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Biomechanical Analysis of Tibial Tuberosity Medialization and Medial Patellofemoral Ligament Reconstruction

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Abstract

Biomechanical studies are commonly performed to evaluate the influence of medial patellofemoral ligament (MPFL) reconstruction and tibial tuberosity medialization on patellar tracking and patellofemoral contact pressures. The most common method is in vitro simulation of knee function, but computational simulation of knee function and computational reconstruction of in vivo motion can also be utilized. The current review of the biomechanical literature indicates that MPFL reconstruction and tibial tuberosity medialization reduce lateral patellar tracking. Decreased lateral patellofemoral contact pressures have also been noted. For MPFL reconstruction, the most commonly noted biomechanical concerns are graft over-tensioning and non-anatomical attachment on the femur leading to over-constraint of the patella and elevated medial contact pressures. For tuberosity medialization, the influence of altered tibiofemoral kinematics on post-operative function is unknown. Future biomechanical studies should emphasize inclusion of anatomical features and tracking patterns related to patellar instability, with comparison between the surgical approaches for continued development of treatment guidelines.

Keywords

Patellar instability; MPFL reconstruction; tibial tuberosity medialization; computational simulation; in vitro testing; diagnostic imaging; biomechanics

Introduction

Numerous surgical approaches are available to treat recurrent lateral patellar instability. Biomechanical studies are commonly performed to assess the efficacy of approaches that aim to improve stability by decreasing the lateral force acting on the patella or augmenting the resistance to lateral subluxation. To date, biomechanical studies have primarily focused on medialization of the tibial tuberosity and reconstruction of the medial patellofemoral ligament (MPFL).

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Medialization of the tibial tuberosity reduces the lateral component of the force applied to the patella by altering the orientation of the patellar tendon. The approach is currently recommended for recurrent instability associated with a lateralized tibial tuberosity [1] and persistent lateral patellar maltracking. For patients with lateral or distal articular cartilage lesions, tuberosity medialization can be combined with anteriorization (anteromedialization) [2, 3] in an attempt to reduce patellofemoral contact pressures by increasing the moment arm of the patellar tendon about the flexion axis of the knee and reducing the component of the patellar tendon force compressing the patella into the trochlear groove.

MPFL reconstruction replaces the native MPFL with a stronger and stiffer graft that acts as a passive checkrein to resist lateral patellar subluxation. The graft attachment points on the femur and patella and the resting length are set to limit lateral patellar translation. In particular, the femoral fixation point is chosen to approximate the native MPFL attachment and maintain a consistent distance between graft attachment points at low flexion angles, while allowing the distance to decrease beyond 60° of flexion. Although multiple techniques have been developed to identify the anatomic attachment point on the femur [4, 5], malpositioning of the femoral attachment has been shown to occur in approximately one-third of MPFL reconstructions [6].

In vitro simulation of knee function with cadavers, computational simulation of knee function, and computational reconstruction of in vivo motion have all been used to characterize how tuberosity medialization and MPFL reconstruction influence patellar tracking (patellar lateral shift and tilt) and/or patellofemoral contact pressures. While the resulting data is valuable to assess how the procedures influence knee function, each study has a limited ability to reproduce the complex combination of anatomy, muscle loading conditions, and functional activities that cause patellar instability. This article reviews the strengths and limitations of previous biomechanical studies to highlight clinically relevant information that could guide treatment decisions.

Approaches to Evaluate Patellar Tracking and Pressures

In vitro simulation studies replicate knee function with cadaveric knees. Knees are fixed to a testing frame that induces tibiofemoral motion through application of quadriceps forces, sometimes in combination with hamstrings forces and/or representation of body weight (Fig. 1). Tibiofemoral and patellofemoral reaction forces, and the forces carried by ligaments and retinacular structures, control the motion of the knee. These studies utilize motion tracking systems to characterize patellofemoral motion based on anatomical coordinate systems and pressure sensors to quantify patellofemoral contact pressures.

Computational reconstruction of in vivo function utilizes three-dimensional models to reproduce motion performed by patients within a diagnostic scanner. Diagnostic imaging (CT and/or MRI) is utilized to create models representing the bones of the knee at multiple flexion angles, with shape matching techniques used to represent all positions with a single set of bones (Fig. 2). Post-operative imaging can also be obtained for representation of post-operative motion. Patellar tracking is characterized within an anatomical coordinate system by creating coordinate axes for the patella and femur. The studies are primarily limited by

motion attainable within a diagnostic scanner and representation of a single surgical treatment method per subject analyzed.

