Biomechanics of the lateral meniscus: evidences from narrative review

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Abstract: Lateral meniscus plays a crucial role in the knee stability and function. Although complex settings are required for lateral meniscus biomechanical assessment, such characteristics have been investigated over time to optimize the daily clinical practice surgical procedure. The aim of the present study was to provide an overview of literature knowledge regarding the biomechanics of lateral meniscus and give further insights about novel experimental analyses. Studies regarding lateral meniscus mobility, effect on knee laxity, and contact mechanics were included in the review. The effect of meniscal lesion, meniscal repair, partial meniscectomy, and meniscus allograft transplantation were retrieved for either *in vivo*, cadaveric, or in-silico computational settings. Knee laxity was evaluated both in presence of isolated meniscal tears and in anterior cruciate ligament (ACL) deficient knees. Surgical navigation systems and robots were mainly used for the investigations *in vivo* and in cadaveric studies, while accelerometers emerged as an alternative for ambulatory assessments. Contact mechanics was only assessed in cadaveric and computational studies. Great effort has been put into exploring lateral meniscus biomechanics from multiple perspectives. Strong evidence emerged regarding the importance of lateral meniscus repair: increased knee stability at high degrees of knee flexion and reduction of peak contact pressures on tibial cartilage were the most reported benefits. The meniscus allograft transplantation also emerged as a concrete solution for irreparable tears and further studies are needed to investigate its long-term influence on knee stability.

Keywords: Biomechanics; meniscus repair; partial meniscectomy; meniscus allograft transplantation

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Introduction

Menisci are crucial structures of the knee joint and effectively contribute to maintaining a normal articular function. Their peculiar anatomy and mechanical properties provide joint congruity, minimize the shocks on the articular cartilage by distributing the loads, and grant joint stability in a synergic role with the surrounding knee structures (1,2).

The biomechanical role of the menisci has been extensively investigated over time (3-6). The differences between medial and lateral meniscus, their role at different

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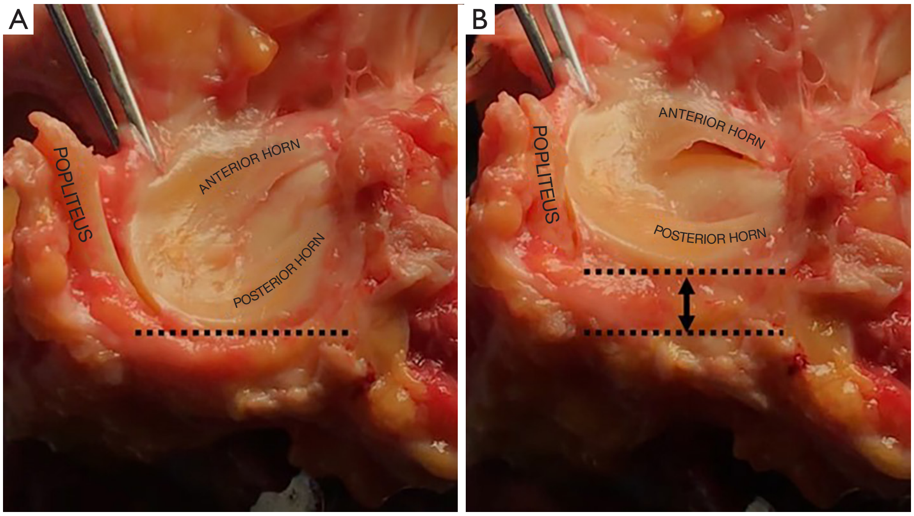

Figure 1 Shape and mobility of lateral meniscus. With the traction of the forceps on the anterior horn it is possible to appreciate the motility to the lateral meniscus, from basal state (A) to the maximum anterior translation (B).

degrees of knee flexion, and the effect of different surgical treatments have been the most debated issues. The research on the latter issues contributed to extending the knowledge on the function of the menisci, leading to influence the choices of daily clinical practice and to develop new solutions, such as biological/artificial transplantation.

In this scenario, greater attention has been given to the biomechanics of the medial meniscus, while less on the lateral one. This was probably due to the primary effect of the medial meniscus in articular cartilage preservation and anterior-posterior (AP) knee stability and a more difficult assessment of lateral meniscus function (4,7,8). Indeed, the lateral meniscus was proved to have a key role in rotatory instability (8-11), which requires a more complex evaluation setting, either *in vitro* or *in vivo*.

The aim of the present study was to provide an overview of literature knowledge regarding the biomechanics of lateral meniscus and give further insights about its role through novel experimental analyses from our study group.

