Age-Based Patellofemoral Morphology in the Immature Knee

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Abstract

Purpose: Patellar instability (PI) is a common cause of anterior knee pain and disability in the pediatric population. The use of patellofemoral measurements on MRI provides a quantitative means for PI assessment and has now become an important diagnostic tool, but these techniques largely rely upon adult standards. Our goal is to describe morphologic trends in the skeletally immature knee and to predict the age at which adult norms can reliably be used in the evaluation of the pediatric knee.

Methods: We retrospectively reviewed 144 normal knee MRIs in 133 skeletally immature patients that presented between 2002 and 2014. Patients were equally distributed by age and gender with ages ranging from 1-16. MRI exclusion criteria included: moderate to severe effusions, cartilaginous defects, patellofemoral abnormalities, ligamentous injury, neoplasms, infection, congenital disease, or arthritic changes. All 1 and 2 year olds were included due to lack of MRIs and only females younger than 15 were used to account for anticipated physical closure. All measurements used cartilaginous landmarks and results were stratified based on age and gender. Each measurement was charted in a linear regression model or analyzed with Student’s t test.

Results: Each measurement can reliably be performed at all ages with good inter- and intra observer reliability. All MR measurements were graphically represented in a linear regression model and are shown to approach adult norms with increasing age. The age at which there is no statistical difference between our pediatric patients and the adult norms is shown as the “regression cutoff”. Further t-test analysis suggests a 2nd cutoff that serves as the age at which younger should not be compared to adult norms.

Conclusion: The measurements commonly used to evaluate for patellar instability in the adult population are subject to considerable variation throughout skeletal maturation. Based on our analysis, children < 10 years of age should not be compared to adult standards. Conversely, children ≥ 10 appear to have reached near patellofemoral maturation and show consistent and progressive development of patellofemoral morphology with increasing age.

Significance: The ability to predict morphologic abnormalities in the first decade of life may lend to earlier surgical intervention or realignment procedures. Surgical outcomes may be augmented by remaining patellofemoral growth and remodeling, especially in those patients under 10 years of age.

INTRODUCTION

Primary patellar dislocation is a multi factorial disorder that is estimated to occur in 5.8 in 100,000 individuals [1]. Although the underlying etiology is unclear, anatomical abnormalities involving the distal femur, patella, and the surrounding soft tissues have been shown to disrupt mechanical and structural mechanisms of the knee, resulting in patellar instability [2,3]. Three of the most significant anatomical variants include trochlear dysplasia, patella alta, and tibial tubercle – trochlear groove distance [2,3].

Plain radiographs and computed tomography were first used to describe anomalous anatomical features associated with patellar instability [2]. More recently, MRI has become an important diagnostic tool, as it is able to visualize soft-tissue abnormalities and can differentiate between the cartilaginous and osseous contours of the patellofemoral joint [4-11].

Normative patellofemoral morphology has been established on MRI, but there remains a lack of data within the pediatric cohort [12]. Our objectives are to (1) describe age-based normative patellofemoral morphology in the pediatric population, and (2) to determine if adult measurements can reliably be used in the evaluation of the pediatric knee.

MATERIALS AND METHODS

Study Population

After institutional review board approval, we retrospectively reviewed “normal” knee MRIs in 131 pediatric patients (77 knee MRIs in 71 males, 67 knee MRIs in 60 females) ages 1 thru 16 with an open physic who presented from 2002-2014. All these patients obtained a knee MRI to evaluate knee pain or clinically suspected knee pathology. For the purposes of this study, “normal” MRIs were defined as those with no developmental abnormalities (e.g.
nopatella alta, trochlear dysplasia, or tibial tubercle – trochlear groove distance greater than 20mm). Normal MRIs included baker’s cysts, discoid menisci, and small effusions in this study. To account for anticipated physical closure, we included female knee MRIs from age 1 to 14 and male knee MRIs from age 1 to 16. With the exception of 1-2 year olds (n=14 knee MRIs, 7 males and 7 females), knee MRIs from 5 males and 5 females were randomly selected to represent each age group from 3 to 14 ages, and additional 10 male knee MRIs (5 each) were randomly selected from boys ages 15 and 16. Thus, a total of 144 knee MRIs from 131 patients (11 had bilateral MRIs, while 2 had repeat ipsi lateral MRIs performed at a later age) were included and analyzed in this study. Each MRI was read by a pediatric-trained radiologist to ensure the knee MRI met “normal” defined in this study, without any other development abnormalities. The included knee MRIs were stored in our Picture Archiving and Communication Systems (PACS) for further analysis.