Computational simulation studies represent knees with computational models, using springs to represent soft tissue structures and force vectors to represent muscle forces (Fig. 3). The models can be developed from diagnostic imaging of knees with patellar disorders. Material properties are assigned to cartilage to quantify reaction forces as the femur and patella come into contact. Contact pressure patterns are determined by balancing reaction forces and moments within the cartilage with the forces and moments applied to the patella by the quadriceps muscles, patellar tendon and retinacular structures. Computational models include the most flexibility to represent variations in graft properties and measure output, but are limited by the mathematical approximations of tissue properties and interactions. Computational models are commonly validated with respect to data generated from in vitro simulation of knee function or computational reconstruction of in vivo motion.

MPFL Reconstruction

In vitro biomechanical testing has identified the MPFL as the primary passive restraint to pathologic lateral translation of the patella. Based on cadaveric studies applying an isolated lateral force to the patella, the MPFL provides more than 50% of the passive resistance to lateral translation [7, 8]. A cadaveric study and computational simulation study focused on the path length of the normal MPFL as a function of the flexion angle indicated that the length tends to decrease beyond 60° of knee flexion [9, 10], although another in vitro study indicated the MPFL length tends to increase beyond 60° of knee flexion [5]. Several in vitro simulation studies have evaluated the influence of the native MPFL on patellar tracking. Sectioning the MPFL has increased patellar lateral shift and tilt of knees tested on a simulator by up to 9 mm and 8°, respectively, primarily near full extension [11–16]. Larger changes have been noted with a lateral force directly applied to the patella [14, 17, 18]. Cutting the MPFL has been shown to decrease the peak medial patellofemoral contact pressure but have no influence on the lateral pressure [17], with similar results obtained for the total contact pressure [19]. Other studies showed elevated mean lateral contact pressure after cutting the MPFL, with a similar decrease in the mean medial pressure [15, 16].

In vitro studies simulating knee function have generally shown that MPFL reconstruction decreases lateral patellar tracking, with varying results with respect to knees with an intact MPFL. The results range from decreased lateral tracking but not to the level of the intact knee [18], to correcting elevated lateral tracking caused by MPFL injury [12, 15], and even overcorrection of lateral tracking [11]. In some studies the results were obtained with a lateral force applied directly to the patella [11, 12] or with the tibial tuberosity lateralized [15]. MPFL reconstruction has been shown to restore the total medial contact pressure, and reduce the total contact pressure applied to lateral cartilage [19] for one study, with another study showing MPFL reconstruction decreases elevated mean lateral pressures [15].

In vitro simulation studies have characterized the influence of the point of femoral fixation on patellar tracking and contact pressures. One in vitro study showed similar patellofemoral contact pressure values for an isometric femoral attachment (posterior medial epicondyle)

and a non-isometric femoral attachment (adductor tubercle) with a quadriceps tendon graft [20]. Other studies related non-anatomical femoral attachment to elevated medial tracking and pressures. With the graft tension set at 2 N, femoral tunnels 5 mm proximal or distal to an anatomical location increased peak and mean medial pressures and medial patellar tilt and shift [16, 21].

Other in vitro studies have focused more specifically on the tension within the graft while simulating knee function. Several studies have indicated that over-tensioning a graft shifts the patella medially and increases medial contact pressures. Multiple studies have shown that 2 N of graft tension restores lateral patellar shift and tilt and mean and peak medial and lateral contact pressures similar to the intact knee [16, 17, 21]. The result was found to be independent of graft type for double strand gracilis tendon, quadriceps tendon, and tensor fasciae latae allograft grafts [16]. Increasing graft tension to 10 N has been shown to over-medialize the patella compared to the intact knee [16, 17, 21]. Increasing graft tension to 10 N also increased mean and peak medial contact pressures at low flexion angles [16, 21], with the effect most prominent when setting the graft length at full extension [21]. Increasing graft tension to 30 N or 40 N produced larger increases in peak and mean medial contact pressure [16, 17, 21].

