# Effect of Patellofemoral Geometry and Simulated Tibial Tubercle Osteotomy on Patellar Stability

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*Abstract*— **Articular geometry is known to affect joint function and be correlated with pathology; however, its effect on treatment outcomes is not well understood. The influence of trochlear groove depth on lateral patella stability following simulated tibial tubercle osteotomy was investigated. A statistical shape model was used to produce knee models with trochlear groove geometries ranging from shallow to deep. A Monte Carlo approach was used and 750 musculoskeletal models were generated with varying trochlear groove depths and patellar tendon medial and anterior transfer distances. An overground walking trial was simulated for each model using the COMAK routine and a 200N lateral perturbation force was applied to the patella during early stance. The lateral displacement of the patella resulting from this perturbation was used as a measure of patellar stability. In knees with deep trochlear grooves, patella displacement due to the perturbation decreased with increased medial patellar tendon transfer, indicating increasing stability. However, in knees with shallow trochlear grooves, stability was maximized at ~1 mm of medial patellar tendon transfer, but decreased for patellar tendon insertions medial or lateral of this point. Additionally, the medial patellofemoral ligament was more important to maintaining joint stability for larger patellar tendon transfer distances in knees with shallow trochlear grooves. These results emphasize the importance of considering joint geometry in surgical planning.**

*Keywords*— **statistical shape model, musculoskeletal model, patella stability, tibial tubercle osteotomy**

## I. Introduction

Articular geometry can influence function of a joint and is related to pathology. In the patellofemoral joint, trochlear groove depth and the inclination of the lateral facet have been found to affect joint biomechanics. Shallower trochlear grooves have also been associated with both patellofemoral pain and instability [1,2], indicating the importance of this geometrical feature. However, it is not well understood how trochlear groove geometry may influence the outcomes of treatments for these pathologies.

Tibial tubercle osteotomy is a procedure used to treat patellofemoral pain and chronic patellar instability through translation of the tibial insertion of the patellar tendon medially and/or anteriorly. The goal of the surgery is to reduce pain and improve stability. In a previous study [3], we used statistical shape modelling to vary patellofemoral geometry and combined this with musculoskeletal simulation to investigate how trochlear groove depth interacts with patellar tendon transfer distance and direction to affect cartilage contact pressures. We found that cartilage contact pressure was typically minimized for medial transfer distances of ~1 cm, but that knees with shallow trochlear grooves were much more sensitive to medial patellar tendon transfer distance.

One of the main goals of tibial tubercle osteotomy is to improve patellar stability, which was not assessed in our previous work. Therefore, the aim of this study was to investigate the influence of trochlear groove depth on patellar stability following simulated tibial tubercle osteotomy.

## II. Methods

### *A. Statistical shape model*

Magnetic resonance images of the knees of fourteen asymptomatic participants were manually segmented to produce surface meshes of the distal femur, proximal tibia, and patella bone and cartilage. Meshes were registered to their automatically generated anatomical coordinate systems and node correspondence was established among the meshes using the Coherent Point Drift algorithm [4]. Meshes were then scaled and aligned using a Procrustes analysis and principal component analysis was applied to generate a whole-joint statistical shape model.

The second principal component (PC2) captured the lateral inclination angle and femoral trochlear groove depth. PC2 was used to generate seven new knee geometries that ranged from a shallow to deep trochlear groove based on -3 to +3 standard deviations (SD) of the scores for this PC. A morphable multibody knee model was used to place muscle wrapping surfaces and fourteen ligaments on the geometries. Ligaments were fixed to nodes in the statistical shape model to ensure they were appropriately placed on each geometry. Similarly, muscle wrapping surfaces were based on statistical shape model nodes.

### *B. Musculoskeletal models*

The multibody knee models were incorporated into a lower-extremity musculoskeletal model [5]. Tibiofemoral and patellofemoral joints were represented by 6 degree-of-freedom joints and cartilage contact was modelled with a nonlinear elastic foundation formulation.

