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Lateral patellar maltracking due to trochlear dysplasia: A computational study

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ABSTRACT

Background: The study focuses on the influence of trochlear dysplasia on patellar tracking related to patellar instability.
Methods: Knee extension against gravity and dual-limb squatting were simulated with seven models representing knees being treated for recurrent instability. Trochlear depth was altered to represent lateral trochlear inclination (LTI) values of 6°, 12° and 24°. Repeated measures analyses compared patellar lateral shift (bisect offset index) across different LTI values. Peak bisect offset index during extension and squatting was correlated with patella alta (Caton–Deschamps index) and maximum lateral position of the tibial tuberosity.
Results: Bisect offset index varied significantly ($p < 0.05$) between different LTI values at multiple flexion angles throughout simulated knee extension and squatting. Average bisect offset values were 1.02, 0.95, and 0.86 for LTI = 6°, 12°, and 24°, respectively, at 0° of flexion for knee extension. The strongest correlation occurred between peak bisect offset index and lateral position of the tibial tuberosity for knee squatting with LTI = 6° ($r^2 = 0.81$, $p = 0.006$). The strength of the correlation decreased as LTI increased. Caton–Deschamps was only significantly correlated with patellar tracking for LTI = 24° during knee squatting.
Conclusions: A shallow trochlear groove increases lateral patellar maltracking. A lateral tibial tuberosity in combination with trochlear dysplasia increases lateral patellar tracking and the risk of patellar instability. Patella alta has relatively little influence on patellar tracking in combination with trochlear dysplasia due to the limited articular constraint provided by the trochlear groove.

1. Introduction

Patellar instability, generically describing patellar dislocation, patellar subluxation, and general symptomatic patellar instability, accounts for more than 20% of all injuries in runners [1]. Particularly, patellar dislocation is an acute knee injury causing significant functional impairment to young, active patients, with an incidence rate of 43 per 100,000 children below the age of 16 [2–5]. Patellar dislocations are associated with a tear of the medial patellofemoral ligament (MPFL), which is the primary passive stabilizer resisting lateral displacement of the patella [6]. Trochlear dysplasia (TD), patella alta, and a lateral position of the tibial tu-

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berosity are also commonly associated with patellar instability [7,8]. In particular, TD refers to a pathological trochlear groove that limits the resistance to lateral subluxation [9,10], contributing to lateral patellar maltracking during knee function [11,12]. A shallow trochlear groove due to dysplasia has been noted in more than 90% of unstable knees [13,14]. TD is commonly associated with recurrent instability following initial conservative treatment, although most commonly in combination with other forms of pathology [15–17]. Trochleoplasty to deepen the trochlear groove is considered a viable surgical option to treat recurrent patellar instability associated with TD and lateral maltracking, with other options available for addressing a lateral position of the tibial tuberosity or patella alta as the primary pathology [18].

Previous studies focused on the influence of TD on patellar tracking have used two approaches to represent TD. Patellar tracking has been correlated with trochlear geometry within a population of subjects being treated for patellofemoral disorders, including a range of TD along with other pathological conditions [11,12,19], and within a population of cadaveric knees [20]. To focus specifically on TD, normal knees have been modified for parametric variation of trochlear depth [21–23]. The previous studies all showed that lateral patellar tracking increases as the depth of the trochlear groove decreases. Additional information is needed to improve assessment of the risk of recurrent patellar instability following an initial dislocation and the potential benefit of trochleoplasty, such as the influence of isolated variations in trochlear depth on patellar tracking for symptomatic knees and how both patella alta and lateral position of the tibial tuberosity interact with trochlear depth to influence patellar tracking.

The current study utilized computational simulation of dynamic function for knees being treated for recurrent patellar instability to evaluate the influence of TD on patellar tracking. Dynamic simulation was used to characterize how isolated variations in trochlear depth influence patellar tracking for symptomatic knees. How the influence of patella alta and lateral position of the tibial tuberosity on patellar tracking varies with trochlear depth was also evaluated.

