Isolated Meniscus Allograft Transplantation with soft-tissue technique effectively reduces knee laxity in the presence of previous meniscectomy: In-vivo navigation of 18 consecutive cases.

Stefano Di Paolo [a], Gian Andrea Lucidi [b, c], Alberto Grassi [c], Luca Macchiarola [c], Luca Ambrosini [c], Piero Agostinone [c], Giacomo Dal Fabbro [c], Stefano Zaffagnini [c].

[a] *Dipartimento di Scienze per la Qualità della Vita QuVi, Università di Bologna, Bologna, Italy.*

[b] *Dipartimento di Scienze Biomediche e Neuromotorie DIBINEM, Università di Bologna, Bologna, Italy.*

[c] *II Clinica Ortopedica e Traumatologica, IRCCS Istituto Ortopedico Rizzoli, Bologna, Italy.*

Corresponding author: Piero Agostinone, piero.agostinone@studio.unibo.it

Postal address: Via G.C. Pupilli 1, 40136, Bologna, Italy

Telephone: +39-3934057504

The investigation was performed at II Clinica, Istituto Ortopedico Rizzoli, IRCCS, Bologna, Italy.

Conflict of interest:

SZ is a consultant from Smith and Nephew and Depuy-Attune, is a board member of the International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS), and editor-in-chief of Journal of Experimental Orthopedics (JEO).

Funding:

No funding was received for the preparation of this manuscript.

Ethical approval:

This study was approved by the local Institutional Review Board (General Protocol n. *0008900*).

Informed consent:

All the patients included in the study signed an informed consent.

Acknowledgements:

Not applicable.

Author's contributions:

All listed authors have contributed substantially to this work: SDP, GAL, LM, LA, PA and GDF collected data, performed statistical analysis, literature review and primary manuscript preparation. SZ, and AG performed the surgeries, assisted with interpretation of the results, initial drafting of the manuscript, as well as editing and final manuscript preparation. All authors read and approved the final manuscript.

Isolated Meniscus Allograft Transplantation with soft-tissue technique effectively reduces knee laxity in the presence of previous meniscectomy: In-vivo navigation of 18 consecutive cases.

Abstract

Objectives: Although meniscal allograft transplantation (MAT) is a well-established procedure with satisfactory clinical results, limited in vivo kinematic information exists on the effect of medial and lateral MAT performed in the clinical setting. This study aimed to evaluate the biomechanical effect of arthroscopic isolated medial and lateral MAT with a soft-tissue fixation on pre- and post-operative knee laxity using a surgical navigation system.

Methods: 18 consecutive patients undergoing MAT (8 medial, 10 lateral) were enrolled. A surgical navigation system was used to quantify the anterior-posterior displacement at 30 and 90 degrees of knee flexion (AP30 and AP90), the varus-valgus rotation at 0 and 30 degrees of knee flexion (VV0 and VV30) and the dynamic laxity on the pivot-shift test (PS), which was determined through the anterior displacement of the lateral tibial compartment (APlat) and posterior acceleration of the lateral tibial compartment during tibial reduction (ACC). Data from laxity before and after MAT were compared through paired t-test ($p<0.05$).

Results: After medial MAT, there was a significant decrease in tibial translation of 3.1 mm (31%; p=0.001) for AP30 and 2.3 mm (27%; p=0.020) for AP90, a significant difference of 2.5° (50%; p=0.002) for VV0 and 1.7° (27%; p=0.012) for VV30. However, medial MAT did not determine any reduction in the PS kinematic data. Lateral MAT determined a significant decrease in the tibial translation of 2.5 mm (38%; p<0.001) for AP30 and 1.9mm (34%; p=0.004) for AP90 as well as a significant difference of 3.4° (59%; p<0.001) for VV0 and of 1.7° (23%; p=0.011) for VV30. There was also a significant reduction of the PS of 4.4 mm (22%; p=0.028) for APlat and 384.8 mm/s^2 (51%; p=0.005) for ACC.

Conclusion: MAT with soft-tissue fixation results in a significant laxity reduction in an in-vivo setting. Medial MAT improved knee kinematics by determining a significant reduction with particular emphasis to AP translation and VV maneuver. Conversely, Lateral MAT determined a massive reduction of the PS and a mild decrease of the AP translation and VV maneuver.

