SCIENTIFIC ARTICLE

Relationship between Patellar Tracking and the "Screw-home" Mechanism of Tibiofemoral Joint

Li-kang Zhang, MM†, Xiao-meng Wang, MM†, Ying-zhen Niu, MM, Hui-xin Liu, MM, Fei Wang, MD

Department of Orthopedics, Third Hospital of Hebei Medical University, Shijiazhuang, China

Objective: To demonstrate the effect of the screw-home motion on the stability of the patellofemoral joint, and investigate its mechanism of regulation of patellar tracking.

Methods: Twenty volunteers who met the criteria were examined. All subjects had axial computed tomography (CT) scanning performed on bilateral knees at 0° and 30° of flexion. Scanning began above the femorotibial articulation and femoral trochlear groove, and moved sequentially down to the level of the anterior tibial tubercle. The following measurements were obtained: tibial rotation relative to the femur (TRRF), tibial tuberosity–trochlear groove (TT–TG) distance, lateral patellar displacement (LPD), patellar tilt angle (PTA), and congruence angle (CA). We assessed the change (Δ) in each variable at both flexion angles, and analyzed this to investigate the corresponding relationship between the patella, the femur, and the screw-home mechanism. The differences between the values measured at 0° and those measured at 30° flexion were analyzed using the paired sample *t*-test. The differences between men and women were analyzed using the *t*-test. Pearson's correlations were performed to determine the relationship between ΔTT–TG distance and ΔLPD, ΔPTA and ΔTRRF, and ΔCA and ΔTRRF.

Results: There were 10 women and 10 men enrolled in the present study, with an average age of 25 years and an average body mass index of 21.8 kg/m^2, and all volunteers had no history of knee injuries. Compared with measurements taken at 0° flexion, TRRF at 30° flexion was significantly increased, and the PTA, CA, LPD, and TT–TG distance were significantly decreased (all $P < 0.01$). There was no difference between men and women at 0° and 30° flexion, respectively ($P < 0.01$). In this respect, there was no sex difference, but the change was greater for men than for women. Both ΔPTA and ΔCA demonstrated significant correlation with the ΔTRRF (both $P < 0.01$); a significant correlation between ΔLPD and ΔTT–TG distance was also demonstrated ($P < 0.01$).

Conclusions: As the tibiofemoral joint rotated, the patellofemoral joint became more stable and aligned, which indicates that the screw-home mechanism plays an important role in regulating patellofemoral joint alignment.

Key words: Kinematics; Patellar tracking; Patellofemoral joint; "Screw-home" mechanism; Tibiofemoral joint

Introduction

Patellar tracking is defined as the motion of the patella relative to the femur or the femoral groove during knee flexion and extension. Patellar maltracking is thought to relate to many disorders of the patellofemoral joint[1]. Consequently, normal patellar tracking is the basis of the kinematics of knee. Normal patellar tracking depends on a variety of dynamic and static structures around the patella, and previous studies have investigated patellar tracking with varying results[2,3]. In general, the patella is gradually aligned to the femoral trochlear groove during knee flexion from 0° to 30°. In this range of flexion, the patella is not yet confined to its femoral groove, thus giving room for free patellar movement; this is referred to as "capture." "Capture" is affected by tibial rotation, through tensioning of the patellar ligament and the lateral and medial retinacula, which is an important premise for normal patellar tracking[4,5].

The effects of longitudinal tibial rotation on the patellofemoral joint have attracted increasing attention over the past two decades[5,6]; however, the specific mechanism remains

Address for correspondence Fei Wang, MD, Department of Orthopaedics, Third Hospital of Hebei Medical University, No. 139 of Ziqiang Road, Shijiazhuang, China 050051 tel: 0086-018533112821; Fax: 0086-0311-88602613; Email: wangxiaomeng0318@126.com
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†These two authors contributed equally to this work and are first co-authors.
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unclarified. In the normal knee, internal rotation of the tibia relative to the femur commonly occurs during knee flexion. However, Coughlin *et al.* report that 81% of the rotation movement occurred during knee flexion from 0° to 30°[7]; this particular motion was referred to as the "screw-home" motion. Research shows that the screw-home mechanism is coupled internal–external rotation, which could improve the mechanical efficiency of the knee joint[4,8,9]. Some authors report that screw-home motion is characteristic of healthy knee motion, and its absence is often thought to be an indication of instability or joint disease[4,8,10,11].

