrogenic physeal injury risk.

Level of evidence: N/A (descriptive anatomic study).

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https://doi.org/10.1016/j.jisako.2022.04.008
Received 27 October 2021; Received in revised form 4 March 2022; Accepted 30 April 2022
Available online xxxx

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Please cite this article as: Randhawa S et al., Paediatric reference anatomy for ACL reconstruction and secondary anterolateral ligament or lateral extra-articular tenodesis procedures, Journal of ISAKOS, https://doi.org/10.1016/j.jisako.2022.04.008
Introduction

The anterolateral knee provides stability for both anterior translation and anterolateral rotation of the knee. Following ACL reconstruction, such stability is crucial to maximise the performance of outcome measures and minimise the risk of re-tear. Surgical techniques for optimal knee stabilisation continue to evolve for intra- and extra-articular techniques [1–4]. Combined ACL reconstruction with LET or ALL reconstruction procedures continue to advance [3–6] reflecting a growing body of evidence regarding the role of anterolateral structures as secondary stabilisers and the biomechanical impact of anterolateral injury and repair on tibial internal rotation [7–9]. These procedures may involve anatomic reconstruction of the anterolateral capsule and/or non-anatomic stabilising procedures of the anterolateral tissues either by free graft harvest or illiotibial band (ITB). In adults, studies have shown reduction in rotational laxity in ACL reconstruction combined with LET compared to those receiving ACL reconstruction alone [2], and studies on two-year complication rates and functional outcome scores for combined ACL and ALL reconstruction have shown promising results [10].

ACL reconstruction procedures combined with extra-articular stabilising techniques are gaining interest and being evaluated for high-risk patient populations—especially paediatric athletes in which re-tear rates have been reported up to 29% of patients younger than 20 years of age [11]. Physeal-sparing ACL reconstruction as described by Micheli [12] utilises a harvested ITB to create a combined extra-articular tenodesis as well as intra-articular ACL reconstruction without drilling osseous tunnels and has shown excellent short-term [13] and long-term [14] outcomes. In a paediatric population, Wilson and Ellis [15] showed only a 5.3% reinjury rate with the combined transphyseal hamstring autograft and ITB LET procedure. Most recently, the multicentre, randomised control trial STABILITY [3] of young athletes with a high-risk of failure has shown that hamstring graft ACL reconstruction with ITB LET led to a statistically and clinically significant reduction in graft rupture and rotatory laxity at 24 months postoperatively [4]. Furthermore, to evaluate the reported increased pain and possible lateral compartment over-constraint with added ITB LET, STABILITY also monitored functional outcomes and found them to be unaffected and not inferior to ACL reconstruction alone [16].

The basis for any surgical reconstruction is precise knowledge of anatomy and biomechanics. Adult reconstructive techniques for ALL reconstruction and LET procedures reference the anterolateral knee anatomy, specifically the LCL, popliteus tendon and ITB insertion at Gerdy’s tubercle; however, data are sparse regarding the locations of these structures for the paediatric population.

Knowledge of these structures’ anatomic relationships is essential to address the specific concerns in paediatric ligament reconstruction of iatrogenic physical damage, growth arrest and deformity and to implement techniques for physeal-sparing tunnel placement.

What is already known?

- Paediatric athletes are at high-risk for re-tear after anterior cruciate ligament (ACL) reconstruction, causing surgeons to consider combining ACL reconstructions with extra-articular stabilising techniques like lateral extra-articular tenodesis (LET) or anterolateral ligamentous/capsular (ALL) reconstruction.
- In adults, these extra-articular stabilising techniques reference the anterolateral knee anatomy, specifically the lateral collateral ligament (LCL), popliteus tendon and ITB insertion at Gerdy's tubercle; however, data are sparse regarding the location of these structures for the paediatric population.
- Knowledge of these structures’ anatomic relationships is essential to address the specific concerns in paediatric ligament reconstruction of iatrogenic physical damage, growth arrest and deformity and to implement techniques for physeal-sparing tunnel placement.