Exclusion criteria included presence of a closed physic, abnormal radiographic findings that may affect patellofemoral morphology, including moderate to severe effusions, cartilaginous defects, anatomic abnormalities, ligamentous injury, neoplasms, infection, or arthritic changes.

MRI Protocol

All MR imaging was performed at our institution utilizing a 1.5-3.0T imaging system with a knee coil. Each patient had routine knee images as per our hospital protocol. Knees were placed in extension with axial and sagittal measurements obtained from T2 or PD sequences for optimal cartilage visualization. Axial slice thickness varied between 3-5mm, whereas sagittal slices were 2-4mm in thickness. Each knee reviewed on MRI was shown to have an open physic.

MRI Measurements

After collaboration with a pediatric-trained radiologist, all measurements were recorded in PACS individually by two authors, both of whom were pediatric orthopaedic research residents at the time of the study and had extensive training on the study protocol and MRI imaging reading. Each was blinded to the other’s results. All measurements were performed to include cartilaginous landmarks on the distal femur and patella (Figure 1). To maintain reproducibility, five axial measurements (lateral trochlear inclination (LTI), trochlear facet asymmetry (TFA), trochlear depth (TD), tibial tuberosity-trochlear groove (TTTG), and sulcus angle (SA)) were taken at a single sequence (Figure 2). The six measurements are outlined in Table 1. The six adult patellofemoral measurements were selected based on published work that demonstrated reproducibility, as well as, predictability in assessing patellofemoral pathology [2,4,7,9,13-23]. Normative values as described by Charles et al. were utilized [4]. He and his colleagues compared 40 recurrent patellar instability patients to 81 control patients, and were able to delineate them based on patellar tilt measurements. (To the editor: No gender or age distributions were mentioned in the paper)

![Figure 1 Lateral Trochlear Inclination (LTI). The angle between the lateral trochlear facet (b) and the line along the posterior condyles (a) is measured.](https://example.com/figure1)

<table>
<thead>
<tr>
<th>Table 1: Description of Measurements.</th>
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<td><strong>Lateral Trochlear Inclination (LTI):</strong></td>
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<td><strong>Trochlear Facet Asymmetry (TFA):</strong></td>
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<td><strong>Trochlear Depth (TD):</strong></td>
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<td><strong>Tibial Tuberosity - Trochlear Groove (TTTG):</strong></td>
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<td><strong>Sulcus Angle (SA):</strong></td>
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<td><strong>Patellar Height Ratio (PHR):</strong></td>
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Lastly, we used the Insall-Salvati (IS) index as a measurement of patella alta, which can be shown in 24% of cases of patellar instability [12,16,17]. IS ratio is perhaps the most commonly used measurement technique and has been adapted to MRI, with a ratio of ≥ 1.3 considered abnormal [17].

**Statistical Analysis**

Each of the measurements taken by the two recorders were first averaged and then used to describe the distributions of each patellofemoral measurement across ages among pediatric participants. Linear regressions were used to model each of the six patellofemoral measurements against age, respectively. Predicted means of each of six measurements conditional on age were estimated, along with their 95% confidence intervals (CIs) Figure (2).

We treated each of the adult normative values (fixed values) as the population means and assumed that as age increased, the predicted pediatric means would approach the population mean Figure (3). The interval whereupon the population mean fell outside the 95% CI of the predicted pediatric mean was defined as statistically significant. To visualize the analysis, we plotted the regression lines along with their 95% CI lines, as well as, a reference line (population mean) in the scatter plot of each measurement versus age. The oldest age at which there is statistical significance is considered the “regression cutoff,” or the first cutoff. We then used a t-test analysis to examine whether there were statistically significant differences between our observed age-based pediatric means, assuming our regression cutoff to be most similar to population means, we compared the cumulative pediatric mean values at and above the regression cutoff to the age-based mean values below the cutoff. By doing so, we determined a “t-test cutoff”, or the second cutoff, demonstrated by the oldest age at which statistical significance was first seen (p < 0.05) when these two groups were compared.