Interestingly, both of these important components of knee movement, the capture mechanism and the screw-home motion of the patellofemoral joint, are exhibited in the early stage of knee flexion. Time synchronization suggests that there must be intrinsic biomechanical and kinematical relationships between the screw-home mechanism and the capture mechanism of the patellofemoral joint. Computed tomography (CT) is useful in the diagnosis of patellar malalignment, and many studies have carried out CT examination at varying degrees of knee flexion[12,13].

The aim of the present study was to investigate the effect of the screw-home motion on the stability of the patellofemoral joint, and to explore its mechanism of regulation of patellar tracking so as to further enhance our understanding of knee kinematics.

Materials and Methods

Participants

Volunteers were screened based on the following criteria. Inclusion criteria: (i) the human age ranges from 18 to 40 years; and (ii) 19 kg/m^2 ≤ body mass index ≤ 25 kg/m^2.

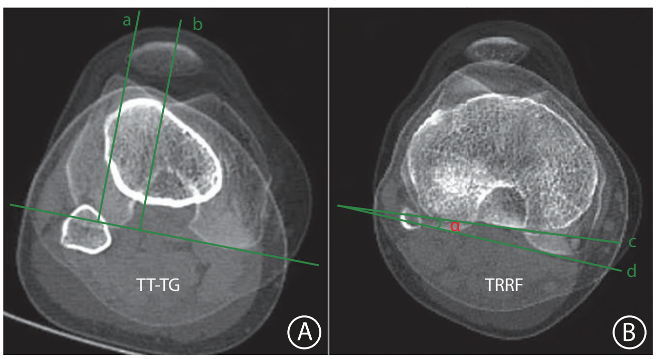

Fig. 1 Measurement of tibia tuberosity-trochlear groove (TT–TG) distance and tibial rotation relative to the femur (TRRF). (A) TT–TG distance: the distance between the axial section depicting the deepest part of the trochlear groove (a) and the center of the tibial tuberosity (b), while ensuring that the measurement was parallel to the posterior condylar axis of the femur; (B) TRRF on axial computed tomography scan: the angle (α) between the line (c) drawn through the posterior border of the proximal tibia and the line (d) drawn through the two most posterior points of the posterior femoral condyles. F, femur; T, tibia.

32 Volunteers with any of the following conditions were excluded: (i) symptoms such as knee pain, swelling, and/or dislocation; (ii) varus or valgus deformity of the knee and patella alta; (iii) joint hypermobility syndrome and joint hyperextension; (iv) suppurative, rheumatoid, or tuberculosis arthritis; (v) history of knee surgery or trauma; (vi) intra-articular tumor or tumor-like lesion; (vii) radiologic evidence of asymptomatic patellar instability such as patellar tilt and/or subluxation. A total of 32 volunteers were excluded. The present study was approved by the local ethics committee of our institution. All subjects provided written informed consent.

Computed Tomography Measurements

All subjects had axial CT scanning performed on bilateral knees at 0° and 30° of flexion in the supine position, with the limbs fixed by equipment to support the joint at the correct angle[14]. The flexion angle was monitored using a hand-held goniometer. The CT scanning plane was perpendicular to the longitudinal axis of the femur at full extension or flexion of 30°.

Computed Tomography Protocol

For all diagnostic examinations, a Phillips LXC CT Scanner (Phillips Medical System, Best, Netherlands) was used to create transaxial images (1-mm slice thickness, 1-mm slice gap, 3.8-s scan time, 150 mA, 100 kVp, 250 FOV, 570 mAs) in all participants. Scanning began above the femorotibial articulation and femoral trochlear groove, and moved sequentially down to the level of the anterior tibial tubercle.

Parameters for Measurement

Dejour *et al.* report that a tibial tuberosity trochlear groove distance (*TT–TG*) > 20 mm is generally considered pathological and as an indication for medial tibial tubercle transfer in symptomatic participants[15]. Tibial rotation angle relative to the femur was defined as the relative rotational difference between the femur and the tibia[16]. Patellar tilt angle, congruence angle and lateral patellar displacement could indicate the matching index of the patellofemoral joint[17,18]. As a result, the following measurements were obtained.

