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Rotational Malalignment of the Knee Extensor Mechanism

Defining Rotation of the Quadriceps and Its Role in the Spectrum of Patellofemoral Joint Instability

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Background: Osseous rotational malalignment of the lower limb is widely accepted as a factor contributing to patellofemoral instability, particularly in pediatric patients. Patellar instability occurs when the lateral force vector generated by the quadriceps exceeds the restraints provided by osseous and soft-tissue anatomy. The anatomy and activation of the quadriceps are responsible for the force applied across the patellofemoral joint, which has previously been measured using the quadriceps (Q)-angle. To our knowledge, the contribution of the quadriceps anatomy in generating a force vector in the axial plane has not previously been assessed. The primary aim of this study was to introduce the quadriceps torsion angle, a measure of quadriceps rotational alignment in the juvenile population. The secondary aims of this study were to determine the inter-assessor and intra-assessor reliability of the quadriceps torsion angle in the juvenile population and to investigate whether a large quadriceps torsion angle is a classifier of patellar dislocator group membership in a mixed cohort of patellar dislocators and typically developing controls.

Methods: Participants between the ages of 8 and 19 years were recruited as either controls or recurrent patellar dislocators. A total of 58 knees in both groups were assessed from magnetic resonance imaging scans of the entire lower limbs. Axial cuts midway between the superior aspect of the femoral head and the articular surface of the medial femoral condyle were used to calculate the proximal reference for the quadriceps torsion angle. The quadriceps torsion angle was defined as the angle between the line connecting the anterior aspect of the sartorius and the junction of the anterior and posterior compartments at the lateral intermuscular septum and the posterior condylar axis line. Inter-assessor reliability was calculated using the intraclass correlation coefficient. The relationship between the quadriceps torsion angle and the femoral torsion was assessed in the entire cohort. These values were compared between the control group and the dislocator group to determine if the raw values or an interplay between the 2 factors played a role in the pathoanatomy of recurrent patellofemoral dislocation.

Results: The quadriceps torsion angle was a reproducible assessment in both inter-assessor and intra-assessor reliability analyses. A moderate positive correlation ($r = 0.624$; $p < 0.01$) was found between the femoral torsion and the quadriceps torsion angle. Although the quadriceps torsion angle was a fair classifier of patellar dislocation group membership, femoral torsion was not.

Conclusions: This study has quantified the rotational alignment of the extensor mechanism using the quadriceps torsion angle. The measurement is shown to be reliable and reproducible and a fair classifier of patellofemoral instability.

Clinical Relevance: This article introduces an objective measure of soft-tissue rotational malalignment in the pathogenesis of recurrent patellar dislocation.

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Rotational malalignment of the lower limb is thought to play a part in the pathogenesis of many orthopaedic conditions, particularly in the pediatric population[1,2]. Lower-limb rotation commences during the seventh week of gestation when the limb bud rotates 90° medially, causing the extensor mechanism to lie at the ventral aspect of the leg[3]. Rotation of the femur and tibia is thought to continue until the age of 7 years[4]. Although this temporal sequence of lower-limb development is well defined, the factors contributing to torsional malalignment and the development of patellofemoral instability are more difficult to determine. It is conceivable that the stresses and strains placed on the developing musculoskeletal system, as well as lower-limb biomechanics during early childhood[5,6], contribute to the onset of patellofemoral instability. Although measurements and prediction of longitudinal growth have been validated, the literature on rotational growth is scarce.

Patients with patellofemoral instability frequently present with abnormal lower-limb axial alignment, and investigations will generally include measures of femoral neck anteversion and tibial torsion[1,7]. Additional measures to determine the mechanism of patellofemoral instability include osseous measures of trochlear dysplasia, the tibial tubercle to trochlear groove distance, patella alta, genu valgum, and soft-tissue measures of medial patellofemoral ligament integrity, vastus medialis obliquus activation and volume, and the presence of generalized ligamentous laxity[7-9]. Measures of soft-tissue axial alignment have not previously been described in the assessment of pediatric patellofemoral instability. From a biomechanical point of view, patellar stability is determined by the force vector exerted by the quadriceps mechanism in all 3 planes, the axial plane being represented by rotation. The external rotation of the quadriceps musculature may contribute to a lateralizing force on the patella, which, if not constrained, will result in patellar dislocation. To understand if the quadriceps can exert a rotational force on the patella, it is necessary to understand the axial anatomy of the musculature. To our knowledge, a reliable measure of quadriceps alignment in the axial plane (i.e., the torsion of the quadriceps muscle itself) has not previously been documented in the literature.