Study design: Controlled laboratory study.

Keywords: meniscus, meniscectomy, meniscus allograft transplantation, surgical navigation system, knee kinematics.

What are the new findings?

- In patients with previous isolated total or subtotal monocompartimental meniscectomy, soft-tissue MAT technique determines a significant laxity reduction in an in-vivo setting from the pre- to the postoperative assessment
- The medial MAT showed a significative reduction in knee AP translation and VV maneuver, but did not have any effect on rotational instability
- The lateral MAT reduced the global knee laxity with particular emphasis on the rotatory knee parameters

Introduction

The primary function of the menisci is to provide shock absorption and load transmission across the knee [1]. However, the menisci also play a synergistic role together with the bony morphology, the ligaments and the soft tissue envelope in providing knee joint stability [2]. The medial and the lateral meniscus are important secondary knee stabilizers for both rotational and antero-posterior (AP) translation. The patients with combined ligamentous and meniscus lesion show significantly increased laxity, greater pivot shift (PS), and AP translation than the patients with intact menisci [3–6].

However, despite the overwhelming evidence about the crucial role of the meniscus, meniscectomy is still the most performed knee surgery across the globe [7–9].

While MAT procedures have been performed for over 40 years and are now widely accepted as a possible treatment to reduce pain, preserve knee function and delay osteoarthritis progression, the biomechanical behavior of the MAT is still unknown as well as its effectiveness in restoring knee stability similarly to the native meniscus in the real clinical setting [10,11].

Moreover, the soft tissue MAT technique was evaluated only in one robotic study (only lateral meniscus) [12], and in one in-vivo study performed on patients with previous ACL-reconstruction [13]. Additionally, the latter reported results partially in contrast with the literature and evaluated patients only with clinical exam and telos-stress x-rays [13]. Therefore, even though commonly performed, there is a lack of biomechanics studies evaluating the effect of isolated MAT using soft tissue fixation.

The aim of the present study was to assess the biomechanical effect of arthroscopic isolated medial and lateral MAT with soft-tissue fixation on pre- and post-operative knee laxity using a surgical navigation system. The hypotheses of the study were that (1) medial MAT reduces significantly AP laxity but does not influence the PS, and (2) lateral MAT results in a significantly greater PS reduction when compared with medial MAT.

Methods

Patient Selection

Eighteen patients undergoing isolated medial or lateral MAT were prospectively enrolled in the study from August 2018 to November 2021. The inclusion criteria were stricter than the general indications for MAT: patients with no need for an associated surgical procedure or previous history of knee surgery rather than isolated medial or lateral meniscectomy were screened for eligibility. Detailed inclusion and exclusion criteria are shown in Table 1.

Table 1

Inclusion and Exclusion Criteria.

Inclusion Criteria
Previous isolated total or subtotal monocompartimental meniscectomy
Symptomatic “Post-Meniscectomy syndrome” with Kellgreen-Lawrence grade up to II
Age between 18 and 50 years
Axial malalignment lower than 4°
Complete kinematic evaluation using the intraoperative navigation system
Exclusion Criteria
History of knee surgery other than isolated mocompartimental meniscectomy
Need for associated concomitant ACL reconstruction, knee osteotomy or cartilage procedures
Intraoperative Kellgreen-Lawrence grade III-IV
Patients not willing to participate in the present study

Note: ACL = Anterior Cruciate Ligament.

Ethics

All patients undergoing MAT were adequately counseled regarding the risks and benefits of the procedure and surgical alternatives. Patients willing to participate in the study also received information regarding the navigation system, the intraoperative evaluation protocol, and the aims of the present study.

All the enrolled patients signed informed consent forms to undergo surgical procedure, and the research study was approved by the Institutional Review Board (IRB approval: *0008900).*

Surgical technique

Fresh-frozen (−80°) non-irradiated and non-antigen-matched allografts were used in all the cases. The MAT was performed by a single surgeon (S.Z.) arthroscopically using a double-tunnel technique without bone plugs. Peripheral suture to the capsule was performed with “all-inside” stitches (non-absorbable ULTRABRAID #0 wire and poly-l-lactide bio-absorbable implants, Smith & Nephew, Andover, MA, USA) and (non-absorbable, polyether ether ketone, PEEK, anchors, DePuy-Mitek, Raynham, MA, USA). The anterior and posterior horn were secured with a transosseous suture (Figure 1). Further details on meniscus sizing, surgical step, and rehabilitation are provided in previous studies [14,15].