We present the following article in accordance with the Narrative Review checking checklist (available at https://aoj.amegroups.com/article/view/10.21037/aoj-20-123/rc).

Literature overview and authors' experience

For the sake of clarity, the literature overview on the biomechanics of lateral meniscus was divided into three sections, namely "Mobility", "Laxity" and "Contact mechanics". In each section, different clinical procedures such as meniscal repair, meniscectomy, and meniscus allograft transplantation (MAT) were considered. The authors' experience was also reported in terms of experimental analyses.

Mobility

Meniscus mobility is aimed to ensure the largest contact surface between femur and tibial during the entire knee range of motion. This allows to avoiding cartilage overloading and to increasing overall knee stability. The lateral meniscus mobility has been widely investigated. As compared to the medial one, the lateral meniscus shows higher mobility during knee motion (*Figure 1*). In particular, there is a more pronounced posterior translation of the lateral meniscus compared to the medial one as knee flexion increases. With a fully flexed knee, the lateral meniscus drops off from the posterior rim of the tibia (12). This happens because of its structural characteristics: lateral meniscus has a more circular shape, is thicker at the periphery and is less firmly attached to the lateral collateral ligament and to the popliteal hiatus (13). Moreover, the convex posterior aspect of the lateral tibial plateau allows a higher posterior displacement of the lateral meniscus in deep flexion (14). During the knee range of motion from 0° to 90°, the maximum posterior displacement of the lateral meniscus has been identified for the anterior horn, average respectively in 9.5 mm in weightbearing conditions and 6.3 mm in non-weightbearing conditions (14).

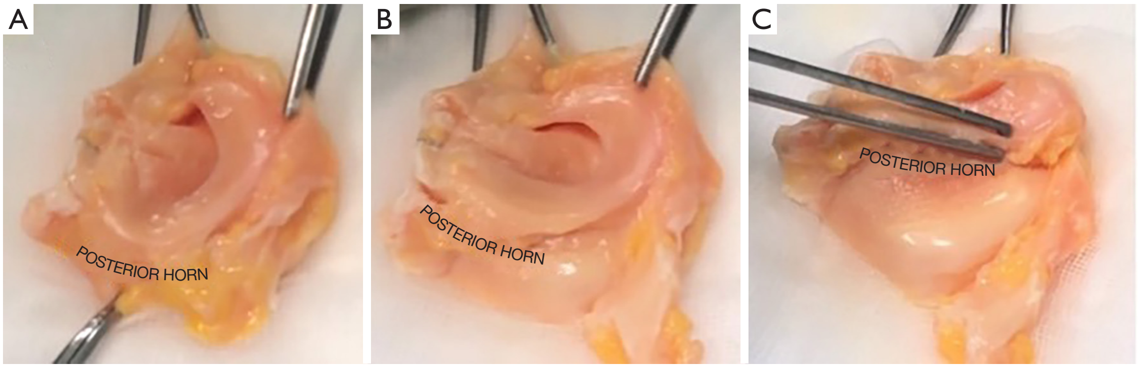

Figure 2 Structures playing a role in meniscus stability. With the intact posterior meniscal restraints, it is possible to elicit only a limited anterior translation (A). After sectioning the popliteo-meniscal fascicle it is possible to increase the anterior translation, however without fully dislocating the meniscus (B). Only after sectioning the posterior meniscotibial ligament, the posterior horn can be completely mobilized anteriorly (C).

Simonian *et al.* (15) investigated the contribution of the anteroinferior and posterosuperior popliteomeniscal fasciculi to the mobility of lateral meniscus. The authors performed a subsequent resection of the two fasciculi and applied a 10-N load to 7 fresh-frozen cadavers. They highlighted that the popliteal hiatus both provides higher mobility to the lateral meniscus and is crucial to preserve the stability of the posterior horn (*Figure 2A,2B*). However, the section of both anteroinferior and posterosuperior popliteomeniscal fasciculi was never able to allow anterior meniscal displacement and to cause meniscal locking. Therefore, other structures such as menisco-tibial ligament play a role in meniscal stability under extreme antero-posterior excursion (*Figure 2C*). Thus, the lesion or absence of these structure could be responsible of different clinical symptoms, from catching and popping to real knee unreducible locking.

These peculiar characteristics makes the lateral meniscus a key structure in dynamic movements since it supports the activity of anterolateral complex in stabilizing the knee during high demanding daily life activities and sport.

