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Dynamic tracking influenced by anatomy following medial patellofemoral ligament reconstruction: Computational simulation

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ABSTRACT

Background: Continued patellar instability can occur following medial patellofemoral ligament (MPFL) reconstruction. Computational simulation of function was used to investigate the influence of the lateral position of the tibial tuberosity, trochlear dysplasia and patella alta on lateral patellar tracking following MPFL reconstruction.
Methods: Multibody dynamic simulation models were developed to represent nine knees being treated for recurrent patellar instability. Knee extension against gravity and dual limb squatting were simulated with and without simulated MPFL reconstruction. Graft resting lengths were set to allow 10 mm and five millimeters of patellar lateral translation at 30° of knee flexion. The bisect offset index, lateral tibial tuberosity to posterior cruciate ligament tibial attachment (TT–PCL) distance, lateral trochlear inclination, and Caton–Deschamps index were quantified at every five degrees of knee flexion to characterize lateral tracking, lateral position of the tibial tuberosity, trochlear dysplasia, and patella alta, respectively. For the pre-operative and post-operative conditions and each type of motion, bisect offset index was correlated with the anatomical parameters using stepwise multivariate linear regression.
Results: For both motions, the pre-operative and post-operative bisect offset indices were significantly correlated with lateral trochlear inclination and lateral TT–PCL distance. For both motions, the adjusted r^2 decreased with MPFL reconstruction, but was still approximately 0.5 for MPFL reconstruction allowing five millimeters of lateral translation.
Conclusion: MPFL reconstruction decreases but does not eliminate lateral maltracking related to trochlear dysplasia and a lateralized tibial tuberosity. Patients with these pathologies are likely at the highest risk for instability related to maltracking following MPFL reconstruction.

1. Introduction

For patients with recurrent patellar instability related to maltracking or trauma, medial patellofemoral ligament (MPFL) reconstruction is commonly performed to provide a checkrein limiting lateral patellar tracking with respect to the trochlear groove. While rates of recurrent instability following MPFL reconstruction are generally reported at less than four percent [1,2], rates as large as eight percent to 17% have also been reported [3–6]. Studies utilizing diagnostic imaging of knees with instability to characterize tracking have indicated that trochlear dysplasia and the lateral position of the tibial tuberosity are correlated with patellar lateral tracking [7–10]. Imaging studies

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performed with asymptomatic subjects and subjects with patellar pain have related patella alta to elevated lateral tracking [11–13], but alta was not correlated with lateral tracking for the studies evaluating knees with instability [7,8]. Trochlear dysplasia [4,14] has also been noted as a characteristic of knees with recurrent instability following MPFL reconstruction, but the relationship between pathologic anatomy and post-operative patellar tracking has yet to be characterized.

Relating knee anatomy to patellar tracking following MPFL reconstruction requires characterization of pathologic anatomy and patellar tracking with respect to the trochlear groove over a range of flexion angles. Ideally, MPFL reconstruction should be represented without other concurrent stabilization procedures and be represented with consistent graft positioning and tensioning techniques. While characterizing the relationship between anatomy and patellar tracking for simple activities performed during a clinical exam is beneficial, optimal evaluation should also include activities more representative of in vivo function.

The current study was performed to further investigate the influence of lateral position of the tibial tuberosity, trochlear dysplasia and patella alta on lateral patellar tracking related to instability in the pre-operative condition and following MPFL reconstruction. The study uses computational simulation of function based on symptomatic knees to characterize the relationship between anatomy and patellar lateral tracking. The computational approach simulates simple knee extension against gravity and a more demanding functional activity (dual limb knee squat).

2. Materials and methods

2.1. Computational models of subjects

Computational models were created to represent one knee from each of nine subjects being treated for recurrent lateral patellar dislocation related to trauma or maltracking. Conservative treatment was unsuccessful for each subject. The subjects were also included in previous studies that utilized computational reconstructions from diagnostic imaging performed with the knee at multiple flexion angles to relate knee anatomy to patellar tracking [7,8]. The subjects included seven females. The average age was 16 years (range: 12 to 19 years). The Institutional Review Board (IRBs) of the two treating institutions provided approval for the study.