A Monte Carlo approach was used and 750 models were generated. For each model, one of the seven geometries was randomly chosen and the tibial insertion of the patellar tendon was randomly translated between -1 and 2 cm medially and 0 and 2 cm anteriorly to simulate tibial tubercle osteotomy.

### *C. Gait simulation and patellar stability*

The same overground walking trial was simulated using the Concurrent Optimization of Muscle Activations and Kinematics (COMAK) routine [6]. In COMAK, pelvis kinematics, ground reaction forces, and hip, tibiofemoral flexion, and ankle angles were set to measured values and numerical optimization was used to simultaneously solve for muscle activations and secondary knee kinematics.

To assess patellar stability, the walking trials was simulated again while a perturbation force was applied laterally to the patella at the instant of peak tibiofemoral contact force, which occurred in early stance (Fig. 1). The force was linearly increased from 0-200N (0.33BW) over 0.05s and then back to 0N over another 0.05s. The lateral displacement of the patella induced by this perturbation was used as a measure of patellar stability.

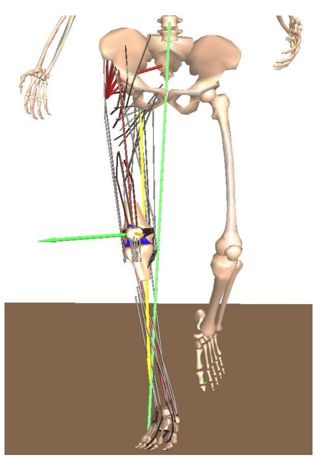

Fig. 1 Lateral perturbation force applied to the patella.

## III. Results

In knees with deep trochlear grooves, the patella displacement due to the perturbation force continually decreased with increasing medial patellar tendon transfer distance, indicating increased stability (Fig. 2). However, in knees with shallow trochlear grooves, the relationship was parabolic, with patellar displacement minimized at ~1 mm of medial patellar tendon transfer. Patella displacement likely decreased as medial transfer distance increased past 1 mm as the patella became disengaged from the trochlear groove, reducing stability. Anterior transfer distance had little effect on patellar stability (Fig. 2).

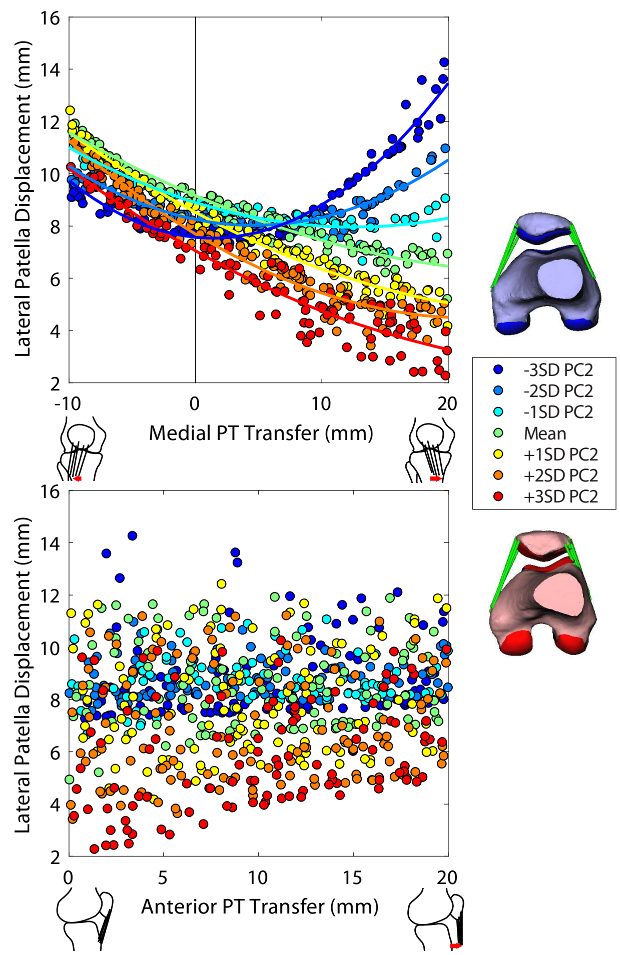


Fig. 1 Lateral patella displacement due to the lateral perturbation force applied to the patella for different trochlear groove depths (-3SD PC2 = shallow, +3SD PC2 = deep). The relationship to both medial and anterior patellar tendon transfer distance is shown. A quadratic fit is shown for each geometry on the medial transfer plot.