2. Materials and methods

2.1. Computational models of subjects

Computational models were created to represent seven knees from subjects being treated for recurrent patellar instability. The subjects included five females. The average age was 15.8 years, ranging from 12 to 20 years. The study was approved by the Institutional Review Boards (IRB's) of the two treating institutions, and each subject provided informed consent. The computational model of each knee was reconstructed (3D Doctor, Able Software Corp; 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). 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 were also obtained from reconstruction of the MRI scans.

2.2. Simulated motion

The multibody dynamic simulation approach has been previously described in detail [24,25]. Each model was individually validated by simulating a functional activity performed by the corresponding subject during diagnostic imaging. The functional activity performed was knee extension against gravity for two subjects and isometric knee extension against resistance at multiple positions of knee flexion for five subjects. The simulations produced patellar tracking patterns similar to those measured from the subjects, including peak lateral tracking near full extension [11]. Root-mean-square errors for comparisons between simulated lateral patellar shift and tilt and measurements based on diagnostic imaging of the subjects were 2.7 mm and 3.7°, respectively [25]. Simulations also produced correlations between knee anatomy and patellar tracking similar to those determined from the subjects [26].

The models included ligaments, tendons, joint capsule, and retinacular structures represented by tension-only springs, including assigned properties for stiffness, damping, and pre-strain at full extension based on previous studies [27–31]. The MPFL was not included in the medial retinacular structures to account for injury following an instability episode. Forces were applied to the knee to represent quadriceps and hamstring muscles (Figure 1-A). The quadriceps force was divided among the vastus medialis obliquus, vastus lateralis, and a combination of the vastus intermedius, rectus femoris, and vastus medialis longus based on previous studies [32,33]. Due to the weakened state, only five percent of the quadriceps force was applied through the vastus medialis obliquus, with approximately 21% applied through the vastus lateralis and approximately 74% through the combination of the vastus intermedius, rectus femoris, and the vastus medialis longus. The motion of anatomical coordinate systems fixed to the femur and tibia [34] determined tibiofemoral flexion based on the floating axis convention [35]. Patellofemoral and tibiofemoral contacts were represented by simplified Hertzian contact [36,37].

For evaluation of TD, loading and boundary conditions were applied to all models to represent knee extension against gravity from 50° of flexion to full extension (0° of flexion), and dual-limb knee squatting from 0° to 90° of flexion. The two separate activities were simulated to represent examination of the knee in a clinical setting and a more demanding functional activity. For knee extension, the total quadriceps force was set for each knee to initiate motion (average of 470 N at 50°), decreasing to a level that maintained continuous motion to full extension (average of 342 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 [38]. Dual-limb knee squatting was represented with loading and boundary conditions based on in vitro simulation of dynamic knee squatting [39,40] that produced continuous knee flexion. An ankle joint was represented with three rotational degrees of freedom. A hip joint was simulated to allow flexion/extension, varus/valgus rotation, and proximal/distal translation. A total hamstrings force equal to one-