Computational studies have shown that a single error in graft attachment position or tensioning has some influence on patellar mechanics, and that combined errors can further increase medial tracking and elevate medial pressures. A study based on the anatomy of normal knees indicated that the combination of a pre-tensioned graft (resting length 3 mm shorter than the graft length at full extension) and 5 mm proximal malalignment of the femoral attachment elevated medial contact forces and the peak medial pressure [22]. For a dynamic simulation study based on the anatomy of knees being treated for patellar instability [23], standard MPFL reconstruction reduced elevated levels of patellar lateral tilt and shift, particularly near full extension. Posterior malpositioning of the femoral attachment by 5 mm increased medial patellar shift and tilt. The combination of posterior malpositioning and a pre-tensioned graft (resting length 2 mm shorter than set with the knee flexed to 25°) also increased peak medial contact pressures.

Other options for MPFL reconstruction have been proposed. A dynamic MPFL reconstruction utilizing the semitendinosus tendon, detached from the tibial insertion but still affixed to the muscle and transferred behind the medial collateral ligament to the patella, showed an influence on patellar tracking similar to static MPFL reconstruction [12]. Another study focused on dynamic MPFL reconstruction with a graft looped around the adductor tendon showed that the dynamic technique produced peak contact pressures similar to the native knee, while static reconstruction elevated peak contact pressures with the knee flexed [24].

Tibial Tuberosity Medialization

Tibial tuberosity medialization is reserved for patients with a lateralized tibial tuberosity and persistent lateral maltracking. In vitro simulation of knee function has provided data to characterize how a laterally positioned tibial tuberosity influences patellar mechanics. One

study showed significant increases in patellar lateral shift and tilt caused by lateralizing the tibial tuberosity by 15 mm [25]. The mean lateral contact pressure also increased, while the mean medial pressure decreased. Another study did not identify an increase in mean or maximum patellofemoral contact pressures due to increasing the lateral orientation of the patellar tendon by up to 15 mm [26]. With the tuberosity in a lateralized position, the increase in the lateral shift and tilt caused by a lateral displacement force applied directly to the patella also increased [25].

In vitro simulation of knee function has generally shown that tibial tuberosity medialization decreases patellar lateral tracking. Multiple studies have shown that medialization of the tibial tuberosity tends to decrease patellar lateral shift [11, 27, 28] and tilt [11, 27]. One indicated that anteromedialization was not as effective as medialization for reducing lateral tracking [27], while another showed similar patellar lateral shift and tilt for medialization and anteromedialization, but decreased patellar flexion for anteromedialization [28].

A study based on reconstruction of in vivo function also found that tuberosity medialization decreases lateral patellar tracking [29]. Knee motion was reconstructed based on pre-operative and post-operative dynamic CT scans acquired during knee extension. Tuberosity medialization decreased patellar lateral shift and tilt at low flexion angles, although five of the six patients studied were treated with simultaneous MPFL reconstruction.

In vitro simulation studies have generally shown that tibial tuberosity medialization decreases patellar contact pressures and shifts pressure medially, but some variation has been noted between studies. One study did not find a benefit to medializing the tibial tuberosity from a lateral position at 15° or 45° of knee flexion, but found that over-medializing the tibial tuberosity tended to increase mean and peak patellofemoral contact pressures [26]. Another showed mean lateral pressure decreases due to medializing the tibial tuberosity from a lateral position, but did not show further decreases with over-medialization [25]. Medialization also decreased the maximum contact pressure [27] and decreased the maximum lateral pressure and increased the maximum medial pressure [28] in other studies. Anteromedialization of the tibial tuberosity has been shown to shift the patellofemoral center of force medially and decrease the pressure applied to the lateral trochlear surface [30]. One study showed a larger decrease in the maximum contact pressure for anteromedialization than medialization [27]. Another study showed pressure values for anteromedialization were similar to those for medialization [28].

A computational simulation study also indicated that tibial tuberosity anteromedialization decreases mean and maximum patellofemoral contact pressures [31]. Computational models were developed from imaging data of patients diagnosed with patellofemoral joint osteoarthritis and lateral subluxation. The multibody computational models assessed contact based on overlap of cartilage surfaces in response to applied quadriceps forces.

Altering the orientation of the patellar tendon also influences the forces and moments acting on the tibia. One in vitro study showed that medializing the tibial tuberosity primarily influenced tibiofemoral kinematics by increasing tibial external rotation [32]. The increased external rotation moves the tibial tuberosity back toward the position before surgery.