A computational model of each knee was reconstructed (3D Doctor, Able Software Corp and Mimics, Materialise) from a high resolution magnetic resonance imaging (MRI) scan (3.0 T, proton density weighted, slice thickness ranging from 0.6 mm to 1.5 mm). Anatomical structures reconstructed from the MRI scans determined the shape of the bones and cartilage surfaces, orientation and attachment points for the quadriceps and hamstrings muscles, and attachment points for the anterior and posterior cruciate ligaments and patellar tendon.

2.2. Simulated motion

The multibody dynamic simulation approach has been described in detail previously [15,16]. The model of each subject was individually validated. The pre-operative and post-operative function of the subjects captured during diagnostic imaging was simulated (RecurDyn, FunctionBay). The root mean square error of the comparison between in vivo and simulated lateral patellar shift was 2.7 mm, with a root mean square error for decrease in lateral shift following surgical stabilization of 2.9 mm [16]. Forces are applied to the knee to represent the quadriceps and hamstring muscles (Figure 1). The quadriceps force is divided among the

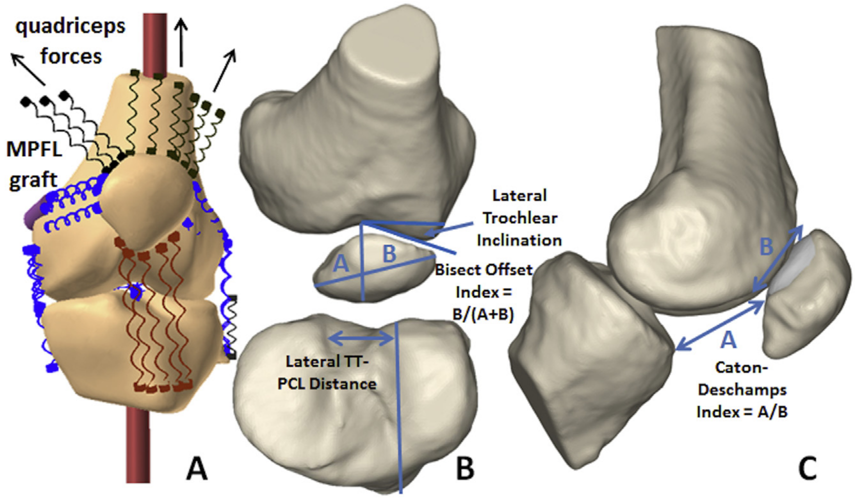

Figure 1. Computational model for multibody dynamic simulation for one knee (A). The measures used to quantify the bisect offset index and lateral tibial tuberosity–posterior cruciate ligament distance (B), as well as the Caton–Deschamps index (C), are shown.
Panel A adapted from the European Society of Sports Traumatology, Knee Surgery, Arthroscopy [Springer Berlin Heidelberg] (Allowing one quadrant of patellar lateral translation during medial patellofemoral ligament reconstruction successfully limits maltracking without overconstraining the patella. Elias, J.J., Jones, K.C., Lalonde, M.K. et al. Knee Surg Sports Traumatol Arthrosc (2017). https://doi.org/10.1007/s00167-017-4799-9) [16].

vastus medialis obliquus (in a weakened state), vastus lateralis, and combination of the vastus intermedius, rectus femoris, and vastus medialis longus based on previous studies [17,18]. Approximately 74% of the quadriceps force was applied through the combination of the vastus intermedius, rectus femoris, and vastus medialis longus, with approximately 21% applied through the vastus lateralis, and five percent through the vastus medialis obliquus. Tension-only springs, including stiffness, damping, and pre-strain at full extension based on previous studies, represent the ligaments, tendons, joint capsule, and retinacular structures [19–23]. Patellofemoral contact and tibiofemoral contact are represented by simplified Hertzian contact [24,25]. The motion of anatomical coordinate systems fixed to the femur and tibia [26] determines tibiofemoral flexion based on the floating axis convention [27].