The management of patellofemoral instability is multifaceted, with an extensive number of treatment options available[10-13]. Sound mechanical osseous alignment with balance of the associated soft-tissue structures are integral components to management when a surgical procedure is required. Surgical intervention involves assessment of the severity of instability and the underlying etiological factors to formulate a patient-specific management plan[10,14]. A greater understanding of the role of the rotational alignment of the quadriceps muscles may help to differentiate patients requiring more aggressive soft-tissue management of their pathology.

The primary aim of this study was to introduce the quadriceps torsion angle, a measure of quadriceps rotational alignment in the pediatric and adolescent population. The secondary aims of this study were to determine the inter-assessor and intra-assessor reliability of the quadriceps torsion angle in the pediatric and adolescent population and to investigate whether the relationship between quadriceps torsion angle and femoral torsion is associated with patellar dislocator group membership in a mixed cohort of patellar dislocators and typically developing controls. It was hypothesized that the quadriceps torsion angle would have good to excellent inter-tester and intra-tester reliability and would be a factor influencing patellar dislocator group membership.

Materials and Methods

A cross-sectional prospective radiographic analysis was conducted at the Queensland Children's Hospital in Brisbane, Queensland, Australia, on participants between the ages of 8 and 19 years. Participants were recruited as either controls or recurrent patellofemoral joint dislocators. Control participants with no history of lower-limb injury or pathology were recruited from the local community. Recurrent patellofemoral joint dislocators were recruited prospectively from pediatric orthopaedic clinics and were defined as patients having multiple (i.e., ≥2) dislocations of minimal energy. There were no refusals. Participants were excluded if they had any of the following conditions: congenital limb abnormalities, previous surgical intervention affecting the anatomy of the knee or extensor mechanism, any medical history of osseous or soft-tissue trauma or infection that may have affected osseous or soft-tissue anatomy, and inability to tolerate magnetic resonance imaging (MRI) scanning or being deemed unsafe for MRI after having completed the MRI safety questionnaire.

Participants were not paid but were offered free parking on the day of their medical imaging appointment. Study approval was obtained from the Children's Health Queensland Hospital and Health Services human research ethics committee and participants' guardians provided informed consent.

The Quadriceps Torsion Angle

A full lower-body MRI scan (1.5-T scanner, MAGNETOM Avanto^{fit} syngo MR VE 11-B; Siemens), including the pelvis and bones of the lower limbs, was performed with the participant in a supine position. The participant's feet were positioned in a rigid coil and were securely tightened with cushions to ensure neutral alignment. Three axial cuts were reconstructed in the picture archiving and communication system (PACS) to produce slices through the limb: (1) the femoral neck was reconstructed along its axis to visualize the version of the femoral neck, (2) a distal femoral cut was taken at the maximum anteroposterior diameter of the medial femoral condyle measured perpendicular to a line drawn across the posterior condyles, and (3) an axial slice was taken at a point halfway between the superior articular surface of the femoral head and the distal femoral articular surface to assess the quadriceps mechanism.