Tibia Tuberosity–Trochlear Groove (TT–TG) Distance

It was measured by superimposing the axial section depicting the deepest part of the trochlear groove upon the center of the tibial tuberosity, while ensuring that the measurement was parallel to the posterior condylar axis of the femur[19] (Fig. 1A).

Tibial Rotation Relative to the Femur (TRRF)

It measured the angle between two lines drawn through the two most posterior points of the posterior femoral condyles and the posterior border of the proximal tibia, with positive values indicating internal rotation (Fig. 1B).

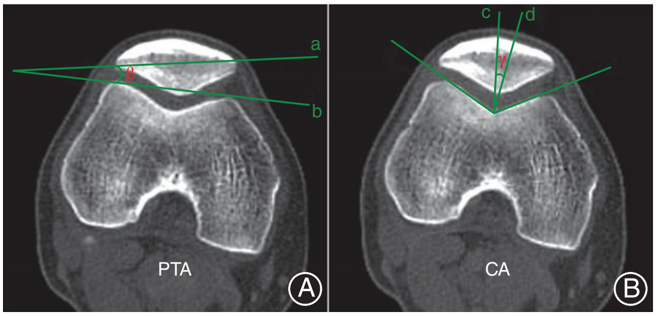

Fig. 2 Measurement of patellar tilt angle (PTA) and congruence angle (CA). (A) PTA, the angle (β) between the line intersecting the widest part of the patella (a) and the line tangential to the anterior surfaces of the femoral condyles (b); (B) CA, the angle (γ) between the line bisecting the sulcus angle (c) and the line connecting the apex of the sulcus to the lowest aspect of the patella ridge (d).

Patellar Tilt Angle (PTA)
It measured the angle subtended by a line through the medial and lateral edge of the patella and another line through the anterior border of both femoral condyles[20] (Fig. 2A).

Congruence Angle (CA)
It measured the angle between the line bisecting the sulcus angle and the line connecting the apex of the sulcus to the lowest aspect of the patella ridge, based on the method described by Kujala *et al.*[21] (Fig. 2B).

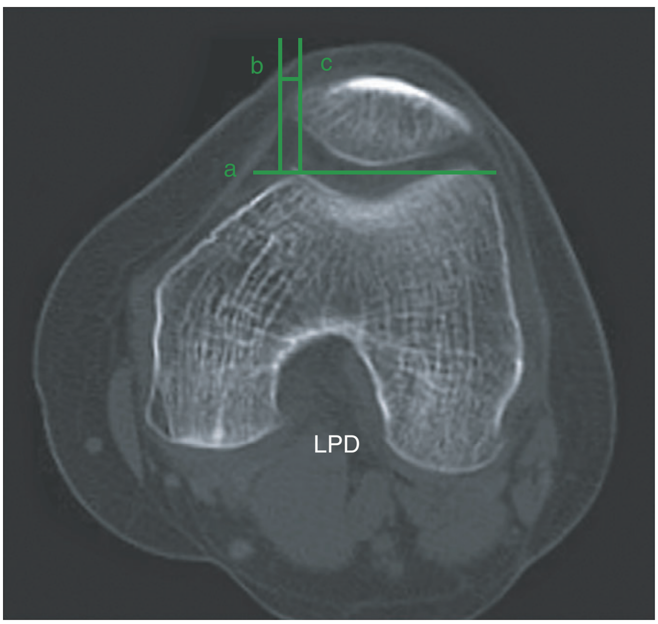

Fig. 3 Measurement of lateral patella displacement (LPD). Line a connects the lateral and medial femoral anterior condyles. Line c is perpendicular to line a through the peak of femoral condyle, and line b is parallel with line a through medial edge of the patella, and LPD is defined as the distance from b to c.

Lateral Patellar Displacement (LPD)
It measured the negative values indicating medial translation, as described by Kujala *et al.*[21] (Fig. 3).