Loading and boundary conditions were applied to represent knee extension against gravity and a dual limb knee squat between 0° and 50° of flexion. At flexion angles greater than 50°, the MPFL graft tends to become unloaded as the distance from the femoral to patellar attachment of the graft decreases [28,29]. For knee extension, the total quadriceps force was set for each knee to initiate motion (average of 436 N at 50°), decreasing to a level that maintained continuous motion to full extension (average of 315 N at 0°). The total hamstrings force was set to one-sixth of the quadriceps force to provide the relatively low co-activation during knee extension [30]. A dual limb knee squat was represented with loading and boundary conditions based on in vitro simulation of dynamic knee squatting [31,32] that produced continuous knee flexion. An ankle joint was represented with three rotational degrees of freedom. A simulated hip joint allowed flexion/extension, varus/valgus rotation, and proximal/distal translation. The total quadriceps force increased from 42 N at full extension to 300 N at 50° of flexion, with a total hamstrings force equal to one-third of the quadriceps force [33] and a constant 200 N body weight applied at the hip. A hip flexion moment initiated motion, but was eliminated over the first few degrees of flexion.

Both motions were simulated in a pre-operative condition, and for two graft tensioning conditions. The Schöttle point [34] was approximated on each femur for femoral fixation of the graft. The graft was fixed to the patella between the medial edge of the vastus medialis obliquus attachment and the medial edge of the patella [35,36]. The grafts wrapped around the medial femoral condyle, with the portion from the femoral attachment to the wrapping surface rigid. A common graft tensioning technique that allows one quadrant of patellar lateral translation with the knee passively flexed to 30° was simulated [37,38]. The resting length of the graft was set with the patella displaced 10 mm laterally from the deepest point of the trochlear groove (range of patellar width: 36 to 43.5 mm). The resting length was also set with the patella displaced by five millimeters to represent a more restrictive surgical approach [3,6,39]. A dual strand gracilis tendon graft for MPFL reconstruction was represented by two springs with a total stiffness of 20 N/mm [40].

2.3. Characterization of patellar tracking and anatomy

Patellar lateral tracking and pathologic anatomy were characterized based on previously described parameters extracted from the computational models [7,8]. Patellar lateral tracking was characterized by the bisect offset index (Figure 1), which quantifies the portion of the patellar width lateral to the deepest point of the trochlear groove. Lateral position of the tibial tuberosity was quantified in terms of the lateral tibial tuberosity to posterior cruciate ligament attachment (TT–PCL) distance. The lateral TT–PCL distance is the distance from the patellar tendon attachment on the tibial tuberosity to the medial border of the posterior cruciate ligament attachment on the tibia (TT–PCL distance) in a lateral direction determined by the posterior condylar axis of the femur. The measure is an adaptation of the TT–PCL distance measured along the medial–lateral axis of the tibia to allow for variations in the measurement with rotation of the tibia as the flexion angle changes [8]. The lateral TT–PCL distance was used instead of the commonly utilized tibial tuberosity to trochlear groove (TT–TG) distance to eliminate the influence of variations in trochlear anatomy [8]. Trochlear dysplasia was characterized by the lateral trochlear inclination, the angle of the lateral ridge of the trochlear groove with respect to the posterior condylar axis of the femur. The maximum slope over a range spanning one-half of the medial–lateral width of the lateral ridge was quantified to determine the lateral trochlear inclination. The maximum slope was used to minimize variations between measurements based on selection of the two points at the deepest point of the trochlear groove and the most anterior point of the lateral ridge. Patella alta was characterized by the Caton–Deschamps index, the ratio of the distance from the distal point of the patellar cartilage to the anterior–superior border of the tibia to the articular length along the patella.

At five degree intervals of knee flexion, the lateral direction was established along the posterior condylar axis of the femur within a plane perpendicular to the long axis of the patella (Figure 1). The most medial and lateral points on the patella determined the medial–lateral axis of the patella. The other landmarks identified on the patella were the proximal and distal extents of the articular surface. On the tibia, the anterior–superior border, the medial border of the PCL attachment, and the center of the patellar tendon attachment at the tibial tuberosity were identified. The medial border of the PCL attachment was identified at the medial edge of the PCL fossa. An automated algorithm (Matlab, MathWorks) determined the deepest point of the trochlear groove and the most prominent point of the lateral trochlear ridge at each flexion angle. The most prominent lateral point was taken within the region from the distal extent of cartilage on the patella to the proximal extent of cartilage within the trochlear groove. The deepest point of the trochlear groove was identified within the same axial slice as the most prominent point on the lateral trochlear ridge.