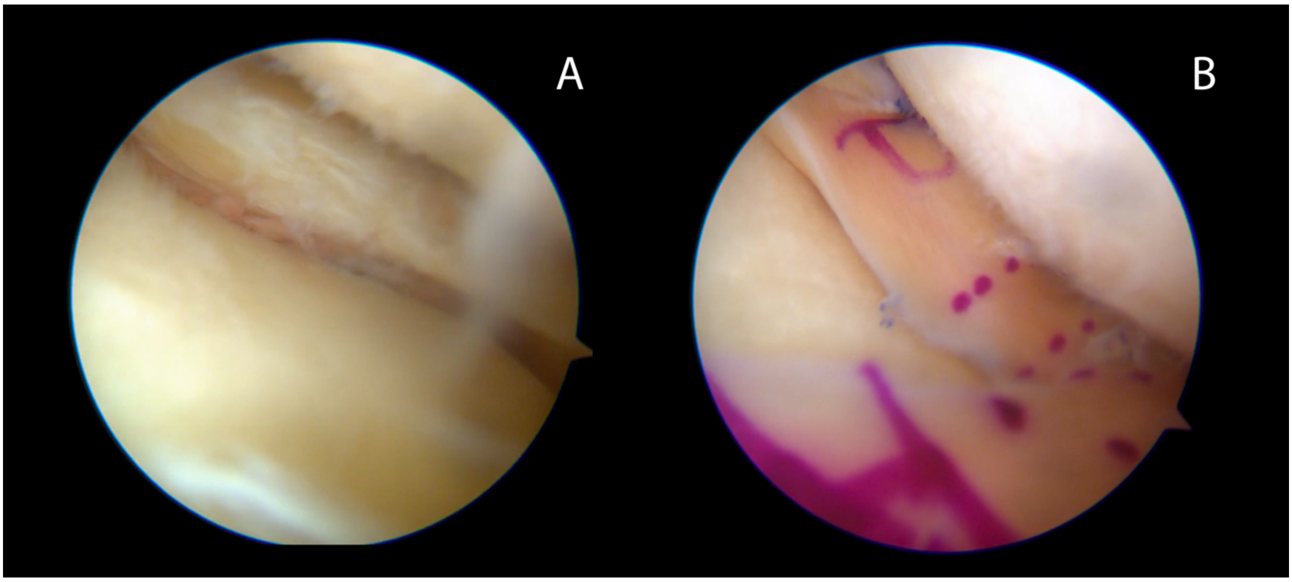

Figure 1: Arthroscopic images of lateral meniscal allograft transplantation with soft tissue fixation. (A) Meniscus-deficient lateral compartment (B) Transplant after definitive fixation.

Testing protocol

A surgical navigation system (BLU-IGS, Orthokey, Lewes, Delaware, DE, USA) was used to reconstruct the real-time anatomy of the tibiofemoral joint and conduct the intraoperative kinematical assessment. The kinematical assessment was carried out through a dedicated software within the surgical navigation system (KLEE, Orthokey, Lewes, Delaware, DE, USA). Two clusters of 3 optical trackers each were fixed one into the proximal tibia and one into the distal femur. The kinematic assessment was performed before MAT, i.e., in meniscus-deficient status (MAT pre-op), and after transplantation (MAT post-op). A set of laxity tests was manually performed at maximum force by the surgeon according to the method developed by Martelli et al. [16]:

- Anterior/posterior displacement at 30° of flexion (AP30);
- Anterior/posterior displacement at 90° of flexion (AP90);

- Varus/valgus rotation at 0° of flexion (VV0);
- Varus/valgus rotation at 30° of flexion (VV30);
- Pivot-shift (PS) test, to assess the dynamic laxity.

The pivot-shift test was quantified, according to the literature [17], through two different parameters: the anterior displacement of the lateral tibial compartment (named APlat) and the posterior acceleration of the lateral tibial compartment during tibial reduction (named ACC).