**RESULTS**

Of 144 knee MRIs analyzed, the average value for lateral trochlear inclination (LTI) was 19.7 degrees (SD=4.1 degrees), trochlear facet asymmetry (TFA) was 73.2 (SD=11.7), trochlear depth (TD) was 4.6 mm (SD=1.4 mm), tibial tuberosity-trochlear groove (TTTG) was 7.8 degrees (SD=4.0 degrees), sulcus angle (SA) was 146.2 mm (SD=7.4 mm), and patellar height ratio (PHR) was 1.0 (SD=0.2). No gender difference was observed for any measurement, except trochlear depth (TD), with males having a TD 0.66 mm greater than females (p=0.004). The six measurements were each plotted by age as a linear regression line, along with 95% confidence intervals (CIs). For each measurement, values from the regression line along with 95% CIs were compared with adult normative values Figure (4). The point at which the adult normative values first fall between the confidence limits is the age at which there is no statistical difference between adult and pediatric data points. The estimated “regression cutoff,” or the first cutoff point based on the regression line, as well as the actual mean of the measurement at the cutoff, is shown in Table (2). For example, at age 14.94, the adult normative value of lateral trochlear inclination (LTI), which is 21.74, first falls between the 95%CI of the LTI regression line plotted, based on the child data from this study. The predictive mean of LTI at age 14.94 from the regression model was 20.50. While the cutoff ages vary amongst the six measurements, it’s seen that when children become approximately 9 years of age or older, the patellofemoral measurements start to show no statistical differences compared to their adult counterparts. Table (3) presents the “t-test cutoff,” or second cutoff point based on results of t-tests. This assumes that children at or above the second cutoff are not statistically different. Again, the cutoff values differ across the six measurements, but it can be seen that children ≥ 10 years of age are not statistically different in each of the six measures Figure (5).

Our mean PHR was 1.04 +/- 0.17 in comparison to the adult standard of 1.08 +/- 0.2 [4]. The regression analysis cutoff age is 9 years old.

**DISCUSSION**

This study aimed to describe age-based normative patellofemoral morphology in the pediatric population through analysis of 144 normal knee MRIs of males and females ages from 1 to 16. The main findings showed that while the cutoff ages based on the regression models vary amongst the six measurements, it is seen that when children become approximately 9 years of age or older, the patellofemoral measurements start to show no statistical differences compared to respective adult normative values.
There are statistically significant differences in knee morphology between adults and children. Data suggest that children ≥ 10 years of age are close to adult norms across all data points. However, these cutoffs should not be considered as absolute values. Furthermore, the regression models exhibit the remarkable remodeling potential of the immature knee, especially among children ages 1 to 10; trochlear depth specifically shows an increase in depth with increasing age. The ability to predict morphologic abnormalities in the first decade of life may lend to earlier surgical intervention or realignment procedures. Surgical outcomes may be augmented by remaining patellofemoral growth and remodeling (Figure 6). Patellar instability is typically associated with one of several anatomical abnormalities: 1) limb malalignment, 2) disruption of soft-tissue stabilizers, 3) abnormal trochlear morphology, 4) patella alta, or 5) increased TTTG [2,24,25]. The diagnostic role of MRI in assessing patellar instability has become an important one: MRI is able to differentiate between soft-tissue disorders, osseous variants, and it allows for visualization of articular contours [12]. Additionally, MRI is often necessary when operative intervention is considered, as surgical restoration of anatomy is essential to patient outcomes [12]. In an effort to standardize pediatric patellofemoral morphology and predict trends, we compared our data to an adult study by Charles et al., which utilized...
Central Sulcus Angle (SA). The angle (\(\theta\)) between the lateral and craniocaudal sequence where subtle dysplasia may be present; has traditionally been measured and considered abnormal and predictive of trochlear dysplasia [12,13]. LTI has been studied on MRI, with a value less than 11° considered abnormal and predictive of trochlear dysplasia [4]. Mean adult LTI was 21.74° compared to our value of 19.66° +/- 4.09 [4]. Kim et al., had a mean LTI of 19.8° +/- 4.6 in children with normal anatomy and an open physic, but used the most proximal sequence for measurement as described by Carillon [14,28]. We found that in younger children, slice thickness significantly impacted proximal trochlear visualization and could not be reliably reproduced. Therefore, we utilized the sequence with the largest condylar width, as it was easily reproducible even in the youngest children. Our linear regression model shows ages 14 and older to be statistically similar to adult norms, supporting the use of LTI in this age group. Additionally, t-test analysis suggests that ages less than 9 should not be compared to adult values. A second measure of trochlear depth, the sulcus angle, was originally described on plain radiographs but has alternatively been used on MRI [22]. The mean sulcus angle on plain radiographs is 138° +/- 6, with a value of > 145° considered abnormal [23]. Our total mean SA was 146.18° +/- 7.4. On adult controls, mean SA is 137.57° +/- 0.93 [4]. Linear regression analysis obtained a cutoff age of 15, with a t-test cutoff at 10 years old. Validating these cutoffs, the SA is found to be considerably higher in younger children and gradually plateau as it approaches adult norms. This is demonstrated by a mean SA of 140.90° in children > 9 years old, which is more similar to the adult standard.