2.4. Statistical analysis

Statistical analysis focused on the relationship between anatomy and tracking for the pre-operative condition and the two MPFL reconstruction conditions. Correlation of the bisect offset index with the anatomical parameters for all knees at all flexion

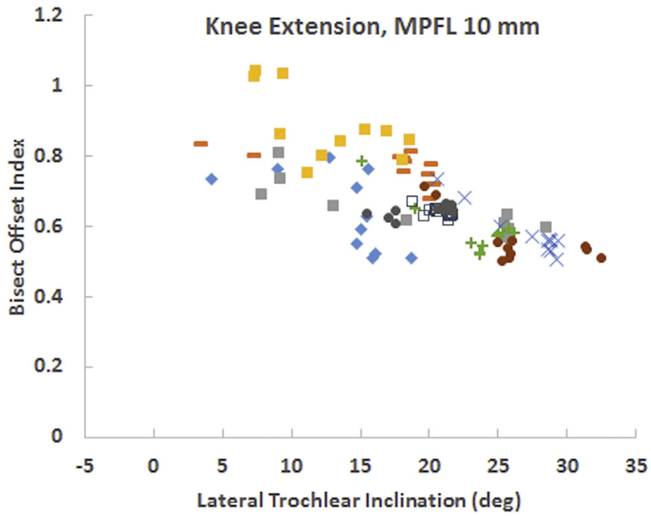

Figure 2. Bisect offset index vs. lateral trochlear inclination for knee extension against gravity for knees with an MPFL graft allowing 10 mm of lateral translation. The nine models are represented by different symbols.

angles was evaluated using stepwise multivariate linear regression analyses (SPSS, IBM Analytics). The square of the correlation coefficient, r^2, with adjustment for multiple variables, was quantified for each regression analysis. The standardized β coefficients, determining the relative predictive values of the independent variables, were also quantified. Additional correlation analyses were performed between the Caton–Deschamps index at 30° and the bisect offset index at only 0°, due to the index changing less with the flexion angle than the lateral trochlear inclination and lateral TT–PCL distance. The lateral tracking tends to be largest at 0°, while 30° of flexion is recommended for clinical evaluation of the Caton–Deschamps index [41,42]. Statistical significance was set at $p < 0.05$ for all analyses. A power analysis related to adding a variable to a multivariate linear regression indicated a power of 0.9 and a significance of 0.05 for an increase in r^2 from 0.55 to 0.6 (G*Power 3.1.9 [43]).

3. Results

For simulated knee extension against gravity, the bisect offset index was significantly correlated with the lateral trochlear inclination (Figure 2) and the lateral TT–PCL distance (Figure 3) for the pre-operative condition and the two MPFL graft conditions. With the knees at 0°, the average lateral TT–PCL distance and lateral trochlear inclination were 19.1 mm (range: 10.1–29.7 mm) and 13.6° (range: 2.3°–21.6°), respectively. With the knees at 30°, the average Caton–Deschamps index was 1.14 (range: 0.97–1.39). The adjusted r^2 decreased from 0.62 for the pre-operative condition to 0.48 for the MPFL graft with five millimeters of allowed lateral translation (Table 1). For the pre-operative condition, the β coefficient magnitude was 1.8 times larger for the

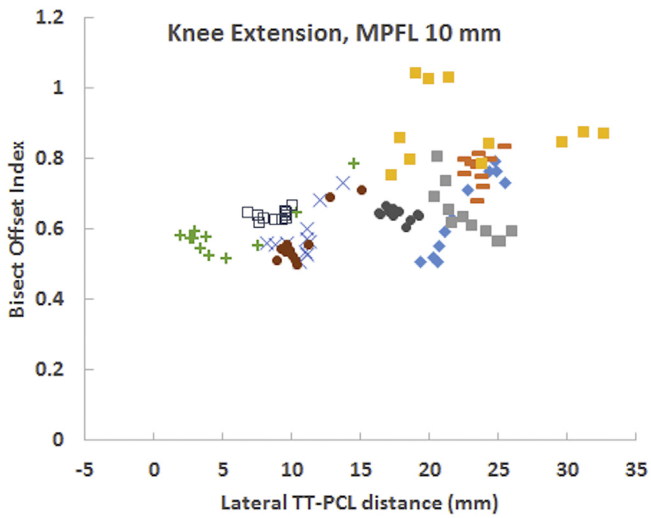

Figure 3. Bisect offset index vs. lateral TT–PCL distance for knee extension against gravity for knees with an MPFL graft allowing 10 mm of lateral translation. The nine models are represented by different symbols.