The validity and reliability of the device for the kinematic assessment of knee joint laxity was evaluated in previous studies [16]. A single experienced surgeon conducted all the kinematic tests. Kinematics was reconstructed offline based on the trackers position and orientation in a custom MATLAB script (The MathWorks Inc, Natick, Massachusetts, USA).

Statistical analysis

The Shapiro-Wilk test was used to verify the normal distribution of the data. Continuous variables were presented as mean ± SD with 95% confidence intervals (CI) and categorical variables were presented as percentage over the total. The paired t-test was used to compare the pre-op and post-op for each kinematic variable. The differences were considered statistically significant if $p<0.05$. The Cohen's d effect size was reported alongside the p-value and was considered small, medium, and large for values 0.2, 0.5, 0.8, respectively.

An a-priori power-analysis was performed based on the results of a study with similar setup but performed on cadavers [18]. A mean difference of 7° with a standard deviation of 6° for IE rotation at 30° was considered between intact menisci group and MAT group. Based on this analysis, at least 10 patients were required to have a power of 90% and a type I error of 0.05. All the statistical analyses were performed in MATLAB.

Results

Overall, 18 patients were included in the analysis. Of these, 10 patients underwent a lateral MAT, and 8 patients underwent a medial MAT. The detailed patients' demographics is shown in Table 2.

Table 2

Patients' demographics

	Medial MAT	**Lateral MAT**
N° of patients	8	10
Age at surgery, y	44.9 ± 7.6 [40.1 - 49.6]	35.5 ± 10.1 [29.3 - 41.8]
Sex, M/F	7/1	9/1
Limb, R/L	4/4	7/3

Medial MAT

After the Medial MAT there was a significant decrease in tibial translation of 3.1 mm (31%; p=0.001, large effect, Figure 2) for AP30 and 2.3 mm (27%; p=0.020, large effect, Figure 2) for AP90, a significant difference of 2.5° (50%; p=0.002, large effect, Figure 2) for VV0 and 1.7° (27%; p=0.012, large effect, Figure 2) for VV30 (Table 3). However, the medial MAT did not show any reduction in the PS kinematic data (moderate-to-small effect, Table 3).

Lateral MAT

The Lateral MAT determined a significant decrease in tibial translation of 2.5 mm (38%; p<0.001, large effect, Figure 2) for AP30 and 1.9mm (34%; p=0.004, large effect, Figure 2) for AP90 as well as a significant difference of 3.4° (59%; p<0.001, large effect, Figure 2) for VV0 and of 1.7° (23%; p=0.011, large effect, Figure 2) for VV30 (Table 3). There was also a significant reduction of the PS of 4.4 mm (22%; p=0.028, moderate effect, Figure 3) for APlat and 384.8 mm/s2 (51%; p=0.005, large effect, Figure 3) for ACC (Table 3).

Table 3

Kinematic assessment before (Pre-op) and after (Post-op) MAT

	Medial MAT				Lateral MAT			
	Pre-op	**Post-op**	**P-value**	**Cohen's d**	**Pre-op**	**Post-op**	**P-value**	**Cohen's d**
AP30 (mm)	9.6 ± 2.5 [7.9 - 11.4]	6.5 ± 1.9 [5.2 - 7.8]	0.001	1.4	6.7 ± 1.9 [5.6 - 7.9]	4.2 ± 1.8 [3.1 - 5.3]	0.000	1.4
AP90 (mm)	6.7 ± 2.3 [5.1 - 8.3]	4.5 ± 1.4 [3.5 - 5.5]	0.020	1.2	5.2 ± 1.7 [4.2 - 6.3]	3.3 ± 1.5 [2.4 - 4.3]	0.004	1.2
VV0 (°)	5.0 ± 2.1 [3.5 - 6.4]	2.4 ± 1.6 [1.3 - 3.5]	0.002	1.4	5.5 ± 2.2 [4.1 - 6.9]	2.1 ± 1.0 [1.5 - 2.7]	0.000	2.0
VV30 (°)	5.5 ± 1.5 [4.5 - 6.6]	3.8 ± 1.0 [3.1 - 4.5]	0.012	1.3	5.7 ± 2.3 [4.2 - 7.1]	4.0 ± 1.2 [3.2 - 4.7]	0.011	0.9
PS -Aplat (mm)	16.7 ± 2.7 [14.9 - 18.6]	15 ± 5.5 [11.2 - 18.8]	n.s.	0.4	18.7 ± 5.1 [15.5 - 21.9]	14.3 ± 6.8 [10.1 - 18.5]	0.028	0.7
PS - ACC (mm/s^2)	240.1 ± 177.2 [117.3 - 362.9]	131.8 ± 54.9 [93.8 - 169.9]	n.s.	0.8	491.5 ± 383.9 [253.5 - 729.4]	106.6 ± 44.5 [79 - 134.2]	0.005	1.4