Subsequently, the following measurements were conducted in the PACS. The proximal reference for femoral neck version was measured from the midpoint of the anterior and posterior femoral neck cortices to the center of the femoral

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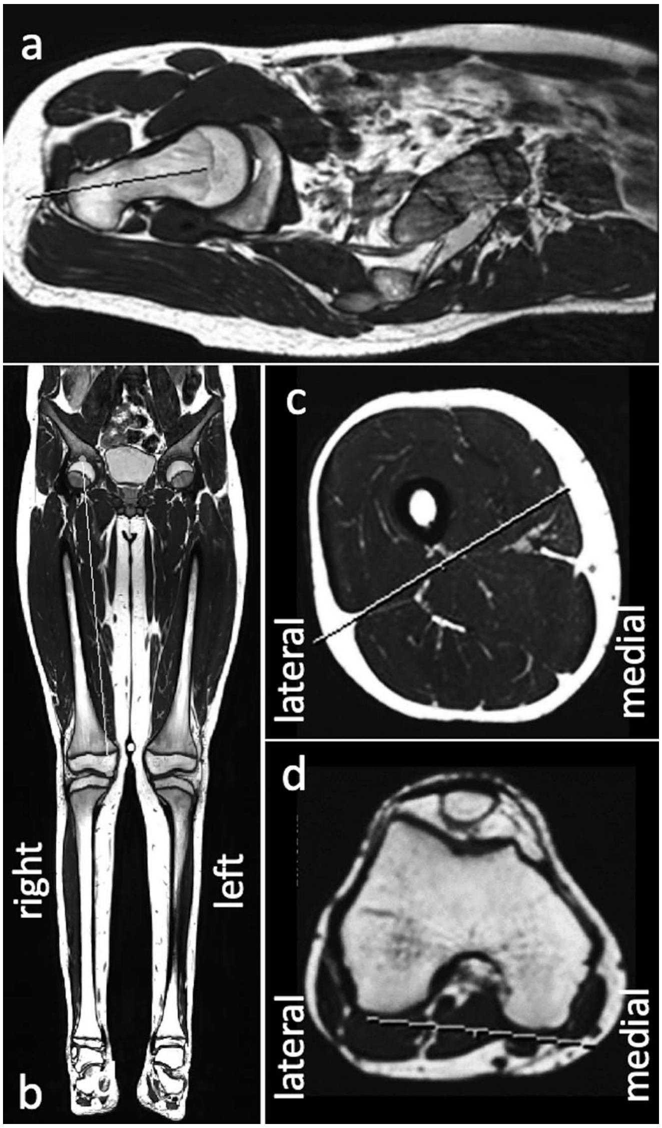

Fig. 1

Figs. 1-A through 1-D Imaging of a study participant. **Fig. 1-A** Measurement of the proximal reference of the femoral neck version from the midpoint of the anterior and posterior femoral neck cortices to the center of the femoral head. **Fig. 1-B** Measurement of the proximal reference for the quadriceps torsion at the midpoint of the thigh. **Fig. 1-C** A line connecting the anterior aspect of the sartorius to the junction of the anterior and posterior compartments at the lateral intermuscular septum. **Fig. 1-D** Femoral torsion and quadriceps torsion angle were calculated relative to the posterior condylar axis.

head (Fig. 1-A). The proximal reference for the quadriceps torsion was measured at the midpoint of the thigh (Fig. 1-B), and it was created by a line running from the anterior aspect of the sartorius medially, across the leg to the junction of the anterior and posterior compartments at the lateral intermuscular septum and reported relative to a horizontal line (Fig. 1-C). The posterior condylar axis was measured relative to a horizontal line using the margin of the articular cartilage (Fig. 1-D). The femoral neck version reference line and the quadriceps torsion reference line were calculated relative to the posterior condylar axis to determine the femoral torsion and quadriceps torsion angle.

Data Analysis

The above-mentioned measurements were performed on all participants by the treating clinician, and a subset of 12 knees (7 control knees and 5 patellar dislocator knees) were measured by a second clinician and again by the treating clinician. Intraclass correlation coefficients (ICCs) were calculated for inter-assessor and intra-assessor reliability (2-way random with absolute agreement) and were interpreted according to Koo and Li[15]. Following the reliability analysis, radiographic measurements were performed on the bilateral knees of 29 participants (58 knees). A bivariate Pearson correlation analysis was performed to assess the relationship between the femoral torsion and the quadriceps torsion angle. Receiver operating characteristic (ROC) curves were used to determine whether the femoral torsion and quadriceps torsion angle were significant classifiers of patellar dislocation, with optimal cut-points being calculated with the Youden index (J)[16] and being interpreted with caution when <0.5. The femoral torsion and quadriceps torsion angle measurements for a randomly selected lower limb for control participants and the affected lower limb of patellar dislocators were entered as variables into a hierarchical cluster analysis to determine whether any natural clusters of data existed independent of group membership. Between-group linkage was chosen as the cluster method and the squared Euclidian distance was chosen as the distance measurement. Data were standardized to Z scores to ensure equal weighting in the cluster analysis solution.