Table 1
Multivariate linear regressions relating bisect offset index to lateral trochlear inclination (LTI) and lateral TT–PCL distance.

	Adjusted r^2	p-Value		Beta coefficient	
		LTI	TT–PCL	LTI	TT–PCL
Knee extension					
Pre-operative	0.62	<0.001	<0.001	−0.57	0.31
MPFL − 10 mm	0.56	<0.001	0.04	−0.60	0.24
MPFL − 5 mm	0.48	<0.001	0.04	−0.58	0.18
Knee squat					
Pre-operative	0.73	<0.001	<0.001	−0.25	0.68
MPFL − 10 mm	0.63	<0.001	<0.001	−0.47	0.41
MPFL − 5 mm	0.55	<0.001	<0.001	−0.38	0.45

lateral trochlear inclination than for the lateral TT–PCL distance, indicating a stronger correlation between the bisect offset index and the lateral trochlear inclination. The β coefficient for the lateral TT–PCL distance decreased from the pre-operative to the post-operative conditions, with the β coefficient for the lateral trochlear inclination nearly constant. The Caton–Deschamps index was not correlated with the bisect offset index for the pre-operative condition or the MPFL reconstruction conditions for the multivariate regressions including all flexion angles ($p > 0.13$) or the individual regressions at 0° of flexion ($p > 0.25$).

For simulated knee squatting, the bisect offset was significantly correlated with the lateral trochlear inclination (Figure 4) and the lateral TT–PCL distance (Figure 5) for the pre-operative condition and the two MPFL graft conditions. The adjusted r^2 decreased from 0.73 for the pre-operative condition to 0.55 for the MPFL graft with five millimeters of allowed lateral translation (Table 1). In contrast to knee extension, the β coefficient magnitude for the lateral TT–PCL distance was 2.8 times larger than the magnitude for lateral trochlear inclination for the pre-operative condition. The β coefficients for the lateral TT–PCL distance and lateral trochlear inclination were similar for the MPFL reconstruction conditions. The Caton–Deschamps index was not correlated with the bisect offset index for the multivariate regressions including all flexion angles ($p > 0.15$) or the individual regressions at 0° of flexion ($p > 0.60$).

4. Discussion

The results of the study indicate that lateral patellar tracking (bisect offset index) for knees with patellar instability is correlated with trochlear dysplasia (lateral trochlear inclination) and the lateral position of the tibial tuberosity (lateral TT–PCL distance). Patella alta (Caton–Deschamps index) was not significantly correlated with lateral tracking at 0° of flexion or when evaluated in combination with the other factors over all flexion angles. MPFL reconstruction, and decreasing the resting length of the MPFL graft, decreased the strength of the relationship between the anatomical factors and lateral tracking. For the shortest resting graft length simulated (five millimeter condition), however, the lateral trochlear inclination and lateral TT–PCL distance still accounted for approximately 50% of the variation in the bisect offset index across all knees at all flexion angles based on the adjusted r^2 values. The relative contributions of trochlear dysplasia and lateral position of the tibial tuberosity to the correlation with lateral tracking varied with the activity. For simulated knee extension, the pre-operative and post-operative bisect offset

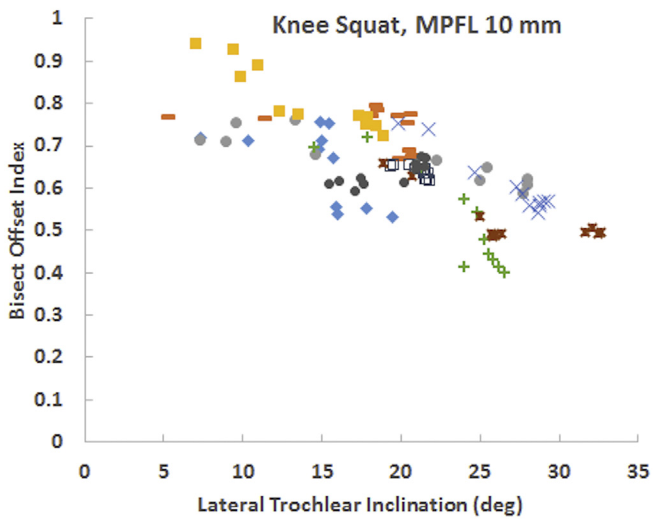

Figure 4. Bisect offset index vs. lateral trochlear inclination for knee squatting for knees with an MPFL graft allowing 10 mm of lateral translation. The nine models are represented by different symbols.