Anteromedialization of the tibial tuberosity also increased tibial posterior translation in comparison to medialization alone. A study based on reconstruction of in vivo function also found that tuberosity medialization increased tibial external rotation [29].

Summary of Results and Limitations

Based on the accumulation of studies, several conclusions can be drawn related to MPFL reconstruction. Although the MPFL is a passive stabilizer of the patella, the ligament plays a role in limiting patellar lateral translation and tilt during normal function. An MPFL injury seems to reduce medial patellofemoral contact pressures, but a corresponding increase in lateral pressures was not consistently found. MPFL reconstruction tends to decrease lateral patellar tracking, with trends noted for reducing lateral patellofemoral contact pressures. A primary concern for MPFL reconstruction is over-correction that elevates medial contact pressures. Non-anatomic femoral attachment and over-tensioning the graft at implantation are noted as the contributing factors to over-correction, with the combination of both sources of graft tension further constraining patellar tracking and loading medial cartilage. Elevated medial contact pressure is a concern due to the prevalence of medial cartilage fibrillation and erosion associated with recurrent instability due to contact between the medial facet of the patella and the lateral condyle of the femur [33]. Loss of flexion and medial pain have been noted as consequences of MPFL reconstruction with an over-tensioned graft or non-anatomic femoral attachment [34].

Several conclusions can also be drawn from the literature on tibial tuberosity medialization. A lateralized tibial tuberosity tends to increase lateral patellar shift and tilt, while medializing the tibial tuberosity tends to decrease lateral patellar tracking. Medializing the tibial tuberosity tends to decrease lateral patellar contact pressures and increase medial pressures. Anteromedialization of the tibial tuberosity also has been shown to reduce lateral contact pressures, but the change was not consistently greater than achieved with medialization. Medialization of the tibial tuberosity also has been shown to increase tibial external rotation. Tibial external rotation in response to tuberosity medialization reduces the applied surgical correction, which can limit correction of patellar tracking but may also reduce the risk of over-correction. A post-operative increase in tibial external rotation will alter tibiofemoral contact points during knee function, but the influence on tibiofemoral cartilage is currently unknown.

In vitro simulation of knee function has been the primary approach for biomechanical assessment of MPFL reconstruction and tibial tuberosity medialization, so the limitations should be well understood. These studies have been performed with normal knees, with the loading conditions and/or position of the tibial tuberosity frequently manipulated to induce lateral patellar tracking. The studies do not account for trochlear dysplasia or patella alta, or consistently account for a lateralized tibial tuberosity, that are common anatomical features of knees with patellar instability [35, 36]. Computational reconstruction of in vivo function studies have indicated that, for subjects with patellar instability, the level of trochlear dysplasia and the lateral position of the tibial tuberosity are correlated with lateral patellar tracking, particularly at low flexion angles [37, 38]. An in vitro simulation of knee function study also indicated that trochlear dysplasia is associated with increased contact pressures

[39]. Without accounting for these anatomical factors, the simulated in vitro function does not produce lateral tracking or elevated contact pressures to the degree noted for symptomatic knees. For knees being treated for instability, the increase in lateral shift and tilt of the patella from a flexed position to knee extension is on the order of 10 mm and 10° [29]. Lateral shift and tilt from flexion to extension were not as large for any of the in vitro simulation studies in absence of a lateralizing force applied to the patella. The ability of MPFL reconstruction and tibial tuberosity medialization to improve lateral patellar tracking of this magnitude cannot be directly extrapolated from the in vitro studies. A mechanical testing environment includes other limitations, such as muscle loads typically lower than forces applied during in vivo function and experimental error that can influence measurements from sensors used to characterize patellar tracking and pressures. Due to the limitations of in vitro simulation, finding similar results from other modes of testing is important to verify the in vitro trends.

Computational reconstruction of function is limited to analyzing motions that can be performed with a patient in an imaging system. The primary modes of imaging patellar motion to date have been MRI and CT scans. Patients with instability also experience pain and apprehension which limit the activities they are capable of performing. Computational reconstruction of function also allows assessment of the influence of only the surgical procedure performed for each patient, instead of isolating how a specific surgical approach influences post-operative function, as demonstrated by the combination of MPFL reconstruction and tuberosity medialization for 5 of 6 subjects analyzed previously [29].