A single experienced orthopedic surgeon (X.M.W.) performed all measurements. Each value was measured three times, and the average was calculated. The subjects' identifying information (name, age, and sex) was blinded.

Statistical Analysis
The data obtained were statistically analyzed using SPSS 21.0 software (Chicago, IL, USA). All data were expressed as the mean ± standard deviation. The differences between the values measured at 0° and those measured at 30° flexion were analyzed using the paired sample *t*-test. $P < 0.01$ was considered statistically significant. The differences between men and women were analyzed using the *t*-test. Pearson's correlations were performed to determine the relationship between ΔTT–TG distance and ΔLPD, as well as the relationship between ΔPTA and ΔTRRF, and that between ΔCA and ΔTRRF. A Shapiro–Wilk normality test confirmed that all variables were normally distributed.

Results

Characteristics of Participants
Twenty volunteers (10 women and 10 men) who met the criteria were examined. The subject age was 25 ± 2.3 years (range, 21–34 years), the body mass index was 21.8 ± 2.1 kg/m^2, and the height was 172.0 ± 5.5 cm.

Measurement Results
All planned measurements were obtained for each knee in every subject, and all measured values were significantly different between 0° and 30° of knee flexion. (both $P < 0.01$, Table 1).

The TRRF measurements showed that at knee flexion of 30°, the angle significantly increased (550%) from −1.8° ± 1.3° to 8.1° ± 1.5° ($P < 0.01$). The TRRF angles was −2.3° ± 2.1° and 7.1° ± 1.2° in male participants, and −1.1° ± 1.7° and 8.7° ± 1.6° in female participants at the knee flexion of 0° and 30°, respectively. There was no difference between male and female participants at 0° and 30° flexion, respectively ($P < 0.01$). Their changed trend was the same as the overall trend (Fig. 4).

With the increase in the flexion angle from 0° to 30°, the PTA significantly decreased (45%), from 14.5° ± 1.1° to 8.0° ± 1.2° ($P < 0.01$). The patellar tilt angle was 15.1° ± 2.3° and 7.2° ± 1.8° in male participants, and 12.7° ± 1.1° and 8.5° ± 1.6° in female participants at the knee flexion of 0° and 30°, respectively. In this respect, there was no sex difference, but the change was greater for men (ΔPTA = 7.9°) than for women (ΔPTA = 4.2°) (Fig. 5).

The CA significantly decreased (131%), from 23.6° ± 2.7° to −7.4° ± 1.8° with the increase in the flexion angle from 0° to 30° ($P < 0.01$). The congruence angle was 22.9° ± 2.1° and −7.0° ± 1.3° in male participants, and 24.5° ± 1.2°

TABLE 1 Measurement results at 0° and 30° flexion (mean±SD)

Indexes	0°(40 cases)	30°(40 cases)	*t*	*P*
TFFR (°)	−1.8 ± 1.3	8.1 ± 1.5**	−25.3	0.000
CA (°)	23.6 ± 2.7	−7.4 ± 1.8**	46.7	0.000
PTA (°)	14.5 ± 1.1	8.0 ± 1.2**	22.5	0.000
TT–TG (mm)	15.4 ± 1.3	9.2 ± 1.4**	18.5	0.000
LPD (mm)	5.8 ± 1.3	−0.8 ± 1.5**	15.4	0.000

** Significant difference between 30° and 0° ($P < 0.01$). CA, congruence angle; LPD, lateral patella displacement; PTA, patella tilt angle; TRRF, tibia rotation relative to femur; TT–TG, tibia tuberosity-trochlear groove distance.

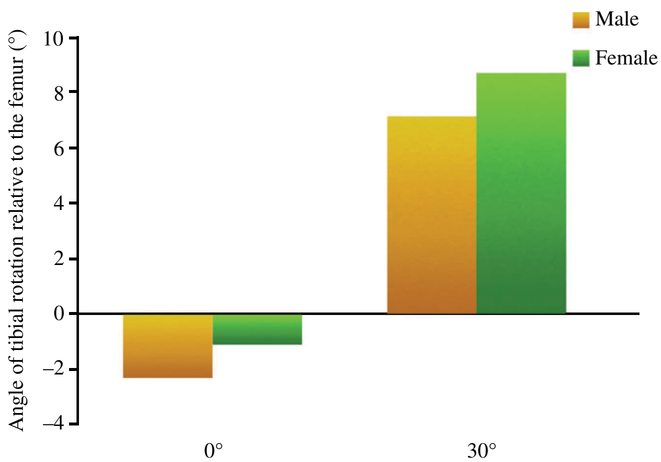

Fig. 4 Bar chart illustrates the angle of tibial rotation relative to the femur (TRRF) at 0° and 30° flexion between men and women.

