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ABSTRACT

Objectives: A tibial tubercle-trochlear groove (TT-TG) distance of 20 millimeters (mm) is typically used when determining whether tibial tubercle medialization is performed for surgical treatment of patellar instability. Without knowledge of the variability of an individual’s TT-TG distance influenced by through-the-knee femorotibial rotation, the use of a specific TT-TG distance during pre-operative planning for patellar instability may lead to incorrect decisions on the use of tibial tubercle medialization. We hypothesized that knee joint IE rotation is related to the TT-TG distance.

Methods: Eight independent human cadaveric knee specimens (age: 32 ± 6 years; 4 males, 4 females) were utilized. A robotic manipulator (ZX165U, Kawasaki Robotics, Wixom, MI, USA) instrumented with a universal force/moment sensor was used to determine knee joint IE rotation under applied moments of ±5 newton-meters (Nm) at full extension. Two independent reviewers selected the trochlear groove and tibial tuberosity points on computerized tomography (CT) images of each specimen to define TT-TG. To determine the influence of knee joint IE rotation on TT-TG distance, three-dimensional (3D) models generated from CT scans were registered to tibiofemoral kinematics. Linear regression was performed to determine the relationship between knee joint IE rotation and TT-TG distance. The regression coefficient and standard error of measurement (α = 0.05), and coefficient of determination ($r^2$) were reported.

Results: At 0° of rotation, the mean TT-TG distance was 14.2 ± 5.0 mm. Knee joint IE rotation averaged 23.0 ± 4.2°. For every degree of knee joint IE rotation, TT-TG distance changed by 0.52 mm.

Conclusion: TT-TG distance was linearly dependent on knee joint IE rotation changing by 0.52 mm for every degree of knee joint IE rotation. Thus, an offset of IE rotation of 10° would lead to
a change in TT-TG distance of 5.2 mm, enough to alter surgical decision-making for/or against tibial tubercle medialization.

**Keywords**: patellar instability, tibial tubercle-trochlear groove distance, medialization, femorotibial rotation, knee joint internal/external rotation

**Level of Evidence**: IV

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

**What are the new findings**

- Tibial tubercle-trochlear groove distance was highly dependent on knee joint internal/external rotation changing by 0.52 mm for every degree of knee joint internal/external rotation.

- An offset of internal/external rotation of 10° would lead to a change in tibial tubercle-trochlear groove distance of 5.2 mm, enough to alter surgical decision-making for/or against tibial tubercle medialization.

- Physicians should pay close attention to knee joint internal/external rotation when measuring tibial tubercle-trochlear groove distance, specifically in patients with a tibial tubercle-trochlear groove distance near 20 mm.
INTRODUCTION

Approximately 3% of all knee injuries are related to patellar instability [1]. Following a first-time dislocation, the risk of subsequent dislocations can range from 30% to 70%, depending on an individual patient’s risk factors [2]–[5]. One of the crucial risk factors is the tibial tubercle-trochlear groove (TT-TG) distance, which measures the lateralization of the tibial tubercle [6]–[9]. A TT-TG distance of 20 millimeters (mm) is typically used as a threshold value when determining surgical treatment options and the decision to offer a tibial tubercle osteotomy [9]–[11].

The “winking” sign, a radiographic finding seen on weight-bearing anterior-posterior (AP) knee radiographs, has been found to correlate with increased tibiofemoral rotation [12]. Recent studies have focused on highlighting the extent of tibiofemoral rotation [13]. With tibiofemoral rotation, TT-TG distance has been noted to change. Specifically, cadaveric studies have shown that TT-TG distance is statistically significantly lower with internal tibial rotation and statistically significantly greater with external rotation [14], [15]. In pediatric patients with a history of patellar instability, TT-TG distance changes by approximately 0.55 mm per degree of tibial internal and external rotation [16]. Therefore, TT-TG distance may be better understood as variable due to tibial rotation rather than a single value. Understanding the potential range of TT-TG distance values in individual patients due to through-the-knee rotation can provide surgeons with a more accurate framework to understand how tibial rotation influences TT-TG distance.

To the authors’ knowledge, no study has determined how each degree of tibial rotation influences TT-TG distance in a normal patient population. Therefore, this cadaveric study sought to assess the variability of TT-TG distance values through the entire arc of through-the-knee

rotation in specimens with no history of patellar instability. The authors hypothesized that TT-TG distance would increase linearly with external rotation and decrease with internal rotation.

METHODS

Cadaveric Testing

After Institutional Review Board approval, a total of 8 cadaveric specimen knees were obtained from a non-profit anatomic donation organization (age: 32 ± 6 years; 4 males, 4 females). Specimens were prepared for testing by removing soft tissue more than 10 centimeters (cm) from the joint line. Ligaments and capsular tissue were left intact. Specimens underwent computerized tomography (CT) imaging for subsequent testing and (Siemens Biograph mCT 64-slice scanner; smallest slice thickness is 0.6 mm) to ensure they were free of any osseous abnormalities. The proximal femur and distal tibia were potted in cylindrical tubes of bonding cement (Bondo, 3M, St. Paul, MN, USA). Further description of the cadaveric test setup is previously described by Imhauser et al. [17].