TABLE I Participant Characteristics and Medical Imaging Measurements for Each Group

	Controls (N = 14)	Dislocators (N = 15)
Sex*		
Male	4	2
Female	10	13
Age† *(yr)*	13.5 ± 2.8	14.8 ± 2.3
Mass† *(kg)*	47.4 ± 10.6	63.2 ± 19.6
Height† *(m)*	1.61 ± 0.13	1.66 ± 0.07
Femoral torsion† *(deg)*	12.0 ± 7.2	
Affected side		17.9 ± 11.1
Unaffected side		18.3 ± 8.5
Quadriceps torsion angle† *(deg)*	41.7 ± 6.7	
Affected side		50.4 ± 7.6
Unaffected side		49.8 ± 7.5

*The values are given as the number of patients. †The values are given as the mean and the standard deviation.

Results

Morphological parameters were gathered for 29 participants (58 lower limbs). There were 15 dislocators (13 female patients) and 14 controls (10 female patients) used for the comparative analysis (Table I). A randomly selected lower limb was used for control subjects (14 limbs), and the limb experiencing recurrent dislocation was included in the patellar dislocator group (15 limbs). Pearson correlation analysis revealed a poor correlation between age and femoral torsion ($r = 0.02$; $p = 0.90$) and a poor correlation between age and quadriceps torsion angle ($r = –0.7$; $p = 0.72$).

Inter-assessor reliability was excellent for the quadriceps torsion angle (ICC, 0.95 [95% confidence interval (CI), 0.87 to 0.99]) and femoral torsion (ICC, 0.91 [95% CI, 0.67 to 0.97]). Intra-assessor reliability was also excellent for the quadriceps torsion angle (ICC, 0.98 [95% CI, 0.94 to 0.99]) and femoral torsion (ICC, 0.91 [95% CI, 0.68 to 0.97]).

Pearson correlation analysis revealed a moderate positive correlation between the quadriceps torsion angle and femoral torsion ($r = 0.624$; $p > 0.01$) (Fig. 2). Predictive analysis revealed that femoral torsion was a poor classifier of patellar dislocation group membership (area under the ROC curve, 0.629 [95% CI, 0.417 to 0.840]; optimal cut-point, 18.4°; $J = 0.39$) and that the quadriceps torsion angle was a fair classifier of patellar dislocation group membership (area under the ROC curve, 0.767 [95% CI, 0.596 to 0.938]; optimal cut-point, 44.7°; $J = 0.44$).

Hierarchical cluster analysis revealed 2 distinct clusters of data with 20 cases in cluster 1, 8 cases in cluster 2, and a single outlier that was subsequently removed (Fig. 3). There were 8 patellar dislocators in cluster 1 and 7 in cluster 2, and there was only 1 control limb, of the 14 limbs, in cluster 2.