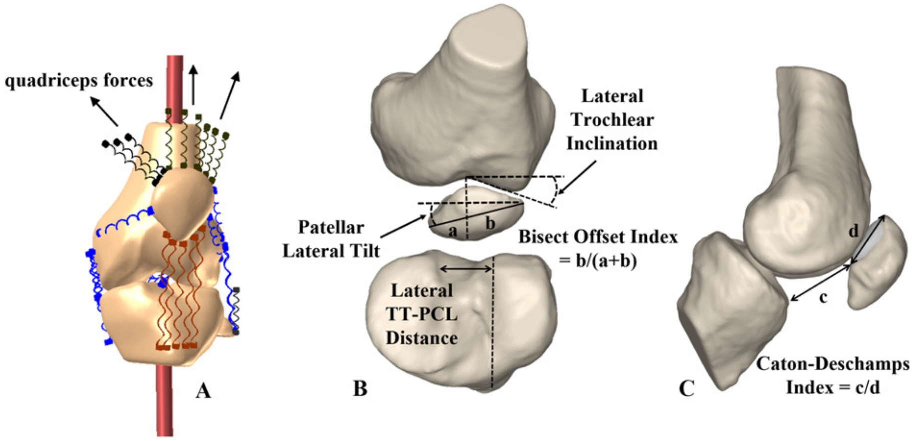

Figure 1. Computational model for multibody dynamic simulation for one knee (A). Measures used to quantify bisect offset index, patellar lateral tilt, lateral TT–PCL distance, lateral trochlear inclination (B), as well as Caton–Deschamps index (C) are shown.
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third of the quadriceps force [41] was applied, with a constant 200 N body weight applied at the hip. A hip moment was implemented solely to initiate the squatting motion and was eliminated within the first few degrees of flexion to avoid effects on overall quadriceps forces for squatting, as well as patellofemoral and tibiofemoral kinematics.

2.3. Systematic modification of trochlear morphology

An automated algorithm was developed (MATLAB, Mathworks, MA) to systematically modify the trochlear groove for the computational models. The algorithm focused on lateral trochlear inclination (LTI) (Figure 1-B) as a measure of trochlear depth based on the angle between the lateral facet of the trochlear groove (the line connecting the deepest point and the most anterior point of the lateral ridge of the trochlear groove) and the posterior condylar axis of the femur. LTI has previously been correlated with patellar tracking [11,12,26]. The algorithm quantified the reference LTI within an axial slice of the femur at the level of the most posterior points on the femoral condyles. For axial slices spanning the trochlear groove, the deepest point of the groove and the most prominent point of the lateral trochlear ridge were identified. Points at the reference slice were elevated or lowered in proportion to their depth to alter LTI to produce reference values of 6°, 12° and 24°. The lowest and highest LTI values approximately span the range of severely dysplastic to normal LTI values [42–44], while 12° represents the lowest LTI that would typically be considered non-dysplastic [45]. Linearly proportional changes were applied in a radial direction throughout the groove to maintain a smooth transition to unmodified proximal and distal ends. The cartilage surface was adjusted accordingly by maintaining a constant cartilage thickness map on the trochlear surface. The algorithm was capable of accurately altering trochlear geometry of the computational 3D knee models, with root-mean-square errors of 0.65° between the desired and measured reference LTI values.

2.4. Characterization of patellar tracking and anatomy

Patellar lateral tracking and pathologic anatomy were characterized based on previously described parameters extracted from the computational models [11,12]. Patellar tracking was expressed by bisect offset index (portion of patellar width lateral to the deepest point of the trochlear groove) and patellar lateral tilt at five degrees intervals of knee flexion throughout the simulation (Figure 1-B). 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 in a lateral direction determined by the posterior condylar axis of the femur, and has previously been correlated with patellar tracking [11,26]. Patella alta was characterized by the Caton–Deschamps (CD) index (Figure 1-C), 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. CD index has been shown to be more strongly correlated with patellar tracking than Insall–Salvati index [46].

2.5. Statistical analysis

Statistical analysis focused on the relationship between trochlear geometry and patellar tracking. Normality of the data distribution was evaluated at each studied flexion angle with Shapiro–Wilk tests (SPSS, IBM Analytics). At flexion angles with a normal data distribution, the tracking parameters were compared across different LTI values using repeated-measures Analysis of

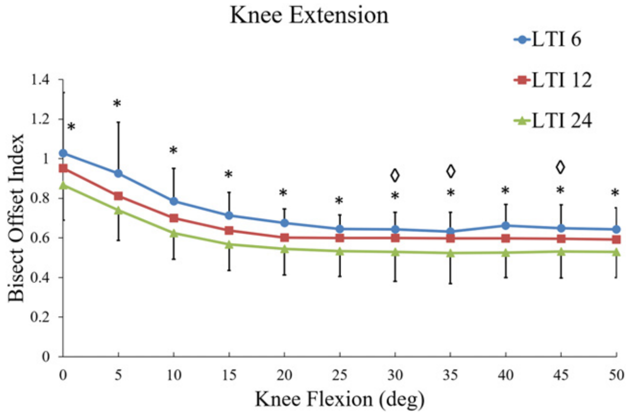

Figure 2. Average (±SD) bisect offset index throughout simulated knee extension. * and ◊ indicate significant differences between LTI = 6° vs. 24°, and 6° vs. 12°, respectively.