Laxity

Due to its larger mobility to the medial one, lateral meniscus plays a greater role in restraining rotatory laxity. Either *in vitro*, in silico, or *in vivo* studies were conducted to assess the role of the lateral meniscus on knee laxity. Cadaveric studies were conducted with heterogeneous settings: either surgical navigation systems or robotic and servo-hydraulic testing systems were used. The pivot-shift maneuver, either mechanized or manually performed by surgeons, was the most investigated test. Limited literature can be found regarding computational knee models including menisci. Musculoskeletal and finite element (FE) analyses often adopt simplification of knee anatomy to reduce model complexity and computational cost (16,17), e.g., menisci or ligaments are not present or are simulated with spring bundles, neglecting the real anatomy (18). The effect of lateral meniscus laxity has been poorly investigated *in vivo*. A difficult clinical setting, the need for highly experienced surgeons with robust reliability in pivot-shift movements, and a limited number of eligible cases are the most likely reasons. Indeed, the effect of lateral meniscus removal or repair was mainly evaluated in association with ACL-deficient or ACL-reconstructed knees.

On the one hand, when assessing anterior tibial translation (ATT) during static tests, e.g., Lachman test, several authors confirmed a limited or null effect of lateral meniscus both in ACL-deficient and ACL-reconstructed knees (19,20). On the other hand, Musahl *et al.* reported an increase of anterior translation of knee lateral compartment after total lateral meniscectomy and ACL reconstruction during manual pivot-shift maneuver evaluated through surgical navigation system (21). Similar findings were also reported in the presence of bilateral meniscectomy after ACL reconstruction (22).

Using a combined musculoskeletal and FE in silico model, Hu *et al.* (23) simulated normal gait with intact menisci and with bilateral meniscectomy. The authors found a more posterior tibial translation and internal tibial rotation in the model without menisci. Liu *et al.* (24) simulated a

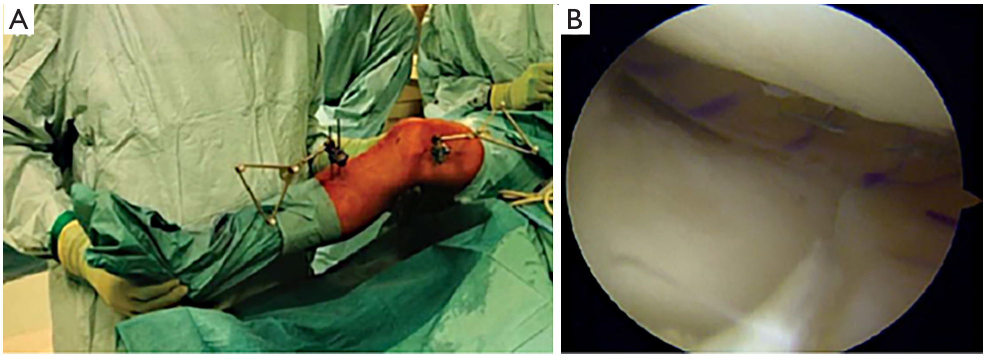

Figure 3 Example of (A) surgical navigation system for the assessment on knee laxity and (B) meniscus allograft transplantation *in situ*.

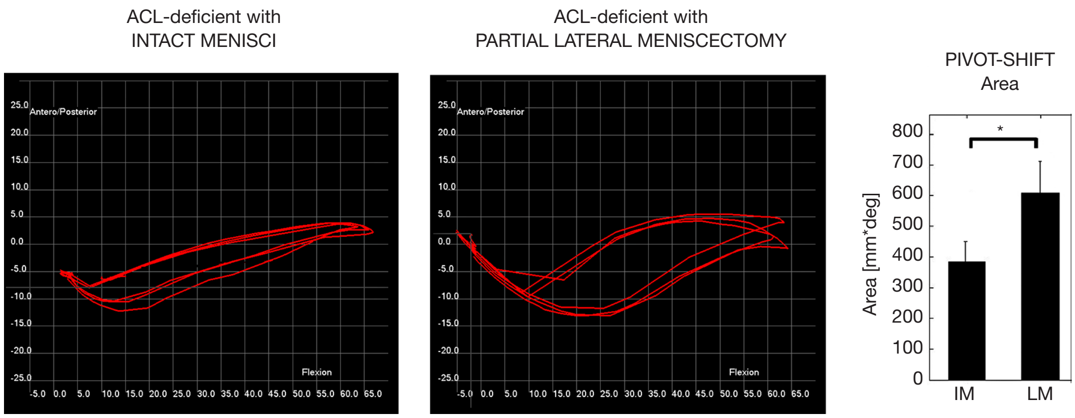

Figure 4 Lateral tibial compartment anterior-posterior translation over flexion (area) during pivot-shift in ACL-deficient + intact menisci and ACL-deficient + partial lateral meniscectomy through surgical navigation system. The presence of partial lateral meniscectomy increased knee laxity during the pivot-shift. Adapted from Grassi *et al.* (9). *, P<0.05.