What are the new findings?

- The popliteus attachment on the femur was found consistently anterior and distal to the LCL origin, which may help with the identification of appropriate femoral socket position.
- The attachment of the popliteus and the LCI origin were consistently distal to the distal femoral physis, suggesting the placement of tunnels or sockets should be in the epiphysis. The femoral origin of this reconstructed tissue can be placed below the physis and above the joint line to avoid physeal injury.
- The ITB insertion at Gerdy's tubercle possessed an inconsistent relationship to the physis—proximal to the physis in 6 specimens and distal in 3 specimens—that may promote surgeon preference to leave the ITB insertion intact and minimise additional tibial fixation.

Materials and methods

An institutional review board (IRB) deemed IRB approval was not necessary for this study, as it did not include patient identifiers, the use of genetic information or contact with patient families as per guidelines by Health and Human Services (www.hhs.gov). A tissue harvesting facility (Allosource, Centennial, CO, USA) sourced the cadaveric tissue, which possessed family consent for use in research purposes prior to conducting this study.

Nine paediatric cadaveric knee specimens underwent dissection to identify the ligamentous femoral origin of the LCL, popliteus and tibial insertion of the ITB. The specimens possessed an age range of 2 months–10 years and were comprised of 7 males and 2 females (5 right, 4 left). Teams of three to four fellowship-trained orthopaedic surgeons conducted the dissections and placed marking pins to localise the central footprint of these structures as described below. Computed tomography (CT) scans (0.625 mm slices, GE Litespeed Scanner, Cincinnati, Ohio, USA) enabled the identification of the pin insertions onto the cortical bone as well as precise measurements among the pinned structures using the Osirix Imaging Software (v10.0.4).

Coronal plane measurements of ITB insertion

During the dissection, the team of surgeons placed four marking pins at the most superior, most inferior, most lateral and most medial aspects of the ITB insertion at Gerdy’s (Fig. 1). On coronal CT image (Fig. 2), the location at which these pins entered the epiphysis or cortical bone formed the points defining the footprint of the ITB insertion. The relevant measurements for this structure included distances between the most superior and most inferior points and the most lateral and most medial points. Using these points, the team defined the centre of the ITB
footprint at Gerdy's tubercle as the point as equidistant between these perimeter points. Lastly, the team calculated footprint size through the measurement of a best-fit ellipsoid area outlined by these perimeter points.

Fig. 1. Dissected specimen with marking pins was placed to denote studied structures. (a) Left knee of a 4-year-old specimen. On the femur, the larger-headed blue pin was placed at the popliteus’ origin, demonstrating the anterior and distal relationship to the smaller-headed blue pin placed at the LCL’s origin. (b) Left proximal tibia of a 10-year-old specimen. ITB reflected inferiorly, exposing Gerdy’s tubercle with green pins marking medial- and lateral-most extent and pink pins marking superior- and inferior-most points (inferior pin obscured by reflected ITB).

Fig. 2. CT images of specimens with pins marking anatomic structures. (a) Coronal CT view of proximal tibia with marker indicating most superior point of Gerdy’s tubercle and its relationship to the physis and cartilaginous articular surface in this specimen. (b) Sagittal CT view of the left distal femur and proximal tibia with markers indicating key labelled structures. Compared to the LCL’s origin, the popliteus’ origin is found anterior and distal. Relation to the physis and cartilaginous articular surface are clearly identified. CT, computed tomography; LCL, lateral collateral ligament.
Sagittal plane measurements of LCL and popliteus origins

The team also placed marking pins during the dissection at the origins of the LCL and popliteus tendon on the femur (Fig. 1). On sagittal CT, the location at which these pins entered the epiphysis or cortical bone similarly formed the reference points for the measurement of distances between these origins, as depicted in Fig. 2. The use of 3D CT renderings assisted with the identification of these locations, illustrated in Supplemental Fig. 1. Other relevant measurements surrounding these structures included their respective distances to the physis and to the joint line as well as the distance from the LCL origin to the cortex of the posterosuperior femoral condyle, exemplified in Fig. 2.