Variance (ANOVA) followed by post-hoc Student–Newman–Keuls tests. For flexion angles at which the data did not pass normality tests, non-parametric Friedman tests followed by post-hoc Student–Newman–Keuls comparisons were conducted to compare tracking parameters across different LTI values. To investigate the effect of TD severity on the correlations between patellar tracking and other types of pathology, stepwise multivariate linear regression analyses (SPSS, IBM Analytics) were performed to correlate bisect offset index and patellar lateral tilt with CD index and lateral TT–PCL distance for each LTI value. The analyses only included the maximum values of bisect offset index, lateral tilt, CD index, and lateral TT–PCL distance for each simulation to focus on the largest levels of lateral patellar tracking and pathology. The square of the correlation coefficient, r^2, was quantified for each regression analysis. The standardized β coefficients, determining the relative predictive values of the independent variables, were also quantified to compare the correlations across different LTI values. For all statistical analyses, significance level was set at $p < 0.05$. A p-value of 0.10 was required to enter the stepwise multivariate linear regressions.

3. Results

For simulated knee extension, the patella tracked more laterally as the LTI decreased. The bisect offset index peaked at full extension, with at least one significant difference between LTI values noted for all flexion angles from 0° to 50° (Figure 2). At 0° of flexion, the average (± standard deviation) bisect offset values were 1.02 ± 0.31, 0.95 ± 0.25, and 0.86 ± 0.18 for LTI values of 6°, 12°, and 24°, respectively. Significant differences in patellar tilt between LTI values occurred from 15° to 50°, with the difference in average lateral tilt between LTI = 6° and 24° approximately equal to 7° (Figure 3).

For simulated knee squatting, similar to knee extension against gravity, the patella tracked more laterally for cases with lower LTI. The largest significant differences in bisect offset index occurred from 15° to 40° of knee flexion (Figure 4). The average bisect offset index was greatest at low flexion angles for all conditions, with a peak value of approximately 0.9 ± 0.2 for all conditions. By 15°, the average bisect offset values were 0.71 ± 0.12, 0.64 ± 0.12, and 0.57 ± 0.13 for the LTI = 6°, 12°, and 24°, respectively.

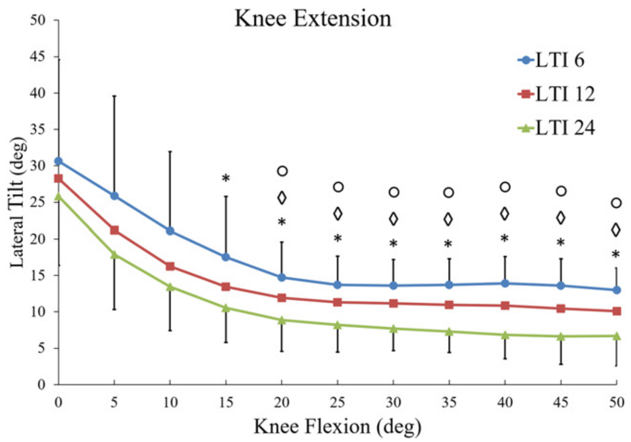

Figure 3. Average (±SD) patellar lateral tilt throughout simulated knee extension. *, ◊, and ○ indicate significant differences between LTI = 6° vs. 24°, 6° vs. 12°, and 12° vs. 24°, respectively.