level walking from gait analysis of ACL-deficient patients with different meniscal lesions (either medial, lateral, and bilateral). Altered kinematics and kinetics were found in the presence of bilateral meniscectomy, with lower abduction-adduction and internal-external moment peaks compared to the control group. Such differences were not found in the presence of isolated lateral meniscectomy.

A recent *in vivo* study (9) provided an extensive intraoperative evaluation (164 patients) of ACL-deficient knee combined with either medial, lateral, and bilateral meniscectomy (*Figure 3*). In the present study, the quantitative kinematical assessment was performed after meniscus treatment and before ACL reconstruction during surgery. The present study confirmed the distinct effect of medial and lateral meniscectomy on knee laxity and particularly highlighted an increased rotatory instability during the pivot-shift maneuver for patients with combined lateral meniscectomy (*Figure 4*).

Navigation systems in cadaver settings were also used to investigate the effect of lateral posterior root lesions in ACL-deficient conditions (25,26). An overall stability reduction during rotational loadings was noted. Particularly, an increase of internal tibial rotation at high degrees of knee flexion was found compared to the isolated ACL-deficiency (25,27).

Other than navigation systems and robots, triaxial accelerometers were used to investigate combined ACL and meniscal lesions in non-invasive clinical ambulatory settings *Figure 5*. Musahl *et al.* (28) quantitatively investigated the knee laxity through iPad image analysis technique in 41 ACL-deficient knees under-anesthesia. Combined lesions to surrounding structures were assessed through MRI. The authors concluded that the presence of lateral meniscus lesion in ACL-deficient knees was associated with an

Figure 5 Assessment of pivot-shift test through single triaxial accelerometer (KiRA - Orthokey, Florence, Italy). Accelerometers can be easily used in ambulatory setting to evaluate the presence of concurrent lateral meniscal tears. The acceleration of lateral tibial compartment during the pivot-shift can be visualized real-time on the dedicated tablet.

increase of rotatory laxity during the pivot-shift maneuver. A further study with a similar setting performed by the same group (29) on 77 patients concluded that the combination of ACL and lateral meniscus injury generates an increase in tibial lateral compartment acceleration and translation and could therefore be a reason for qualitatively-evaluated high rotatory instability. Hoshino *et al.* (30) reached similar conclusions assessing that high rotatory instability during pivot-shift could be symptomatic of combined ACL and lateral meniscal lesion.

Meniscus repair was claimed as the most valuable solution to restore intact knee stability (8,31). Forkel *et al.* found that lateral posterior meniscus root repair can reduce internal rotation in ACL-deficient knee conditions (27). Also, a significant improvement in rotatory knee stability was found by Tang *et al.* (32). The latter studies were both performed in cadaveric conditions. Katakura *et al.* (33) found similar results in 41 patients undergoing ACL-reconstruction and meniscal repair through a triaxial accelerometer.

Residual laxity in animal *in vitro* models was also assessed after arthroscopic centralization techniques for irreparable lateral meniscus defects (34). Significant rotational laxity reduction was found in ACL-reconstructed porcine knees in the presence of arthroscopic centralization.

Few *in vitro* studies investigated the biomechanical effect of lateral MAT. Through a surgical navigation system, Spang *et al.* (35) demonstrated an effective reduction of ATT when MAT was performed. In a similar setting, Novaretti *et al.* (36) demonstrated a partial reduction of AP laxity compared to a meniscectomized knee. In both studies, however, criticisms emerged regarding the restoration of intact knee stability after MAT.

In vivo, a preliminary kinematic analysis of knee laxity was conducted in the presence of lateral MAT and ACL reconstruction (37). Using a surgical navigation system, the authors suggested a synergic role of MAT and ACL in restraining knee laxity, especially AP translation. No other evidence in literature is present regarding the *in vivo* kinematical evaluation of MAT. An unpublished study from the same group was aimed to describe the kinematical effect of lateral MAT by comparing three different conditions: intact ACL with lateral meniscectomy, intact ACL with MAT, and ACL-reconstructed with intact menisci. The analysis was again performed through a surgical navigation system. Both static and dynamic laxity parameters, in particular, AP30, AP90, VV0, and pivot-shift parameters, improved at time zero after MAT surgery. Moreover, patients undergoing MAT showed similar or even lower laxity than patients in ACL-reconstructed with intact menisci conditions (*Figure 6*). These results demonstrated a significant positive effect of MAT on knee laxity, both in ACL-deficient and ACL-injured conditions.