Results

ITB insertion

The location of the centre of Gerdy's tubercle relative to the physis was proximal to the physis in 6 specimens and distal in 3 specimens. Mean distance from the footprint centre to the physis was 1.6 mm proximal (range 7.1 mm proximal to 2.2 mm distal). Fig. 3 depicts how this distance varied with respect to specimen age. Mean distance from the footprint centre to the joint line was 9.6 mm distal (range 5.4 mm proximal to 14.9 mm distal). The ITB insertion at Gerdy's tubercle had an average footprint measuring 28.2 mm² (range 10.3 – 58.4). The distance from the tubercle's superior-most point to the inferior-most point was a mean 8.0 mm (4.6 – 16.1 mm). The distance from the tubercle's lateral-most point to the medial-most point found on the tubercle was a mean 4.5 mm (2.9 mm – 8.3 mm). Table 1 provides per specimen measurements for these quantities, and Supplemental Fig. 2 depicts graphically how the dimensions and area of Gerdy's tubercle vary with respect to specimen age. To provide a normalised distance quantity taking into account varying specimen size, the distance from Gerdy's tubercle to the physis was also represented as a percent of the distance of Gerdy's tubercle to the joint line, provided in Table 1 and in Supplemental Fig. 3.

Fig. 3. ITB insertion distance to proximal tibial physis as a function of age, presented as clustered bar plot. ITB, iliotibial band.

Table 1

<table>
<thead>
<tr>
<th>#</th>
<th>Age</th>
<th>Laterality</th>
<th>GT superior to inferior</th>
<th>GT lateral to medial</th>
<th>Area of GT</th>
<th>GT centre to physis*</th>
<th>GT centre to joint line</th>
<th>GT centre to physis, as % of GT centre to joint line</th>
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<tr>
<td>1</td>
<td>2 mo</td>
<td>L</td>
<td>4.55</td>
<td>2.89</td>
<td>10.32</td>
<td>–1.1</td>
<td>11.0</td>
<td>8.1</td>
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<tr>
<td>2</td>
<td>2 mo</td>
<td>R</td>
<td>5.55</td>
<td>3.73</td>
<td>16.25</td>
<td>4.1</td>
<td>22.4</td>
<td>7.42</td>
</tr>
<tr>
<td>3</td>
<td>2 mo</td>
<td>R</td>
<td>5.3</td>
<td>4.4</td>
<td>18.31</td>
<td>1.42</td>
<td>19.7</td>
<td>26.2</td>
</tr>
<tr>
<td>4</td>
<td>4 mo</td>
<td>L</td>
<td>4.6</td>
<td>4.8</td>
<td>17.33</td>
<td>–1.6</td>
<td>18.9</td>
<td>26.4</td>
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<tr>
<td>5</td>
<td>2 yrs</td>
<td>R</td>
<td>5.81</td>
<td>2.94</td>
<td>13.41</td>
<td>1.74</td>
<td>15.1</td>
<td>27.5</td>
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<td>6</td>
<td>3 yrs</td>
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<td>6.87</td>
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<td>29.07</td>
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<td>L</td>
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<td>–2.16</td>
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<tr>
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<td>9</td>
<td>10 yrs</td>
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<td>45.56</td>
<td>3.94</td>
<td>50.5</td>
<td>14.19</td>
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# refers to specimen number. GT = Gerdy's Tubercle. * = For Gerdy's tubercle centre to physis measurements, negative values indicate Gerdy's tubercle centre being found distal to the physis. All distance units in mm unless specified.