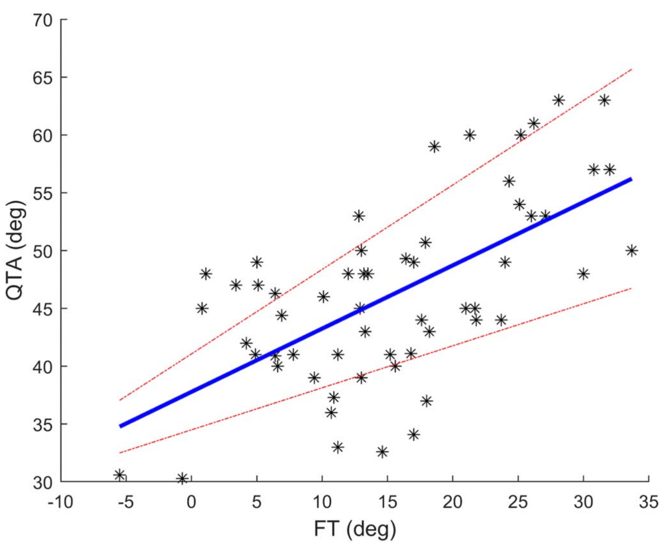

Fig. 2

Scatterplot of Pearson correlation analysis comparing the femoral torsion (FT) and the quadriceps torsion angle (QTA) in which the data points (asterisks) represent both control participants and patellar dislocators. The regression line is represented by the solid blue line, and the 95% CI represented the dashed-dotted red line.

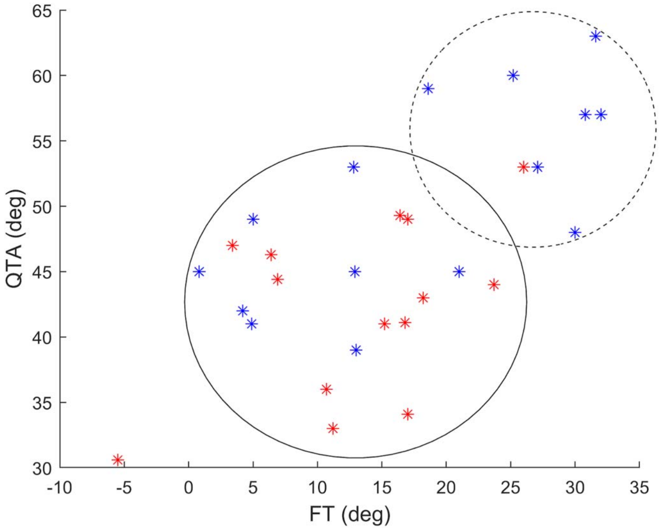

Fig. 3

Scatterplot of a hierarchical cluster analysis comparing the femoral torsion (FT) and the quadriceps torsion angle (QTA). The red data points (asterisks) represent a randomly selected lower limb of the control participants, and the blue data points represent the affected lower limb of the patellar dislocators. The solid line represents cluster 1 and the dashed line represents cluster 2.

Discussion

The quadriceps mechanism is thought to be an important dynamic stabilizer of the patellofemoral joint[17-19]. Composed of 4 muscles (vastus medialis, vastus lateralis, vastus intermedius, and rectus femoris), it exerts a resultant force on the patella dependent on the relative force contribution from each head and the relative anatomical alignment of the quadriceps mechanism with respect to the femur in the coronal, sagittal, and axial planes. The purpose of the current study was to quantify the latter by describing the quadriceps torsion angle. Compared with femoral torsion, the quadriceps torsion angle was a better classifier of patellar dislocation group membership, suggesting that this measure could provide valuable additional information for planning conservative or surgical intervention for patients with patellofemoral joint instability.

Persistent femoral neck anteversion is a common problem in pediatric patients who present with patellofemoral pain or dislocations, particularly in patients with increased femoral neck anteversion accompanied by external tibial torsion or miserable malalignment[20]. Defining abnormal femoral neck anteversion is complicated by both the wide variation in recorded normal values and the dynamic nature of this measurement, which is known to change with skeletal maturation[20-23]. The nomenclature of terminology dealing with rotational alignment is also confusing in the literature. In this study, we chose to define femoral torsion from the reconstructed angle of the femoral neck to the posterior condylar axis, as these were the most identifiable landmarks present. We therefore did not separate torsion into proximal and distal segments. The term torsion is used to quantify the rotation of the femur and was not intended to imply the presence of normal or abnormal anatomy. The effect of femoral torsion on patellar instability is variable and can be confounded by other elements, such as trochlear dysplasia, a large tibial tubercle to trochlear groove distance, patella alta, and generalized ligamentous laxity[11,14,24,25]. In the current study, the unaffected lower limb of the patellar dislocator group demonstrated femoral torsion and quadriceps torsion angle measures similar to the affected lower limb, suggesting that femoral torsion and quadriceps torsion angle should not be measured in isolation but rather as part of a detailed lower-limb evaluation.