Note: Data are presented as mean and standard deviation with 95% confidence intervals. n.s.= non-significant difference (p>0.05)

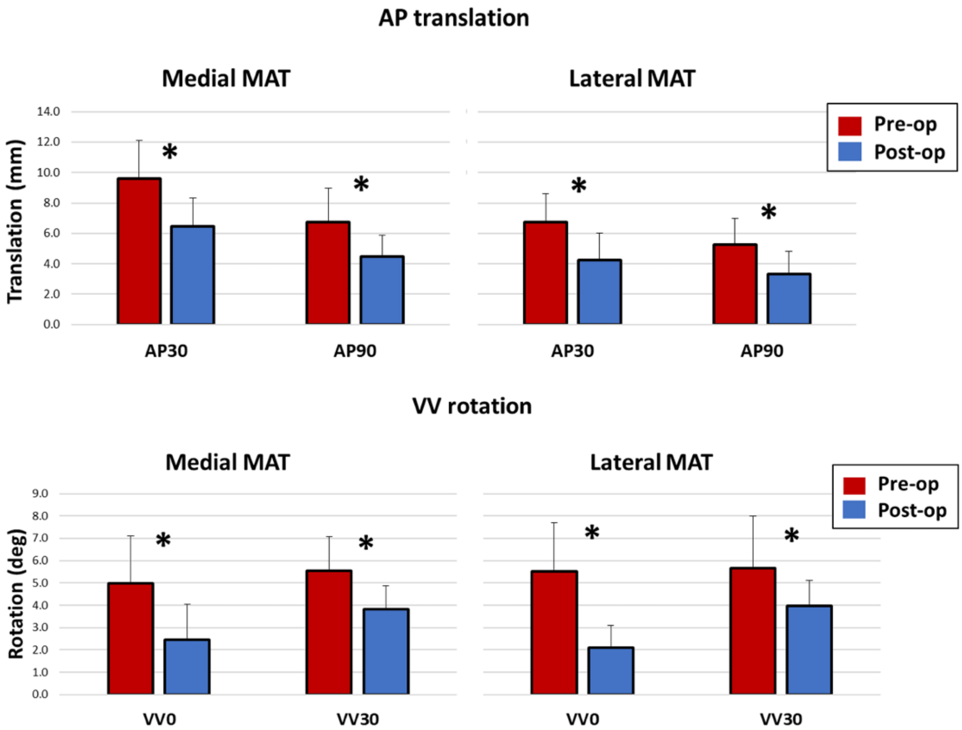

Figure 2: Anterior/posterior translation at 30° (AP 30) and 90° (AP 90) and varus/valgus rotation at 0° (VV0) and 30° (VV30) of knee flexion evaluated before (red, MAT Pre-op) and after (blue, MAT Post-op) MAT. Asterisks represent significant differences (p<0.05) between MAT Pre-op and MAT Post-op.