A six degrees-of-freedom serial robot instrumented with a universal force/moment sensor (Theta, ATI, Apex, NC, USA) was used to load each specimen (ZX165U, Kawasaki Robotics, Wixom, MI, USA). The femur was fixed to the ground, while the tibia was potted and mounted to the robot’s end effector via custom fixtures. The specimens were covered in saline-soaked gauze to keep the soft tissues hydrated throughout testing [18]. Anatomical landmarks were identified on CT and registered to the robot using a three-dimensional digitizing arm with ± 0.23 mm accuracy (G2X, MicroScribe, San Jose, CA, USA) [19], [20]. These landmarks were used to define the coordinate system for the tibiofemoral joint using the previously mentioned
landmarks. All kinematics and loads were described using anatomical directions via established
methods [17], [21]. Neutral rotation was defined as the position of the specimen when no force
was applied to it. After defining the coordinate system, we used previously defined algorithms to
flex the knee to 0°, utilizing one angle for all rotation and TT-TG distance measurements. At this
flexion angle, we applied ±5 newton-meters (Nm) of internal/external (IE) rotation torque and
measured the resulting axial rotation of the tibia relative to the femur.

**TT-TG Point Selection**

The TT-TG landmarks were selected by adapting previously reported methods [22]–[24].
Using the axial CT images, the most posterior points on the medial and lateral posterior femoral
condyles (PFC) were identified. Next, from proximal to distal, on the first axial cut with a
complete view of the femoral notch, the deepest point of the trochlear groove (TG) was
identified as the “TG” point. Finally, the most prominent point of the tibial tuberosity (TT) point
was marked as the “TT” point (Figure 1). Each point was selected by an orthopedic resident and
a pediatric orthopedic research fellow.
**Figure 1.** Coronal (A) and axial (B) examples of point selection for the tibial tubercle (TT) and trochlear groove (TG).

**Statistical Analysis**

Using the previously described points and each specimen’s rotational data, linear regression was performed to determine the relationship between tibial IE (axial) rotation on TT-TG.

To assess the reliability of the method of measuring TT-TG distance, we used intra-class correlation (ICC) to determine the absolute agreement in slope and intercept calculated from point selection between the two raters and determined to be excellent for both slope and intercept (ICC = 0.98 and 0.95, respectively). Furthermore, the two independent reviewers performed the inter-class correlation on the calculated TT-TG distance for each specimen, and it was found to
be moderate-excellent for all specimens. (Table 1). IBM (Armonk, NY) SPSS Statistics version 22 for Windows was used for all statistical analysis.

Table 1. Inter-class Correlation on the Calculated TT-TG distance for each Specimen. Two independent reviewers performed the inter-class correlation on the calculated TT-TG distance for each specimen.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>TT-TG ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.842</td>
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<tr>
<td>2</td>
<td>0.995</td>
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<td>3</td>
<td>0.503</td>
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<td>4</td>
<td>0.748</td>
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<td>7</td>
<td>0.632</td>
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<td>8</td>
<td>0.955</td>
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</table>

TT-TG – tibial tubercle-trochlear groove distance, ICC – inter-class correlation

RESULTS

The range of motion in IE rotation for all specimens averaged 23.0 ± 4.2° (Table 2). The average TT-TG distance at neutral was 14.2 ± 5.0 mm.

TT-TG distance ranged from 7.5 ± 4.9 mm during internal rotation to 19.6 ± 5.2 mm during external rotation (mean range of 12.1 ± 2.8 mm). Regarding our research question, for every degree of tibial rotation, TT-TG distance changed by 0.52 ± 0.07 mm across all specimens tested (Figure 2) (p < 0.001, r² > 0.976).

Table 2. Rotation data for each specimen demonstrating TT-TG distance, rotation, and change in TT-TG distance per degree of rotation.
<table>
<thead>
<tr>
<th>Specimen</th>
<th>Average Range of TT-TG distance (mm)</th>
<th>Range of Rotation (°)</th>
<th>Average Slope* (mm/°)</th>
<th>Alpha** (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.1</td>
<td>21.1</td>
<td>0.66</td>
<td>17.9</td>
</tr>
<tr>
<td>2</td>
<td>13.4</td>
<td>28.9</td>
<td>0.48</td>
<td>6.5</td>
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<td>3</td>
<td>7.0</td>
<td>15.9</td>
<td>0.44</td>
<td>16.9</td>
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<td>14.2</td>
<td>23.8</td>
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<td>16.2</td>
<td>29.8</td>
<td>0.55</td>
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<td>7</td>
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<td>10.3</td>
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<tr>
<td>All Specimens Mean ± SD</td>
<td>12.1 ± 28</td>
<td>23.0 ± 4.2</td>
<td>0.52 ± 0.07</td>
<td>13.8 ± 4.6</td>
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*Average Slope - change in TT-TG distance (mm) for each increase in degree (°) of internal/external rotation, TT-TG – tibial tubercle-trochlear groove distance