In agreement with our first hypothesis, the measurement of the quadriceps torsion angle from MRI had excellent inter-assessor and intra-assessor reliability, and increased femoral torsion was associated with an increased quadriceps torsion angle. This finding was expected, given that both the femoral torsion and the quadriceps torsion angle were measured relative to the posterior femoral condylar axis and the quadriceps torsion angle is largely determined by the proximal attachment of the vastii on the femur. In partial agreement with our second hypothesis, the quadriceps torsion angle was a fair classifier of patellar dislocation group membership and femoral torsion was a poor classifier, indicating that these measures should not be used in isolation to discriminate a group of patellar dislocators from a group of typical controls, due in part to the large amount of variability observed in the typical population. Nonetheless, cluster analysis demonstrated that individuals who presented with excessive femoral torsion and a large quadriceps torsion angle were more likely to be classified as recurrent patellar dislocators. It was found that 88% of cases in cluster 2 were patellar dislocators and no control participants were measured to have a femoral torsion of >24° or a quadriceps torsion angle of >53°. Taken together, these findings suggest that a combined rotational malalignment of the femur and the quadriceps mechanism may be a risk factor for patellar dislocation but also highlights the notion that patellar dislocation is a multifactorial condition, requiring consideration of multiple factors when formulating a surgical prescription[26].

A realignment procedure to correct femoral torsion can have an unpredictable effect on the quadriceps mechanism, as well as the transverse plane joint rotation profile of the lower limb during gait. Conceptually, a proximal femoral derotational osteotomy would rotate the trochlea as well as the femoral quadriceps origin, whereas a distal derotational osteotomy would reorient the trochlea in relation to the quadriceps, thereby rotating only the attachment of the muscle with the origin remaining in the preoperative position. A greater understanding of the relationship between the quadriceps mechanism and the torsion of the femur via an assessment of the quadriceps torsion angle may not only help to determine optimal treatment options but may also guide the most effective site of osteotomies if they are required. Further biomechanical research using patient-specific musculoskeletal modeling may enable us to determine if the location and magnitude of derotational osteotomy would affect recurrent dislocations in the patient population with rotational malalignment.

The effect of the quadriceps mechanism on patellar stability is difficult to quantify, but it is commonly discussed in the clinical management of patellar instability. The quadriceps (Q)-angle is a common clinical measurement used to estimate the action of the quadriceps mechanism applied to the patella in the coronal plane. A substantial limitation of the Q-angle as a determinant of patellar dislocation includes its dependence on the position of the patella relative to the proximal trochlear groove[27,28]. In patients with habitual patellofemoral joint instability, the patella is often subluxated or dislocated in terminal extension and the Q-angle can therefore be erroneously interpreted. It has been found that in patients with patellar