Trochlear facet asymmetry (TFA) and trochlear depth (TD) have also been studied on MRI and provide a quantitative analysis of patellar instability [19]. TFA can be determined by the ratio of the medial to lateral facet, with a ratio less than 2:5 considered dysplastic, whereas a TD less than 4mm is considered dysplastic [19]. Our mean TFA and TD, are 0.73 +/- 0.12 and 4.6mm +/- 1.41 respectively in comparison to adult norms of 0.71 and 5.87mm [4]. Pfirrman et al., depicted measurements at 3cm above the knee joint as the most sensitive and specific for predicting trochlear dysplasia, but values showed statistical significance at 1 to 2cm above the joint which would bear more resemblance to our measurement technique[19]. A study by Kim et al., found a mean TFA and TD of 0.72 and 5.1mm, respectively [28]. TD had a regression and t-test cutoff age of 12 and 10, respectively. Interestingly, TFA had significantly younger age cutoffs at both regression analysis (8 years old), and the t-test (4 years old). This is likely the result of a ratio used to calculate TFA, which resulted in a smaller slope angle on the linear regression model, thus less variation across all ages. This is further exemplified with one of our other measurements, patellar height ratio.

The lateral displacement or malalignment of the patellar tendon in relation to its inferior attachment at the tibial tuberosity is a well-known factor of patellar instability [2,30]. On plain radiographs, the abnormal lateral vector was first depicted by measurement of the Q angle, but CT and MRI use has generated additional measurement techniques, such as the tibial tuberosity-trochlear groove (TTTG) distance 20,30. Although TTTG values have significant variability in patellar instability patients, a value of > 20 mm is predictably abnormal [2,3]. In our study, the mean TTTG was 7.84mm +/- 4.02, in contrast to 5.6mm +/- 3.0 seen by Kim [28]. Dickens et al., singularly measured TTTG in children, however, Charles et al., utilized proximal and distal MRI slices showing statistical significance between patellar instability patients and controls regardless of location of measurement (p < 0.001) [4]. Mean adult LTI was 21.74° compared to our value of 19.66° +/- 4.09 [4]. Kim et al., had a mean LTI of 19.8° +/- 4.6 in children with normal anatomy and an open physic, but used the most proximal sequence for measurement as described by Carillon [14,28]. We found that in younger children, slice thickness significantly impacted proximal trochlear visualization and could not be reliably reproduced. Therefore, we utilized the sequence with the largest condylar width, as it was easily reproducible even in the youngest children. Our linear regression model shows ages 14 and older to be statistically similar to adult norms, supporting the use of LTI in this age group. Additionally, t-test analysis suggests that ages less than 9 should not be compared to adult values. A second measure of trochlear depth, the sulcus angle, was originally described on plain radiographs but has alternatively been used on MRI [22]. The mean sulcus angle on plain radiographs is 138° +/- 6, with a value of > 145° considered abnormal [23]. Our total mean SA was 146.18° +/- 7.4. On adult controls, mean SA is 137.57° +/- 0.93 [4]. Linear regression analysis obtained a cutoff age of 15, with a t-test cutoff at 10 years old. Validating these cutoffs, the SA is found to be considerably higher in younger children and gradually plateau as it approaches adult norms. This is demonstrated by a mean SA of 140.90° in children > 9 years old, which is more similar to the adult standard.

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with a mean of 8.66mm +/- 0.3 [27]. Although variability exists between studies, our comparative analysis suggests that TTTG may have a predictive value of adult measurements, in children as young as 6 years of age. Our study is the first to describe age-based patellofemoral morphologic progression across multiple measurements. Furthermore, we selected measurements that assessed three distinct precipitating factors of patellar instability. Mundy et al., have shown excellent intra- and inter observer variability with such measurements [31, 32].

Some limitations were present with this study. Although bone age would be a better predictor of age-based norms, the retrospective nature of the study is prohibitive in obtaining this information. We also recognize the need for larger studies to corroborate our findings and to further delineate between normal and abnormal patellofemoral anatomy. We believe, however, that by obtaining adequate power and equal distribution of children, we were able to accurately represent morphologic progression.

CONCLUSION

A thorough understanding of normal patellofemoral anatomy is integral to the evaluation of patellar instability as the decision to treat conservatively versus operatively is complex and must account for anatomic derangements, severity of patellofemoral dysplasia, and the remodeling potential of such articulation. Patellofemoral morphology continues to evolve throughout childhood, especially among children ages 1 to 10. Our results suggest the six patellofemoral morphology measurements used in this study can reliably be performed at all ages with good inter- and intra observer reliability. While children ≥10 appear to have reached near patellofemoral maturation and are consistently shown to be within adult norms, children <10 years of age should not routinely be compared to adult values.

ETHICAL APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent: Informed consent was waived by our IRB from all individual participants included in the study, as this was a retrospective review.

REFERENCES


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