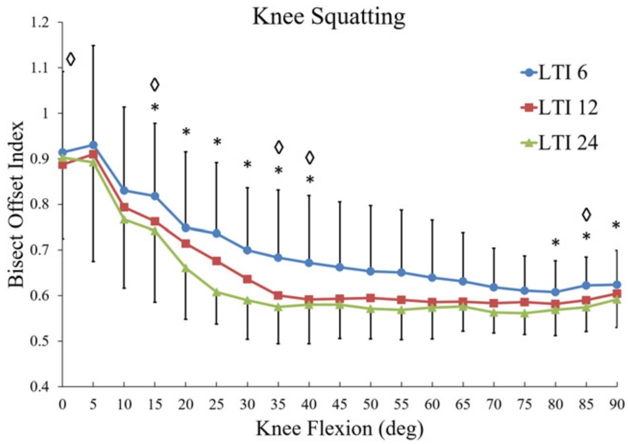

Figure 4. Average (±SD) bisect offset index throughout simulated knee squatting. * and ◊ indicate significant differences between LTI = 6° vs. 24°, and 6° vs. 12°, respectively.

Patellar lateral tilt decreased more consistently from 10° to 90° of flexion, with the largest significant differences in average patellar tilt on the order of 10° (Figure 5).

Lateral patellar tracking was correlated with lateral TT–PCL distance for a shallow trochlear groove (Table 1). The strongest correlation occurred between peak bisect offset index and lateral TT–PCL distance for knee squatting with LTI = 6° ($r^2 = 0.81$, $p = 0.006$, $\beta = 0.9$, Figure 6). Similar correlations were identified for knee extension, with $r^2 = 0.69$, $p = 0.02$, and $\beta = 0.83$ for the correlation between bisect offset index and lateral TT–PCL distance with LTI = 6°. The strength of the correlation between patellar tracking and lateral TT–PCL distance decreased as LTI increased to represent greater trochlear depth. CD index was excluded from all stepwise multivariate regression analyses, except for LTI = 24° during knee squatting, where it replaced lateral TT–PCL distance in the regression model, indicating an exclusive significant correlation with bisect offset index and lateral tilt.

4. Discussion

The results of the study indicate that TD significantly influences patellar lateral tracking throughout the entire range of knee motion in patients with symptomatic patellar instability. In particular, a shallow trochlear groove, characterized by a low LTI value, is linked with significantly higher patellar lateral shift and tilt. The average peak bisect offset index at full extension for LTI = 6° during knee extension of 1.02 indicates a high risk of patellar instability [47]. The peak bisect offset values of 0.95 and 0.86 for LTI values of 12° and 24°, considered to be just above the threshold for dysplasia and normal, respectively, still represent lateral maltracking, but with a significantly lower risk of patellar instability [47]. For knee squatting, significantly elevated lateral maltracking related to a shallow trochlear groove was mainly observed starting at 15° of knee flexion (Figures 4 and 5), as the patella is entering the trochlear groove. Failure of the groove to capture the patella during flexion causes patellar dislocation. The results of this study are in general agreement with the existing literature showing an increase in lateral tracking as the LTI decreases in knees being treated for patellar instability [11,12] and increased lateral tracking for isolated variation of trochlear

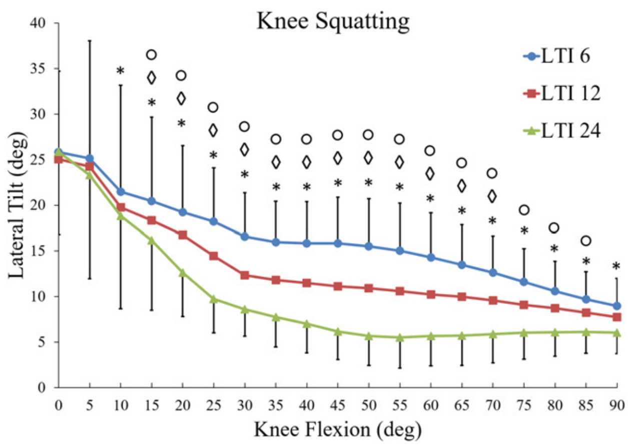

Figure 5. Average (±SD) patellar lateral tilt throughout simulated knee squatting. *, ◊, and ○ indicate significant differences between LTI = 6° vs. 24°, 6° vs. 12°, and 12° vs. 24°, respectively.