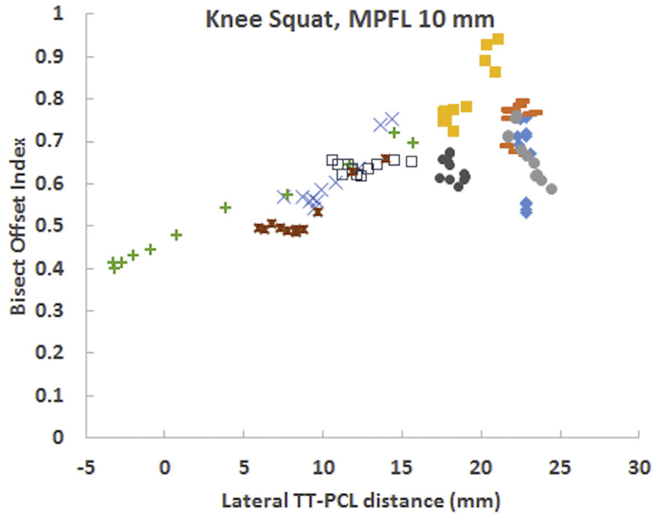

Figure 5. Bisect offset index vs. lateral TT–PCL distance for knee squatting for knees with an MPFL graft allowing 10 mm of lateral translation. The nine models are represented by different symbols.

index was more strongly correlated with lateral trochlear inclination than lateral TT–PCL distance. For knee squatting, the bisect offset index was more strongly correlated with lateral TT–PCL distance in the pre-operative condition, but the contributions of the two parameters to the regression were similar for the post-operative conditions.

The current results are largely in agreement with previous studies focused on anatomical factors that influence pre-operative lateral patellar tracking and repeat dislocations following MPFL reconstruction. Two previous studies utilized computational reconstruction of in vivo patellar tracking for multivariate assessment of anatomical factors correlated with lateral tracking [7,8]. These studies indicated that the bisect offset index is correlated with parameters related to trochlear dysplasia and lateral position of the tibial tuberosity, but not patella alta. The previous studies focused on only pre-operative motion. Several clinical studies have focused on anatomical factors associated with patellar instability. Trochlear dysplasia and a lateral tibial tuberosity, along with patella alta, were associated with recurrent dislocations after an initial episode of instability [44]. Trochlear dysplasia has been associated with recurrent instability [4,14,45] and poorer subjective outcome scores [46] following MPFL reconstruction. Lateral position of the tibial tuberosity has been associated with recurrent instability when combined with trochlear dysplasia [45]. Interpreting the current results within the context of the existing literature indicates that MPFL reconstruction decreases but does not eliminate lateral maltracking related to trochlear dysplasia and a lateralized tibial tuberosity, and patients with these pathologies are likely at the highest risk for instability associated with lateral maltracking following MPFL reconstruction.

For the pre-operative condition, the relationships between tracking and anatomy differed between knee extension against gravity and knee squatting. Lateral tracking was more strongly correlated with trochlear dysplasia for knee extension and more strongly associated with lateral position of the tibial tuberosity for knee squatting. The difference could be related to motion of the femur, with the femur fixed in place for knee extension but connected to the hip joint with two rotational and one translational degrees of freedom for knee squatting. The difference could also be related to applied quadriceps forces, which are larger at 0° for knee extension than for knee squatting due to the orientation of the limb with respect to the direction of gravity. The result indicates that patellar tracking assessed based on knee extension in a clinical setting may be more correlated with trochlear dysplasia than closed chain motions that occur during normal function.

As MPFL reconstruction reduced the magnitude of lateral tracking, the strength of the correlations with lateral position of the tibial tuberosity and trochlear dysplasia also decreased. For both motions, the correlation with lateral position of the tibial tuberosity weakened following MPFL reconstruction, amplifying the relationship between tracking and trochlear dysplasia for knee extension. For knee squatting, the strength of the correlations with lateral tracking for trochlear dysplasia and lateral position of the tibial tuberosity was similar following MPFL reconstruction. Based on one quadrant of allowed lateral patellar translation being considered normal, bisect offset values greater than 0.75 can be considered lateral maltracking [47]. Based on this characterization, several data points show lateral maltracking following MPFL reconstruction allowing one quadrant of lateral translation with the knee flexed to 30° (Figures 2–5), primarily due to the relationships between graft resting length and patellar position set at 30° not being maintained at other flexion angles. These positions of lateral maltracking could become subluxation or dislocation episodes for motions more likely to induce instability than squatting or extension against gravity, such as cutting maneuvers, or for traumatic loading conditions.