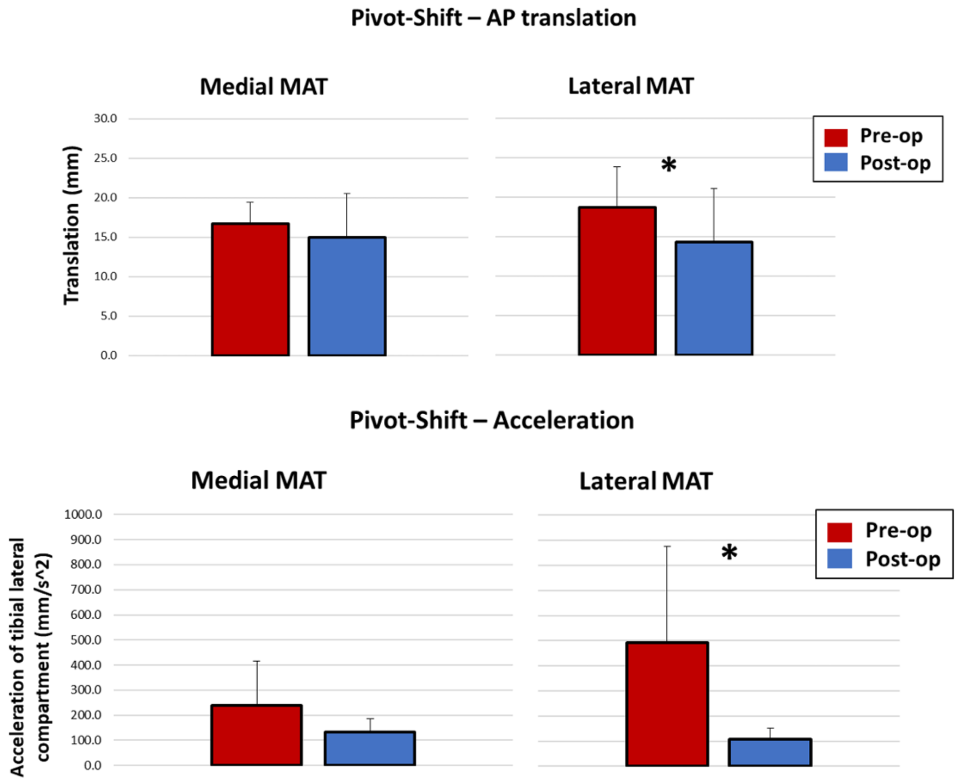

Figure 3: Pivot-shift test dynamic laxity through anterior displacement (APlat) and posterior acceleration of the lateral tibial compartment during tibial reduction (ACC) evaluated before (red, MAT Pre-op) and after (blue, MAT Post-op) MAT. Asterisks represent significant differences ($p<0.05$) between MAT Pre-op and MAT Post-op.

Discussion

The most important finding of the present study was that the MAT with soft-tissue technique determines a significant laxity reduction in an in-vivo setting from the pre- to the postoperative assessment. The lateral MAT reduced the global knee laxity with particular emphasis on the rotatory knee parameters, while the medial MAT reduced the AP and VV laxity but did not control the PS test.

The results of the present study showed that both the medial and the lateral MAT are similarly able to reduce the AP translation of about 2-3mm at different flexion angles (Figure 2, Table 3). Previous in vitro studies investigated the stabilizing effect of the medial meniscus and found an increased anterior tibial translation of about 4 mm after a complete medial meniscectomy under axial load [19,20]. Similarly, an in-vivo study performed under anesthesia found an increase of AP laxity of 3 mm immediately after medial meniscectomy in patients with an ACL-intact knee [21]. Considering that the amount of increased laxity after meniscectomy reported in these studies is similar to the AP reduction obtained after medial MAT, it is possible to hypothesize that such a surgical procedure could counteract the biomechanical effects of a medial meniscectomy.

The stabilizing effect of medial MAT found in the present study becomes even more interesting if we consider one of the main indications for meniscus transplant: based on the international meniscus transplant guidelines, the medial MAT is indicated “as a concomitant procedure to revision ACL reconstruction to aid in joint stability when meniscus deficiency is believed to be a contributing factor to ACL failure” [22]. However, this recommendation is not directly supported by clinical trials but is mainly based on in-vitro biomechanical studies: an increased AP translation caused by a medial meniscus deficiency could further stress the ACL graft and predispose it to failure [3,23]. On the other hand, the present study showed a relevant stabilizing effect on AP translation after medial MAT, even in an ACL-intact knee. Although not directly investigated, it could be hypothesized that the stabilizing effect of medial MAT found in the present study results could determine a positive biomechanical effect on an ACL graft and thus, give strength to the IMREF recommendation.

Regarding the AP stabilizing effect of the lateral MAT compared to the medial one, most of the authors reported a limited effect of partial lateral meniscectomy on AP translation [4,24,25]. However, two recent cadaveric study showed the importance of circumferential meniscus fibers on the lateral meniscus kinematics [26,27]. One study shows that a lateral meniscal posterior root tear significantly increased the anterior tibial translation of about 1 mm even after ACL-reconstruction [26]. A similar increase in anterior tibial translation was observed in another robotic study after a complete radial tear of the lateral meniscus [27].