The force in the medial patellofemoral ligament (MPFL) was increased at the instant of peak perturbation force application compared with the same instant in the unperturbed simulation (Fig. 3). This increase was smaller with greater medial transfer distances. However, while the MPFL force increase was minimal in knees with deep trochlear grooves for medial transfer greater than 10 mm, knees with shallow trochlear grooves always experienced an increase of at least 50N.

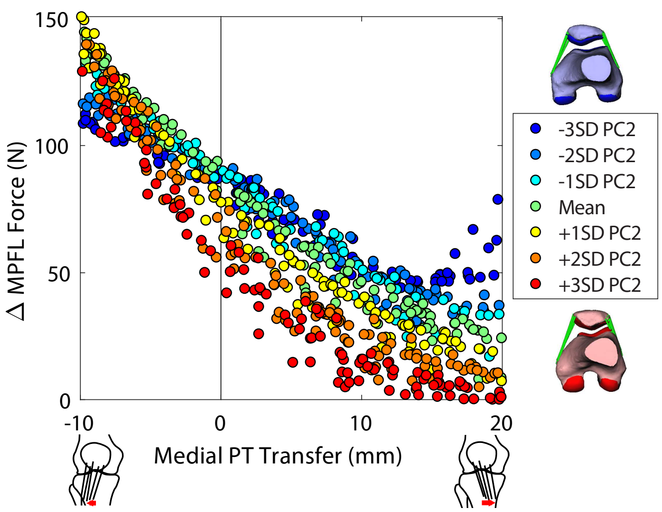


Fig. 3 Increase in medial patellofemoral ligament (MPFL) force at peak perturbation force application compared to the same instant in the unperturbed simulation for different geometries (-3SD PC2 = deep, +3SD PC2 = shallow).

## IV. Discussion

In knees with shallow trochlear grooves, stability was reduced if medial patellar tendon transfer distances were too large. This is similar to our previous finding that cartilage contact pressure could be greatly increased in these knees for medial transfers greater than 10 mm. Both adverse effects are likely the result of the patella becoming disengaged from the trochlear groove. This emphasizes the importance of avoiding over-medialization of the patellar tendon in patients with this geometry.

When using minimization of contact pressure as a criterion, the optimal medial transfer distance was found to be ~10 mm for all geometries. However, the optimal distance for maximizing stability depended on geometry and was as small as 1 mm for the shallowest trochlear grooves. Therefore, it is important to consider and balance multiple criteria when planning surgery.

Anterior transfer had minimal effect on patellar stability for all geometries. The knees with deep trochlear grooves experienced slightly greater lateral displacement with increasing anterior transfer; however, this change was much smaller than that caused by medial patellar tendon transfer.

The MPFL force increased due to the perturbation force in most models. In knees with deep trochlear grooves, the minimal increase in MPFL force for large medial transfer distances (>10 mm) may indicate that the patellar tendon and bony geometry were sufficient to stabilize the joint. However, knees with shallow trochlear grooves always required an increase in MPFL force to resist the lateral perturbation. Therefore, ensuring adequate repair and tensioning of the MPFL may be particularly important in knees with shallow trochlear grooves.

## V. Conclusions

Femoral trochlear groove depth affected the relationship between lateral patellar stability and medial patellar tendon transfer distance in simulated tibial tubercle osteotomy. Additionally, the medial patellofemoral ligament was more important to maintaining joint stability for larger patellar tendon transfer distances in knees with shallow trochlear grooves. These results emphasize the importance of considering joint geometry in surgical planning.

## Acknowledgment

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## Conflict of Interest

The authors declare that they have no conflict of interest.

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