Computational simulation of knee motion was used for the study to overcome limitations of analysis of subjects with patellar instability. The computational models were based on subjects being treated for patellar instability. Previous studies showed that the modeling technique produces patterns of patellar tracking with knee flexion angle and variations in patellar tracking due to surgical stabilization representative of in vivo motion for each knee [15,16]. While previous studies have been performed with subjects being treated for instability to relate patellar tracking to anatomical factors [7,8], the current study allows for post-operative assessment with a consistent approach for MPFL reconstruction, controlled variations in MPFL graft tensioning, and evaluation of both a simple knee extension exercise and a closed chain knee squat.

The computational simulation approach also includes limitations. While knee anatomy, including articular shape, ligament attachments and muscle orientations was based on high resolution MRI scans, many properties of the knees were based on previously published data, rather than individualized for the subjects. Properties from the literature include elastic properties and resting lengths for springs representing ligaments, tendons and retinacular structures, and applied muscle forces. The model also accounted for only quadriceps and hamstrings muscles, without accounting for the influence of muscles that cross the hip joint on femoral rotation in particular. The analysis focused on relating patellar tracking to anatomy during continuous dynamic motion, without using loading conditions that cause patellar instability in the pre-operative or post-operative conditions. The simulated graft attachments and properties do not account for graft elongation or tunnel widening [39] that can occur post-operatively.

The study includes a limited range of anatomical factors based on the subjects evaluated. The anatomical parameters from the models vary from standard clinical measures, but are similar enough to allow comparisons. The anatomical measurements from the models were generally similar to previous measures for patients with patellar instability. For the current study, the average lateral trochlear inclination with the knee extended was 13.6°. The measurements were based on the maximum slope of the lateral trochlear ridge, and are expected to be slightly larger than clinical measurements. Previous studies have provided average values for lateral trochlear inclination at the proximal trochlear groove in subjects with instability of six degrees to 13° [48–50]. The average lateral TT–PCL distance along the posterior condylar axis at full extension was 19.1 mm. Clinical measures of TT–PCL distance, which would generally be larger due to measurement along the tibial medial–lateral axis, of 20 and 22 mm have been reported [51,52]. The average Caton–Deschamps index with the knee at 30° was 1.14. The values were slightly larger with the knee at lower flexion angles. For weight-bearing knees at approximately 15° of flexion, an average Caton–Deschamps index of 1.2 has been recorded for knees with patellar instability [53]. Further studies with additional models providing a wider range of anatomical variations are warranted.

4.1. Conclusion

The dynamic simulations of knee function indicate that lateral patellar tracking is correlated with the lateral position of the tibial tuberosity and trochlear dysplasia pre-operatively and following MPFL reconstruction. The relationship between knee anatomy and lateral tracking differs between a knee extension motion typical of a clinical exam and a knee squatting motion more indicative of knee function, with the relationship between tracking and trochlear dysplasia stronger for knee extension and the relationship between tracking and lateral position of the tibial tuberosity stronger for knee squatting. Although the role of the graft in limiting patellar lateral tracking decreases the strength of the relationship between anatomy and tracking, anatomy is still significantly correlated with lateral tracking following MPFL reconstruction, indicating that lateral dysplasia and a lateralized tibial tuberosity can potentially induce patellar instability related to lateral maltracking following MPFL reconstruction.

Conflicts of interest

John Elias has received research grants from MedShape and NorthShore University HealthSystem and is the PI of the grant from the NIH. Andrew Cosgarea has been a committee member for the American Orthopaedic Society for Sports Medicine and the Patellofemoral Foundation, has received grant funding from the Arthroscopy Association of North America, and textbook royalties from Elsevier. Kerwyn Jones is the PI of the grant from the Pediatric Orthopaedic Society of North America. Joseph Gabra, Melanie Morscher and Cyrus Rezvanifar report no conflicts of interest.

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