Table 1
Results of multivariate linear regression analyses relating bisect offset index and patellar lateral tilt to lateral TT–PCL distance and Caton–Deschamps (CD) index for separate LTI groups. For each regression, either CD index or lateral TT–PCL was eliminated from the analysis due to $p > 0.10$.

	r^2	p-Value		Standardized β coefficient
		Lateral TT–PCL	CD index	
Knee extension				
LTI 6°				
Bisect offset	0.69	0.02	–	0.83
Lateral tilt	0.73	0.015	–	0.85
LTI 12°				
Bisect offset	0.67	0.025	–	0.82
Lateral tilt	0.64	0.03	–	0.80
LTI 24°				
Bisect offset	0.61	0.038	–	0.78
Lateral tilt	0.46	0.09	–	0.68
Knee squatting				
LTI 6°				
Bisect offset	0.81	0.006	–	0.90
Lateral tilt	0.74	0.013	–	0.86
LTI 12°				
Bisect offset	0.78	0.008	–	0.88
Lateral tilt	0.76	0.01	–	0.87
LTI 24°				
Bisect offset	0.65	–	0.028	0.81
Lateral tilt	0.65	–	0.028	0.81

depth [21–23]. By spanning the clinical range of TD, the current results indicate that knees meeting clinical standards for TD are at high risk for recurrent instability following an initial instability episode and that deepening the groove can reduce the risk of continued instability.

The regression analyses indicate that severity of TD affects the extent to which patella alta and a lateral tibial tuberosity contribute to lateral maltracking. Regression analyses indicate an increasingly strong correlation between maximum lateral tracking of the patella and lateral TT–PCL distance as LTI decreases, as demonstrated by an increase in the β coefficient and r^2. A significant correlation between tuberosity position and patellar lateral tracking in patients being treated for patellar instability has been shown previously [11]. With minimal articular constraints acting on the patella from a shallow trochlear groove, the position of the tibial tuberosity, and the resulting orientation of the patellar tendon, significantly influences patellar tracking. CD index was only significantly correlated with patellar tracking for the highest LTI value during knee squatting. With a normal trochlear groove, patella alta delaying entry of the patella into the groove can be a primary contributor to lateral maltracking. The lower influence of patella alta on patellar tracking when combined with TD is likely due to the already limited articular constraint provided by the trochlear groove, with minimal loss in constraint with delayed entry of the patella into the groove. In line with the current results, previous studies showed elevated lateral tracking related to patella alta in knees not being treated for patellar instability [48–51]. Previous studies based on subjects being treated for patellar instability did not show a significant correlation between CD index and patellar tracking [11,12], likely due to a high rate of TD in the symptomatic knees.

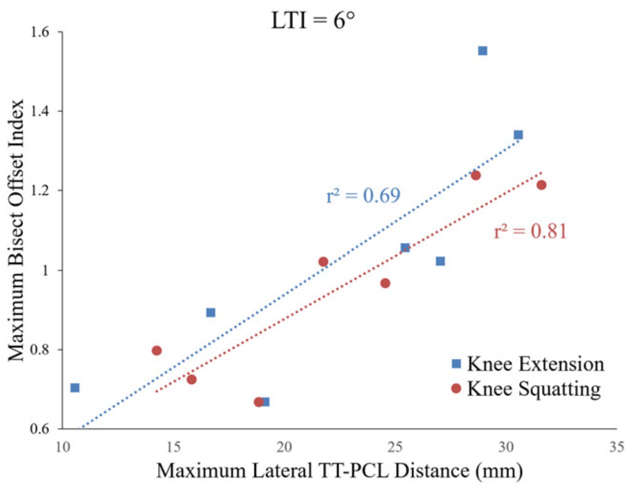

Figure 6. Maximum bisect offset index vs. maximum lateral TT–PCL distance for the seven models during simulated knee squatting and extension for LTI = 6°. Best fit regression lines and the square of the correlation coefficient are shown.