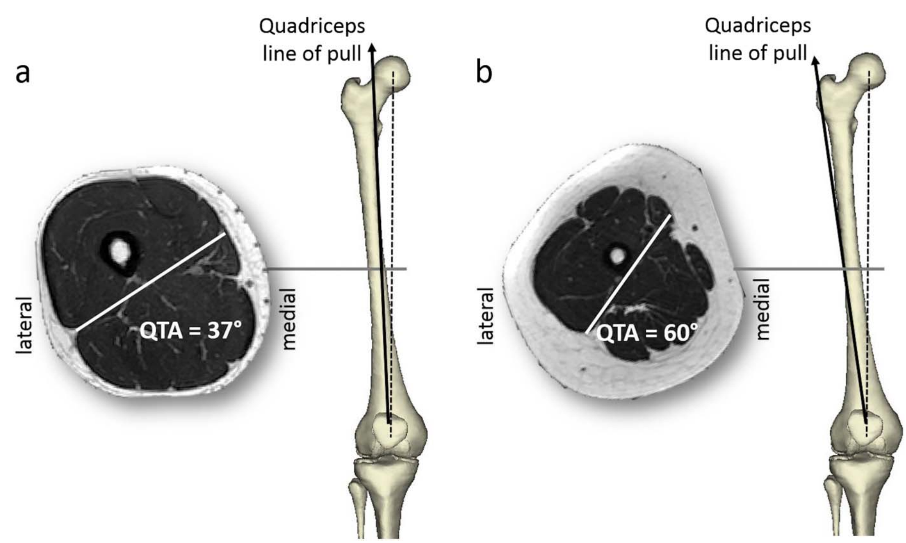

Fig. 4

Figs. 4-A and 4-B Diagram demonstrating the change of the quadriceps torsion angle (QTA) and its effect on the quadriceps line of pull. The solid black arrow represents the lateralized quadriceps line of pull. The dashed line represents the mechanical axis of the femur. **Fig. 4-A** A small QTA may result in a less lateralized quadriceps line of pull relative to the mechanical axis. **Fig. 4-B** The large angle may result in a more lateralized quadriceps line of pull.

instability, the Q-angle measured in extension is negatively correlated with the tibial tubercle to trochlear groove distance[8]. It is also important to note that the Q-angle does not account for total muscle volume. As the Q-angle only indicates a force directed in the coronal plane, it does not represent the true direction of the resultant force vector generated by the quadriceps mechanism on the patella. Therefore, the Q-angle needs to be interpreted with caution. The quadriceps torsion angle may be used to complement the Q-angle to estimate the net proportional medial-lateral force applied to the patella at a given knee angle. Figure 4 demonstrates how a large quadriceps torsion angle may reflect a more lateralized quadriceps line of pull and a small quadriceps torsion angle may reflect a less lateralized quadriceps line of pull, which could subsequently affect the magnitude of the lateral force vector directed by the quadriceps mechanism on the patella. Likewise, the quadriceps torsion angle in isolation does not provide insight into the line of action of the rectus femoris, and, therefore, we recommend that both measures be taken and be interpreted together with measures of osseous geometry and osseous alignment.

In interpreting the findings of the current study, we acknowledge that other factors known to contribute to patellar instability, such as external tibial torsion, patella alta, medial patellofemoral ligament rupture, and trochlear dysplasia, were not considered. We did not define whether femoral torsion occurred proximally or distally. Given that this was a cross-sectional study, we were not able to elucidate whether femoral torsion caused quadriceps malalignment or vice versa. It is proposed that the relationship between the quadriceps torsion angle and the trochlear anatomy may be a better predictor of patellofemoral joint instability in patients who dislocate despite a relatively normal trochlea and tibial tubercle to trochlear groove distance. It is not known if a change in bulk of the quadriceps, in particular, the vastus medialis, or the release of lateral structures would alter the quadriceps torsion angle. Similarly, the effect of medial patellofemoral ligament rupture and reconstruction on the quadriceps torsion angle has not been investigated. Therefore, we cannot conclude whether the quadriceps torsion angle could be used as a predictor of improved stability following physiotherapy or soft-tissue interventions. Furthermore, to include the measurement of the quadriceps torsion angle in a clinical setting, the MRI protocol would have to include a full-length femoral sequence, which is not routinely obtained after patellar dislocation. Finally, our cohort ranged in ages between 8 and 19 years, and it is likely that femoral torsion may change, albeit slightly, in this age group between these years.

This study has quantified rotational alignment of the extensor mechanism using the quadriceps torsion angle within limitations. The measurement is shown to be reliable and reproducible and a fair classifier of patellofemoral instability. Our findings suggest that quadriceps muscle rotational malalignment may play a greater role in the pathogenesis of patellofemoral joint instability than osseous rotational malalignment and can be reliably measured from medical imaging. Further studies of the quadriceps mechanism, as well as the change in the quadriceps torsion angle following various interventions, should be performed to determine the clinical importance of the quadriceps torsion angle in managing patellofemoral instability. ■

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