**Alpha - Rotation data for each specimen demonstrating range of TT-TG distance, range of internal/external rotation, slope (change in TT-TG distance per degree of rotation), and alpha (TT-TG distance at zero degrees of rotation).
**Figure 2.** TT-TG distance through individualized tibial rotation for each specimen. Negative values represent internal rotation, while positive values represent external rotation. (TT-TG – tibial tubercle-trochlear groove distance, S - Specimen Number)

**DISCUSSION**

This study sought to understand the normal range of TT-TG distance in individuals at different degrees of knee rotation. The analysis of 8 cadavers with no surgical history of patellar pathology determined that the rotation through the knee is typically 23°, and TT-TG distance changes by 0.52 mm for every degree of knee rotation. With many surgeons using a TT-TG cutoff when determine the need for medializing procedure, these findings may caution surgeons...
to consider tibial rotation prior to measuring TT-TG as rotation could lead to a falsely elevated or decreased TT-TG.

Previous cadaveric studies have shown that there is a statistically significant difference in TT-TG distance at the extremes of tibial internal and external rotation, with external rotation leading to a larger TT-TG and internal rotation leading to a smaller TT-TG distance [14], [15]. Smith et al. further analyzed this concept through a modeling study using magnetic resonance imaging (MRI) from pediatric patients with a history of patellar instability. Using a constant 10° of rotation for each knee, they found that for each degree of through-the-knee rotation, the TT-TG distance changed by 0.55 mm [16]. To determine a “normal” TT-TG range for patients with no history of patellar instability, our study focused on healthy adult cadaveric specimens without a surgical history of patellar pathology. Furthermore, by using a constant force during testing, our study was able to individualize the rotation through the knee to determine a range of TT-TG distance that is more specific for each patient. The mean rotation through the knee was found to be 23° for IE rotation. Throughout the rotation through the knee, the TT-TG distance was found to change by 12.1 mm, leading to a 0.52 mm change per degree of rotation. These findings corroborate previous findings, demonstrating a change in TT-TG distance per degree of rotation. Surgeons should be aware of differences in external and internal through-the-knee femorotibial rotation impacting TT-TG distance when planning correction for patellar instability.

Lin et al. retrospectively reviewed three cohorts of patients less than 18 years of age: fixed or obligatory dislocators, standard traumatic instability patients, and controls [13]. They measured tibiofemoral rotation on initial axial MRI using the posterior femoral and tibial condylar lines, as well as TT-TG distance [13]. Tibiofemoral rotation averaged 8.5° externally for fixed or obligatory dislocators, 1.6° externally for standard traumatic instability patients, and
3.8° internally for controls [13]. Lin et al. showed that the tibiofemoral rotation through the knee is greater in patients with patellar instability than in controls [13]. As the external rotation through the knee increases, so too do the ranges of TT-TG distance.

While many surgeons typically use 20 mm as their threshold for abnormal TT-TG distance, these findings suggest that what is measured radiographically may not represent the true TT-TG distance of a patient. Specifically, a patient with a radiographically measured TT-TG distance less than 20 mm, but a physical exam notable for a large amount of tibiofemoral rotation through the knee may have an abnormal TT-TG distance and therefore benefit from medialization of the tibial tuberosity. As our study applied internal/external (IE) rotation torque only at 0° flexion in each cadaver knee, future studies performed at various degrees of knee flexion may provide further information to surgeons regarding the variability in TT-TG distance caused by differences in through-the-knee femorotibial rotation.

This study has several limitations. The testing protocol included applying a rotational moment in one direction, releasing the moment, and allowing the specimen to return to the starting point before applying the force in the opposite direction. Therefore, the data was collected as two separate samples, one for internal rotation and one for external rotation. Additionally, the small sample size raises concerns about the generalizability of these findings. The sample size was limited to specimen accessibility over the time frame of the study. However, the small variation in regression coefficients across all knees builds confidence in our conclusions [15], [16]. Future studies may also seek to evaluate the influence rotation has on TT-TG distance at varying degrees of knee flexion. As this study utilized cadaver knees without resting loads on from various muscle and tendons in the leg, the durability of the knee may differ
from living patients. Further studies should seek to determine the dynamic range of TT-TG distance in pre-operative patients with different knee pathologies.

CONCLUSION

This cadaveric study sought to determine the normal range TT-TG distances by analyzing eight specimens in full extension at varying degrees to knee internal and external rotation. The mean range of through-the-knee rotation was 23.0°. Furthermore, the TT-TG distance changed by 0.52 mm for each degree of rotation. While most surgeons use a threshold of 20 mm to signify an abnormal TT-TG distance, our data demonstrates that with a physiologic amount of rotation, TT-TG distance can vary up to 14 mm in some specimens.
REFERENCES


Active Knee Extension on Dynamic Kinematic Computed Tomographic Imaging. 
*Arthroscopy.* 2015;31(9):1748-1755. doi:10.1016/j.arthro.2015.03.015

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Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

| Daniel W. Green reports a relationship with Arthrex Inc that includes: consulting or advisory. Daniel W. Green: Royalties - Arthrex Inc and Pega Medical |