The correlations relating CD index and lateral TT–PCL distance to lateral maltracking for variations in LTI should be understood due to the multiple forms of anatomical pathology that are typical of knees being treated for recurrent instability [15–17]. While the results indicate TD is associated with a high risk of recurrent instability, and a potential need for surgical stabilization, the combination of TD and a lateral position of the tibial tuberosity is especially problematic. For knees with patella alta, deepening the trochlear groove is likely to improve patellar tracking, but unresolved alta may mean patellar tracking is not restored to normal levels.

The study analyzed two separate functional activities. While the results of simulated knee extension against gravity are related to clinical examination of patellar maltracking through characterization of tracking patterns, such as a J-sign [23,52,53], knee squatting represents an activity more likely to induce knee instability due to the trochlear groove not capturing the patella at low flexion angles. Because minimal variations occurred in patellar tracking during knee extension for flexion angles deeper than 40°, simulation of knee extension was limited to 50°, compared with 90° for knee squatting. Several factors can contribute to differences in tracking patterns between knee squatting and knee extension. The femur was fixed in place for knee extension, but was allowed additional degrees of freedom during squatting. The average bisect offset index and patellar lateral tilt near 0° of flexion were higher in simulated knee extension compared with squatting, likely due to the larger quadriceps forces at 0° during horizontal knee extension to resist gravity. More demanding activities with elevated quadriceps forces or tibial external rotation at low flexion angles that would induce instability episodes were not represented to allow for evaluation of motion over the full range of flexion for each knee. Future studies focused specifically on dislocation events are warranted. Overall, the results from knee extension and squatting indicate that TD influences patellar maltracking related to patellar instability throughout the full range of flexion.

Compared with previous studies that have investigated the effects of TD on patellar tracking during knee function [11,12,21–23], the present study benefits from a unique combination of including other forms of anatomical pathology and parametric variation of trochlear depth. Hence, only the current study characterized the influence of isolated variations in TD on patellar maltracking while including other forms of pathology and evaluated the interaction between TD and measures of patella alta and a lateral position of the tibial tuberosity.

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 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, as well as applied muscle forces. The models also accounted for only quadriceps and hamstrings muscles, without accounting for muscles that cross the hip joint, and only represented relatively young subjects. While the scope of the current study focused on the effect of TD on patellofemoral kinematics, future work should also investigate articular pressure distributions to identify potential correlations between anatomical abnormalities such as TD and excessive contact pressures associated with patellofemoral pain and osteoarthritis. The trochlear groove was altered without applying corresponding modifications on the patellar articular surface, influencing congruity of the patellofemoral joint. Although the patellar surface is not altered during a trochlear deepening procedure, this isolated alteration is a limitation for observations related to the influence of TD on the risk of recurrent instability. The observations related to surgical deepening of the trochlear groove do not specifically apply to any type of trochleoplasty, as trochleoplasty typically includes additional anatomical changes, such as eliminating the trochlear bump and lateralizing the groove [54]. The limitations related to congruence and representation of trochleoplasty were necessary for a general characterization of how TD influences patellar tracking relevant to initial assessment of the risk of recurrent instability and surgical planning to stabilize the patella.

5. Conclusions

The current simulations of knee function with parametric variation in the trochlear depth indicate that a shallow trochlear groove increases lateral patellar maltracking and the risk of recurrent instability. Other pathologies associated with patellar instability should also be considered when assessing the risk of continued instability or planning surgical treatment. In particular, for knees with TD, the limited articular resistance leads to a significant influence of the position of the tibial tuberosity on patellar tracking, so that the combination of TD and a laterally positioned tuberosity is more of a concern than isolated TD. Patella alta has relatively little influence of patellar tracking in combination with TD due to the overall limited articular constraint provided by the groove, but may contribute to elevated lateral tracking following surgical deepening of the trochlear groove.

Declaration of competing interest

None.

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