Table 2

<table>
<thead>
<tr>
<th>#</th>
<th>Age</th>
<th>Laterality</th>
<th>LCL to Pop. to joint line</th>
<th>Pop. to LCL to joint line</th>
<th>LCL to pop. to phys*</th>
<th>LCL to phys*</th>
<th>LCL to PSFC</th>
<th>LCL to phys* as % of LCL to joint line</th>
<th>Pop. to phys* as % of Pop. to joint line</th>
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</thead>
<tbody>
<tr>
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<td>2 mo</td>
<td>L</td>
<td>1.89</td>
<td>10.07</td>
<td>11.2</td>
<td>–1.73</td>
<td>–1.01</td>
<td>8.86</td>
<td>17.2</td>
</tr>
<tr>
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<td>2 mo</td>
<td>R</td>
<td>2.73</td>
<td>5.6</td>
<td>6.92</td>
<td>–8.58</td>
<td>–7.06</td>
<td>9.14</td>
<td>153.2</td>
</tr>
<tr>
<td>3</td>
<td>2 mo</td>
<td>R</td>
<td>4.58</td>
<td>7.06</td>
<td>11.9</td>
<td>–7.99</td>
<td>–3.37</td>
<td>10.45</td>
<td>113.2</td>
</tr>
<tr>
<td>4</td>
<td>3 yrs</td>
<td>R</td>
<td>5.45</td>
<td>1.3</td>
<td>8.13</td>
<td>–7.85</td>
<td>–3.85</td>
<td>7.65</td>
<td>603.8</td>
</tr>
<tr>
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<td>4 yrs</td>
<td>L</td>
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<td>8.82</td>
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<td>–9.56</td>
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<td>108.6</td>
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<tr>
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<td>L</td>
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<td>14.17</td>
<td>–12.46</td>
<td>–9.53</td>
<td>19.36</td>
<td>109.4</td>
</tr>
</tbody>
</table>

# refers to specimen number. Pop. = popliteus. * = for the popliteus and LCL measurements to the physis, negative values indicate the popliteus or LCL origin being found distal to the physis. PSFC = posterosuperior femoral condyle. All distance units in mm unless specified.
Fig. 4. LCL and popliteus origin measurements as a function of age, presented as clustered bar plot. (a) Depicts the distance of the LCL origin to the physis, (b) depicts the popliteus origin to the physis, and (c) depicts the distance between the LCL origin and the Posterosuperior Femoral Condyle (PSFC). LCL, lateral collateral ligament.
LCL & popliteus

Of the 9 specimens, 7 had femurs available for CT measurements, with the LCL and popliteus tendon origins readily identified on each of these as exemplified in Fig. 2. On the femur, the popliteus was consistently found deep to the LCL and inserted both distally and anteriorly to the LCL at a mean distance of 4.6 mm (range 1.9 mm–7.6 mm). The LCL measured a mean distance of 12.5 mm (range 6.9 mm–20.4 mm) to the joint line while the popliteus measured a mean distance of 8.2 mm (range 1.3 mm–13.2 mm) from the joint line. Both the LCL and popliteus were consistently distal to the physis for each of the 7 specimens. The LCL was a mean distance of 4.4 mm (range 1.0 mm–9.5 mm) and the popliteus was a mean distance of 8.2 mm (range 1.7 mm–12.5 mm), respectively. The LCL was a mean distance of 11.5 mm (range 7.7 mm–19.4 mm) from the posterosuperior femoral condyle. Table 2 provides per specimen measurements for these quantities. Fig. 4 along with Supplemental Fig. 4 depict how these distances vary with respect to specimen age. To provide a normalised distance quantity taking into account varying specimen size, the distances from LCL and popliteus to the physis were also represented as a percent of their respective distances to the joint line, provided in Table 2 and in Supplemental Fig. 3.

Discussion

The findings of this study provide a quantitative description of the anatomy of paediatric anterolateral knee structures which are key to stabilisation procedures such as LET or ALL reconstruction. In addition to the provided mean dimensions and distances among the aforementioned structures, physis and joint line, several relationships appreciated during this study merit emphasis. First, the popliteus attachment on the femur consistently lay anterior and distal to the LCL origin. Second, both the attachment of the popliteus and the LCL origin were consistently distal to the distal femoral physis. Third and by contrast, the ITB insertion at Gerdy's tubercle possessed an inconsistent relationship to the physis: proximal to the physis in 6 specimens and distal in 3. These relationships may guide physeal-respecting/protecting surgical technique development around the lateral aspect of the knee.