Computational simulation allows the flexibility not afforded to the other methods of analysis. Models can be developed to represent knees with instability, and force levels representative of in vivo loads can be applied. Functional loading conditions that result in lateral subluxation can also be represented with multibody dynamic approaches that allow for large scale relative motions. In addition, anatomical parameters and surgical approaches can be parametrically varied. The approach allows engineers and surgeons to collaboratively develop models of specific patients based on imaging data and evaluate multiple options for surgical patellar stabilization. Computational approaches are limited, however, by mathematical representation of properties of soft tissues, contact interactions, joint constraints and muscle forces that may not represent the in vivo condition. Therefore, computational simulation models should be rigorously validated before being utilized to produce output related to surgical treatment of patellar instability. The validations should optimally include some combination of the anatomical conditions representative of patellar instability, variations in loading representing surgical stabilization, and the output parameters of clinical interest [23, 40, 41]. Representing all the conditions in a single validation is limited by the noted inability to produce all those conditions in an in vitro model or computational reconstruction of in vivo function.

Although each form of biomechanical study has its own inherent limitations, utilizing all types of studies to investigate the influence of surgical stabilization on patellar function mitigates the limitations of any one approach. The in vitro studies have generally shown that MPFL reconstruction reduces elevated lateral patellar tracking, but that non-anatomic femoral fixation and graft over-tensioning can over-constrain patellar motion and elevate

medial graft forces. The limitations of these studies are partially overcome by a dynamic computational simulation study based on the anatomy of symptomatic knees that includes lateral tracking indicative of patellar instability with similar findings [23]. Similarly, in vitro studies on tibial tuberosity medialization have indicated that the procedure reduces lateral patellar shift and tilt and reduces pressure applied to lateral cartilage. The limitations of these studies are partially overcome by a computational simulation study based on the anatomy of knees with patellar subluxation that shows a decrease in lateral pressure with tuberosity anteromedialization [31] and a study that reconstructed in vivo function to show decreases in patellar lateral shift and tilt near full extension for knees treated with tuberosity medialization in combination with other procedures [29].

Conclusion

Biomechanical studies have generally shown the benefits of MPFL reconstruction and tibial tuberosity medialization to reduce lateral patellar tracking. Reductions in lateral contact pressures have also been noted. The most consistent biomechanical concerns of these procedures have been over-constraint of the patella related to over-tensioning a MPFL graft or non-anatomical attachment to the femur and the influence of tuberosity medialization on tibiofemoral kinematics. Future biomechanical studies should emphasize inclusion of anatomical features and tracking patterns related to patellar instability, with comparisons between the approaches for continued development of treatment guidelines.

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Figure 1.

A schematic diagram of in vitro simulation of knee function. Cables applying the forces representing the quadriceps and hamstrings muscles were secured into the tendons and run over pulleys. Patellofemoral and tibiofemoral motion was characterized based on the motion of magnetic tracking sensors secured to the bones. A pressure sensor measured the patellofemoral contact pressure distribution. The tibial tuberosity was osteotomized from the tibia to allow representation of tibial tuberosity medialization. (Adapted with permission from Elias et al. Clin Biomech 2011; 26:841–6).

Figure 2.

Representation of patellar tracking at multiple flexion angles for one knee evaluated with computational reconstruction of in vivo function based on dynamic CT imaging. The patient was analyzed pre-operatively and following surgical patellar stabilization with the combination of tibial tuberosity medialization and MPFL reconstruction. (Reprinted with permission from Elias et al., *Knee Surg Sports Traumatol Arthrosc.* 2014; 22:2350–6.)

Figure 3.

Computational simulation of knee extension based on a multibody dynamic model of the knee. Patellar tracking is shown as a knee extends from a flexed position (A) to full extension (B) in the pre-operative condition, and for the knee extended with an MPFL graft wrapping around the femoral condyle, with a solid used to represent the graft from the femoral attachment to the wrapping point (C). The calculated patellofemoral contact pressure distribution is also shown for one knee with an MPFL graft, with pressure concentrated on the lateral facet of the patella (D). (Modified with permission from Elias et al., *Orthop J Sports Med* 2016;4:2325967116665080)