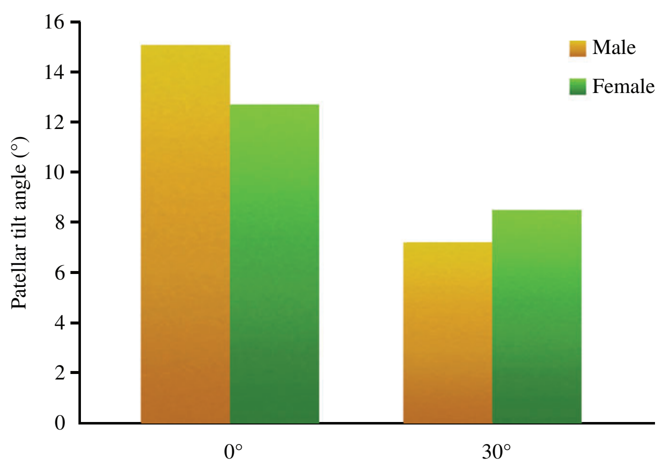

Fig. 5 Bar chart illustrates the patellar tilt angle (PTA) at 0° and 30° flexion between men and women.

and −8.2° ± 2.5° in female participants at the knee flexion of 0° and 30°, respectively. There was no difference between male and female participants at 0° and 30° flexion and the numerical value changed trend ($P < 0.01$) (Fig. 6).

The average TT–TG distance and LPD at 0° flexion were 15.4 ± 1.3 mm and 5.8 ± 1.3 mm, respectively, while at 30° flexion they significantly reduced (40% and 114%) to 9.2 ± 1.4 mm and −0.8 ± 1.5 mm, respectively (both $P < 0.01$). The TT–TG distance was 15.9 ± 1.3 mm and 10.3 ± 2.1 mm in male participants, and 15.1 ± 2.7 mm and 8.7 ± 1.4 mm in female participants at the knee flexion of 0° and 30°, respectively (Fig. 7). The LPD distance was 5.2 ± 2.5 mm and −1.2 ± 1.2 mm in male participants, and 5.9 ± 1.3 mm and −0.5 ± 1.6 mm in female participants at the knee flexion of 0° and 30°, respectively. There was no difference between male and female participants at 0° and 30° flexion ($P < 0.01$). Their changed trend was the same as the overall trend (Fig. 8).

Correlation between Patella Position and Tibial Rotation

The TT–TG distance and LPD significantly decreased between the knee flexion of 0° to 30°. When all knees were analyzed together, a significant correlation was found between ΔTT–TG distance and ΔLPD ($r = 0.905$, $P < 0.01$, Fig. 4). Along with the decrease of the TT–TG, LPD also decreases between the knee flexion of 0° to 30°.

While at 0°–30° flexion, the TRRF significantly fell. With the increase in the flexion angle from 0° to 30°, the PTA and CA significantly decreased. Significant correlations were also found between ΔTRRF and both ΔCA ($r = 0.869$, $P < 0.01$, Fig. 5) and ΔPTA ($r = 0.885$, $P < 0.01$, Fig. 6).

Discussion

The most important finding of this study was the special relationship between the screw-home mechanism and the "capture" mechanism. It was confirmed that the tibiofemoral joint rotation could regulate patellar tracking in order to guarantee the balance of patellofemoral joint alignment during flexion–extension movement of the knee.