Contact mechanics

The shock absorber role for axial and circumferential loads is carried out in synergy by medial and lateral meniscus. They have peculiar viscoelastic material properties that allow substantial shape-changing under weight-bearing conditions. For example, compression stresses (e.g., during standing) are first resisted ("creep" behavior) and then distributed and reduced over time ("stress relaxation" behavior) (3). The lateral meniscus mainly carries circumferential loads and to undergoes shear stresses (38), unloading the tibial cartilage more than how it happens on the medial side (39).

The setup required to investigate menisci contact mechanics is hugely complex and invasive. For this reason, the lateral meniscus has been investigated only in cadaveric and in computer model studies. Several cadaver studies were conducted to analyze knee contact mechanics with lateral meniscus either in intact condition, in the presence of tears, or after transplantation. Setups and loading conditions were highly heterogeneous. In silico studies were used to extend the findings of cadaver studies or to reproduce from scratch

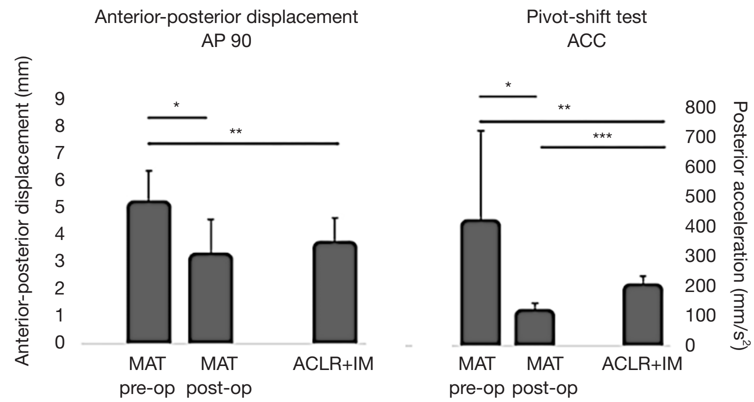

Figure 6 Comparison among before-MAT and after-MAT in ACL intact conditions and ACL-reconstructed with intact menisci condition. Anterior-posterior displacement at 90° of knee flexion and acceleration of lateral tibial compartment during pivot-shift test were evaluated intraoperatively through the surgical navigation system (Macchiarola *et al.*, unpublished data). *, P<0.05; **, P<0.01; ***, P<0.001.

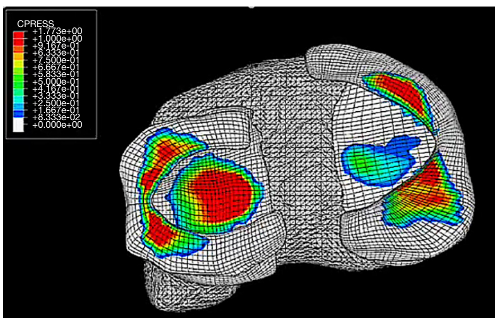

Figure 7 Example of finite element study simulating knee contact pressure on menisci and cartilage under physiological loads. The contact pressure is expressed in MPa and are higher for red values.

either meniscus tears or allograft transplantation contact mechanics (*Figure 7*). Different levels of complexity were adopted, especially in terms of loads applied. Furthermore, meniscectomies, meniscal lesions, and repairs were often evaluated in the same cadaveric or computational study.

Koh *et al.* (40) investigated tibiofemoral contact mechanics in intact lateral meniscus conditions and in the presence of partial lateral meniscectomy. The study was conducted on fresh-frozen cadavers under axial load in full knee extension and at 60°. The author found significantly reduced contact areas and increased peak contact pressure after resection of either only inferior leaf or both leaves. A similar loading condition was simulated in the cadaveric study by LaPrade *et al.* (10), even though the evaluation was performed at more flexion angles, and meniscus repair was investigated as well.