A few studies have described the relationships of these structures in the paediatric context. One previous study of the paediatric anterolateral ligament anatomy notably reported a similar orientation of the popliteal and LCL origins relative to each other [25]. LaPrade et al. demonstrated this same relationship in adult anatomy (mean age of 63 years) [26], suggesting these structures’ relative positioning may be conserved throughout the process of skeletal maturity. Of note, the distance between these two structures reported in LaPrade et al. study is 18 mm, in contrast to 4.6 mm in this study, suggesting that these structures move farther apart with growth. Previous paediatric studies have reported relationships to the physis for some of these structures. One cadaveric study [18] reported a median 9 mm between the LCL origin and femoral physis longer than the median 3.4 mm (mean 4.4 mm) reported in this study. Likely, this difference in median distance reflects a difference in specimen age between the studies’ cohorts: range 7–11 years with a median age of 8 years in the study from Shea et al. vs. range 2 months–10 years with a median age of 3 years for this study. To the best of the authors’ knowledge, little to no previous data exist that reports position of the reported anatomic landmarks with respect to the joint line.

Elucidating the positions of these anterolateral knee landmarks in the context of paediatric anatomy can hopefully guide extra-articular stabilisation procedures such as LET and ALL reconstruction. On the femoral side, appreciating the position of the LCL origin relative to the popliteus may help with the identification of appropriate femoral socket position for ALL reconstruction [27]. Furthermore, given the LCL and popliteus origins being consistently distal to the physis, the placement of tunnels or sockets should be in the epiphysis. Of note, these structures—especially the more proximal LCL origin—lie a short distance from the physis and thus warrant caution when placing tunnels or sockets near them, especially given the undulating nature of the distal femoral physis [28]. Techniques that allow drilling closer to the joint line would potentially create a greater margin of safety from these key structures. From the perspective of ACL reconstruction tunnel placement, this data provide information when using an all-epiphyseal technique, as outlined in past studies [24,29], to produce tunnels that proceed from the ACL femoral footprint to exit posterior to the LCL origin or near the popliteus tendon insertion.

On the tibial side, the variety of extra-articular tenodesis techniques available vary based on their treatment of the ITB insertion, such as maintaining the insertion [5], detracting its insertion [30], looping around with subsequent reattachment to an anterolateral tibial reinsertion point [31] or utilisation of completely independent autograft or allograft [27,32] in the area of the ITB. The variability of the position of the ITB attachment at Gerdy’s tubercle relative to the physis should inform technique selection or implementation. For instance, due to this variability and concerns for physeal injury, a surgeon may prefer leaving the ITB insertion intact and minimising additional tibial fixation. Furthermore, the results of this study suggest that the ITB attachment at Gerdy’s tubercle migrates farther away from the physis with increasing age—potentially between ages 4 and 10 in this study’s data—and lies proximal to the physis at older ages closer to 10 years of age. Thus, for techniques where tibial fixation is necessary, surgeons should consider placing such fixation in older patients proximal to the physis or avoiding tibial fixation altogether by preserving the native ITB attachments on the tibia, if this tissue is used as part of an ALL/LET procedure.