As the medial femoral condyle is longer than the lateral condyle, the tibia rotates internally on the femur during the first stage of flexion; this well-known kinematic phenomenon is called the screw-home movement[4]. Coughlin *et al.* report that 81% of rotational movement occurs during knee flexion from 0° to 30°[7]. Karrholm *et al.* report that the rotational movement of the tibia ranges from 1.6° (external rotation) to 9.0° (internal rotation) during active flexion of the healthy knee joint[20]. The present study demonstrated that tibial internal rotation occurred with knee flexion, and the average angle was 9.9° ± 1.9° during knee flexion at 30°, which was similar to the findings of Karrholm *et al.*[20] Furthermore, rotation of the knee joint reportedly significantly alters the TT–TG distance[22,23]. In the present study, the TT–TG distance significantly reduced during knee flexion from

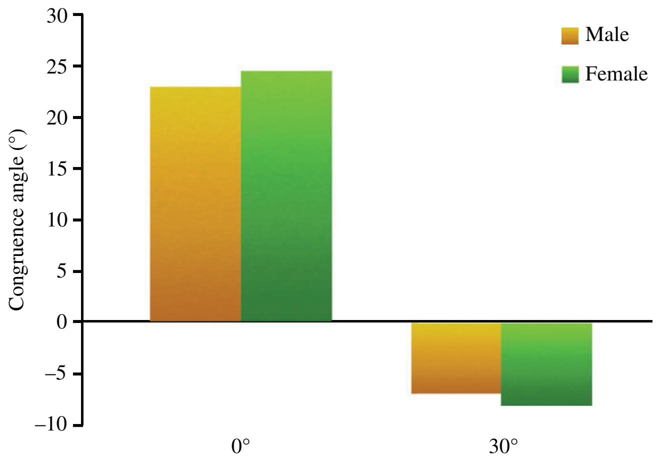

Fig. 6 Bar chart illustrates the congruence angle (CA) at 0° and 30° flexion between men and women.

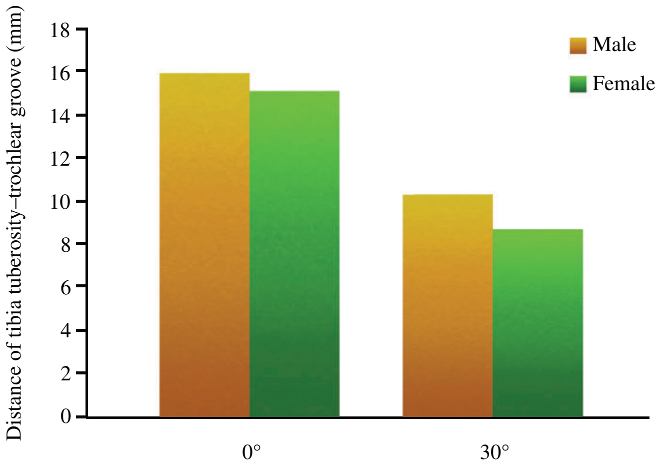

Fig. 7 Bar chart illustrates the distance of tibia tuberosity–trochlear groove (TT–TG) at 0° and 30° flexion between men and women.

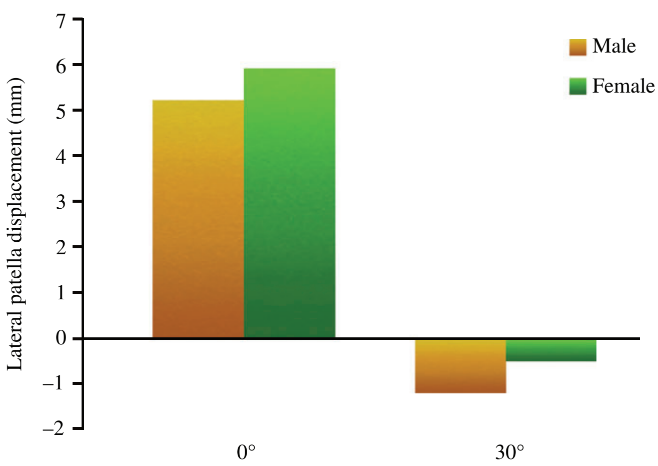

Fig. 8 Bar chart illustrates the lateral patella displacement (LPD) at 0° and 30° flexion between men and women.

0° to 30°; this indicates that screw-home movement has a large influence on patellar position.