A significant decrease in the contact area and an increase in peak contact pressure were found in the presence of meniscal tears at all the flexion angles. Interestingly, the authors demonstrated that pull-out suture repair restored both contact area and pressure to the ones of the intact lateral meniscus only at high degrees of knee flexion (from 45° to 90°), while no differences were found between repair and meniscectomized knees at 0° and 30°. The authors concluded that repair techniques are less effective at lower flexion angles at increasing distances between radial tear and the posterior horn root attachment. A more complex setup was used to simulate human gait in lateral meniscus intact, with radial tears, repaired, and meniscectomized conditions (41). The authors found increased knee contact pressure in all the non-intact conditions. In particular, contact pressures after large radial tears and meniscectomies were statistically equivalent, while significant pressure reduction was found after meniscus repair.

A simple compressive axial load of 1,000 N was applied in the FE study by Bao *et al.* (42). The authors compared contact pressure in three lateral meniscus conditions of ascending complexity: complete radial posterior lateral meniscus root tear, a complete radial posterior lateral meniscus root tear with posterior meniscofemoral ligament deficiency, and total meniscectomy of the lateral meniscus. They concluded that increasing contact pressure and decreased contact area followed the complexity of lateral meniscus condition. Radial tears and partial meniscectomy were evaluated by Mononen *et al.* (43) with a complex MRI-based knee model and simulated gait cycle. The authors suggested anterior radial tears as the main cause for the progression of meniscal rupture and partial meniscectomy as the main risk factor for the progression of lateral tibial cartilage osteoarthritis. The highest contact pressures were found during the mid-stance and loading response of the stance phase. Similarly, Zhang *et al.* (44) simulated longitudinal lesions on the posterior horn during static stance and mid-flexion. The authors concluded that an increased contact pressure was present on the posterior lateral tibial cartilage in the mid-flexion condition.

In vitro models were also adopted to investigate centralization procedures' biomechanical role in the presence of extruded lateral meniscus (45,46) and of meniscal scaffolds (47,48). Significant reduction in contact area and increased contact pressure were found in lateral meniscus extrusion (created by resecting the posterior root) in porcine knee joints (45,46). Centralization procedures showed a restored loading-distribution as well as reduction of lateral meniscus extrusion. Positive biomechanical evidences emerged also from the use of lateral meniscus scaffolds. Although all the studies concluded that *in vivo* evidence is still lacking, promising results emerged from pre-clinical analyses in animal models in terms of load distribution recover (47,48).

The role of MAT on knee contact pressure and area was also evaluated in cadaveric setting. Different techniques were investigated: both bony and keyhole fixation of the native meniscus (49) and bone-block and suture-only fixation of allograft (36) meniscus. Brial *et al.* used a multidirectional dynamic simulator to reproduce two specific instants of the gait cycle (14% and 45% of the stance phase). Compared to the meniscectomized knees, MAT contributes to reducing peak contact pressure and to restoring both contact area and cartilage-to-cartilage contact as in the intact conditions. They concluded that keyhole fixation reproduced the closest intact knee mechanics. Novaretti *et al.* applied multiple combined loading conditions (anteroposterior + axial, internal rotation + valgus torque, external rotation + valgus torque) at different degrees of knee flexion through a robotic system. The authors found that resultant forces on MAT were 50% to 60% of the ones on the intact lateral meniscus, thus strongly contributing to load-bearing function even without restoring the native meniscus conditions. Moreover, they found no differences between bone-block and suture-only MAT fixation techniques.

A computational simulation was also conducted to evaluate the influence of lateral MAT on knee mechanics (50). An MRI-based knee model was used to simulate the stance phase of the gait cycle either in lateral intact meniscus conditions or after lateral MAT. The authors found that the presence of lateral MAT increases the contact stress on the lateral side up to 20% while reducing on it the medial one. This last aspect was considered predictive for reduced risk of medial osteoarthritis onset.

Conclusions

Different aspects emerged from the present literature overview regarding the biomechanics of lateral meniscus. First, great effort has been put into exploring this topic from multiple perspectives, such as laxity and contact mechanics, type of lesion, and repair technique. All the studies agreed on the crucial role of the lateral meniscus in knee biomechanics, both in terms of pivoting movements and daily life activities such as gait. Second, strong evidence emerged from both *in vivo*, cadaveric, and computer model studies regarding the importance of lateral meniscus repair. Increased knee stability at high degrees of knee flexion and reduction of peak contact pressures on tibial cartilage were the most reported benefits from repair. The MAT is also emerging as a concrete alternative in the presence of irreparable tears. Recent studies confirmed its role in restoring intact-like biomechanics and balancing the loads onto the tibial cartilage. Further studies are needed to investigate the influence of MAT on knee biomechanics at long term follow-ups.

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