The limitations of this study include limited samples from each age, consistent with the reality that access to paediatric tissue for cadaveric/anatomic studies is severely limited. The specimens represented a wide age range, but the study was not able to determine correlation with measured quantities and age-adjusted expectations for the lateral knee structures. With inclusion of specimens less than 8 years old, the study’s cohort’s age range is also notably younger than that of paediatric patients most often receiving ACL reconstructions. Some studies have shown variation in knee ligament anatomy and physeal relationship with the growth and development in paediatric knees [33,34], including younger specimens in this study still can provide clinically relevant insight for older skeletally immature patients with open physes. First, the discussed anatomic relationships that are consistent between young patients <1 year of age and adult populations highly suggest the same consistent relationship in older pre-pubescent or adolescent anatomy. Second, despite the size of knees varying considerably between infant and 10-year-old specimens, this contributes to establishing the consistency of structures’ relationship to the physis across a range of development; as discussed, this consistency can potentially guide how a surgeon might choose an LET technique for combined ACL reconstruction or place tunnels for all-epiphyseal ACL reconstruction in older skeletally immature patients with open physes. Furthermore, studies on paediatric ACL injuries or combined ACL reconstruction outcomes have been shown to include patients as young as 5.7 years of age [14] and more frequently patients of 9–11 years of age and also have shown an increase of injuries in the age bracket of 5–12 and 5–14 years old [11,35–37], overlapping with the older specimens in this study. This study’s cohort also consisted of more male specimens than female specimens; therefore, the extrapolation of any data may face limits due to skewed sex representation. Future studies building on this work should incorporate older paediatric specimens with more thorough sex representation where these exceptionally rare specimens become available. Additionally, given the findings regarding the position of the ITB attachment relative to the physis, another future direction of interest could consist of biomechanical analysis comparing LET procedures with ITB that insert proximally to the physis with those that insert distally.

Paediatric athletes as a group are at high-risk for re-tear of their reconstructed ACL [11], causing surgeons to consider and evaluate LET and ALL reconstruction techniques as adjuncts to ACL reconstruction.
with recently promising outcomes for this high-risk group \cite{4,15,16,28}. Work to evaluate these procedures and optimise their outcomes requires an understanding of the lateral knee anatomy, including the LCL, popliteus and Gerdy's tubercle. This study provides an evaluation of such structures and their relationships unique to the paediatric population.

Conclusion

This study quantitatively describes the paediatric anterolateral knee anatomy commonly referenced in descriptions of the anterolateral ligament and techniques for lateral extra-articular reconstruction. Knowledge of the relative and quantitative positions of the LCL and popliteus origins on the femur and ITB attachment at Gerdy's tubercle on the tibia and their respective relationships to the physes will help guide extra-articular procedures that provide extra-articular anterolateral rotatory and their respective relationships to the physes will help guide extra-articular anterolateral rotatory stabilisation in the paediatric patients and may help reduce the risk of iatrogenic physeal injury.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

Based on signed ICMJE disclosure forms from each author, the following authors reported the below declarations.

Dr. Philip Wilson:
- Pylant Medical, educational support in 2018 (cadaveric supply, <3000$) and not related to this study

Dr. Daniel Green:
- Royalties and licenses: Arthrex Inc., Pega Medical
- Consulting fees: Arthrex Inc.
- Payment or honoraria for lectures, presentations, speakers bureaus, manuscript writing or educational events: AO Trauma International, Arthrex Inc.

Dr. Peter Fabricant:
- Participation on a Data Safety Monitoring Board or Advisory Board: On editorial and governing board for Clinical Orthopaedics and Related Research, Paediatric Orthopaedic Society of North America, Research in Osteochondritis of the Knee (ROCK)

Dr. Theodore Ganley:
- Other from Vericel Corporation, other from Arthrex, other from AlloSource, outside the submitted work; and The American Journal of Sports Medicine – associate editor, Paediatric Research in Sports Medicine (PRISM) – committee member, American Academy of Paediatrics Section on Orthopaedics – board or committee member, International Paediatric Orthopaedic Symposium (IPOS) – board or committee member, POSNA – committee member, AAOS – board or committee member.

Dr. Henry Ellis:
- Grants from POSNA, grants from AAOS, outside the submitted work; and Texas Orthopaedic Association - Board of Directors; Paediatric Research in Sports Medicine (PRISM) - Board of Directors.

Acknowledgements

The authors thank Tom CyCota, CEO, and Todd Huft of Allosource (Centennial, CO, USA) for the donation of the cadaveric specimens and non-financial research support. We are grateful to the families that made these remarkable donations to allow us to continue to improve patient care and outcomes.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsakos.2022.04.008.

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