Previous research suggests that patellar tracking is very complex, and can undergo shift, rotation, and tilt relative to the femur[24,25]; as the knee flexes, the patella gradually shifts laterally after a slight medial shift in the early phase of knee flexion. In the range of 0° to 30° knee flexion, patellar translation motion causes the patella to shift towards the medial femoral condyle[26,27]. The present study revealed that the patella shifted internally relative to the femur in the knees during flexion from 0° to 30°. Our data showed that LPD significantly reduced, and that the average patellar medial displacement was 6.6 mm[21]. The present results confirm that the patella showed a slight medial shift during early flexion, similar to other studies[28–30].

Patellar stability depends mainly on the static and dynamic structures around it. During knee flexion from 0° to 30°, the patella is not yet confined to its femoral groove. It is affected by tibial rotation, through tensioning of the patellar ligament and of the lateral and medial retinacula. Hence, these structures play an important role in regulating patellar tracking during knee flexion from 0° to 30°, and the position of the tibial tubercle has a greater influence on patellar position during the early stage of knee flexion[31]. In the present study, LPD decreased as the TT–TG distance decreased. The decrease in LPD represents the medial shift of the patella, and the TT–TG distance represents the tibial internal rotation[32]. The present study found a significant correlation between ΔTT–TG distance and ΔLPD, which suggests that the patellar medial–lateral displacement was affected by the tibial tubercle displacement. Therefore, the greater the angle of internal tibial rotation, the greater the medial patellar translation. The present study also demonstrated that the screw-home mechanism could displace the tibial tubercle and cause medial translation of the patella, aided by the traction of the patellar ligament. A series of actions caused by the tibiofemoral joint rotation causes the patella to gradually slide into the femoral trochlea.

In the normal patellofemoral joint, the patella is aligned to the femur, which ensures normal knee flexion–extension movement and avoids the problems caused by patellar instability and dislocation, such as anterior knee pain and patellofemoral arthritis[33,34]. On CT scans, PTA and CA effectively express the patellofemoral alignment[35]; when the PTA and CA decrease, the stability of the patellofemoral joint improves. The present study showed that PTA and CA significantly decreased at 30° of knee flexion, suggesting that the patellar stability was markedly improved. However, ΔPTA and ΔCA were both correlated with ΔTRRF, which indicates that patellar stability was affected by the tibial rotation, and improved with the increase in flexion and rotation angle. Several studies have reported the relationship between patellar dislocation and tibial torsional deformity, and that good results can be obtained by performing corrective osteotomy[36,37].

During knee flexion, the patella moves into the femoral trochlear groove while rotational movement adjusts the patellofemoral joint stability; this is known as the capture mechanism of the femur, and is very important clinically. The capture mechanism prevents abnormal patellar tracking in the early stage of knee flexion[38]. Notably, as an efficient regulating mechanism, the screw-home mechanism is the insurance of the capture mechanism, and plays an important role in guiding patellar sliding into the femoral trochlear groove. We think that this is a dynamic regulation mechanism of the kinematics of the patellofemoral joint.

There are several limitations to the current study. As this research causes radiation exposure, the sample size was small. We chose to use a static measurement (CT) to measure the changes during knee flexion. Although this cannot reflect the dynamic activity of the knee joint, it could provide more precise measurement data. We only examined knee rotation between the knee flexion from 0° to 30°; thus, our findings were insufficient to discuss total flexion angles. However, as the main purpose of the present study was to evaluate the screw-home mechanism affecting patellar tracking, not patellar tracking itself, it was not essential to assess patellar tracking during the whole range of knee flexion, which did not have a direct effect on the experiment.

This study analyzed the movement of the knee joint as a whole. We believe that the screw-home mechanism could significantly influence the patellofemoral stability. The dynamic regulation mechanism was crucial to knee flexion and contributed to smooth capture movement.

Conclusions

Although current studies show that many factors could affect patellar tracking, the present data demonstrated a special role of the screw-home mechanism in regulating patellofemoral joint movement. The screw-home mechanism not only ensures the stability of knee extension, but also regulates the patellofemoral alignment during knee flexion–extension. As a bridge, it could combine the patellofemoral joint and the tibiofemoral joint and maintain stability of the normal knee kinematics.

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