Finally, an in-vivo biomechanical analysis by Yoon et al. reported that the lateral MAT performed after ACL reconstruction was able to reduce the Lachman and the Anterior-drawer tests at manual examination two years after surgery [13]. However, the same authors failed to confirm these results when they objectively quantified the AP translation with the Telos stress device [13].

In the present study, the medial MAT did not show any significant effect on the kinematics of the PS. Conversely, after lateral MAT, there was a reduction of 4.4mm (-22%) of the translation of the lateral compartment and a massive reduction of the acceleration (-51%) during the PS test.

These data are in line with several in-vitro and in-vivo studies showing that only lateral meniscectomy or lateral meniscus tears impact knee rotatory instability [25,28]. Interestingly, the only other in-vivo study evaluating the biomechanical effect of MAT found that only the medial MAT improved the rotational stability, while the lateral MAT had no influence on the magnitude of the PS test [13]. Such differences could be related to different study protocols and surgical techniques: while Yoon et al. [13] evaluated the patients using a clinical PS grading two years after surgery, in the present study, the PS was quantified using the surgical navigation system which is considered the gold standard for intraoperative kinematic assessment [29]. Additionally, in our study, the PS was performed with the patients under anesthesia, which has been demonstrated to be more reliable, reproducible, and accurate because not influenced by the patient's level of consciousness and pain [30]. Finally, in these two studies, different techniques were used for the MAT and only the soft-tissue one showed a PS reduction after lateral MAT. These data appear to be clinically relevant since graft fixation is one of the most debated topics in the last years [22,31,32]. In fact, while early in-vitro biomechanical studies found that bone-block techniques were superior in terms of contact pressures [33], more recent robotic and clinical studies found no difference in terms of kinematics and patient outcomes [12,31].

The present study has some limitations. First, the reduced number of patients enrolled. The recruitment of patients was complex since the navigation system is an invasive tool, MAT is not a common arthroscopic procedure, and often patients were excluded because they required previous or concomitant surgeries (such as revision ACL or HTO) that could have altered the kinematical analysis of MAT [34]. Nonetheless, this strict selection allowed to investigate the biomechanics of the sole MAT without biases. Moreover, there are two limitations with respect to robotic studies. First, it was impossible to analyze the same knee in the healthy, meniscectomized and transplanted condition, because it would have been unethical in vivo. The second is related to the setting of laxity evaluation, which was performed manually rather than with robotic devices with standardized simulated movements. To reduce this bias, all the tests were performed by a single senior surgeon with more than 15 years of experience in intraoperative surgical navigation, whose reliability in manual kinematic assessment was already evaluated [4,35–37].

The present study also has several strengths. First, it was performed in an in-vivo setting and therefore, all the surgical steps, including the meniscus harvesting and sizing, the meniscectomy, the capsular fixation, and the tunnel drilling and horns fixation, are an authentic representation of the clinical scenario. Additionally, all the in vitro evaluations of MAT available in the literature were performed on specimens from older donors, including only amputated knee, and were performed using additional surgical steps such as arthrotomy or capsular dissections, which are not required in the actual setting. Finally, the present paper is the second to evaluate the kinematical effect of MAT in-vivo condition but is the first to provide to be performed on patients with intact ACL and the only one that uses soft-tissue MAT fixation.

Conclusions

MAT with soft-tissue fixation results in a clinically significant laxity reduction in an in-vivo setting. In addition, Medial MAT improved knee kinematics by determining a substantial decrease with particular emphasis on AP translation and VV maneuver. Conversely, Lateral MAT determined a massive reduction of the PS and a mild decrease of the AP translation and VV maneuver.

References

[1] Fox AJS, Bedi A, Rodeo SA. The basic science of human knee menisci: structure, composition, and function. Sports Health 2012;4:340–51. https://doi.org/10.1177/1941738111429419.

[2] Musahl V, Nazzal EM, Lucidi GA, Serrano R, Hughes JD, Margheritini F, et al. Current trends in the anterior cruciate ligament part 1: biology and biomechanics. Knee Surg Sports Traumatol Arthrosc 2022;30:20–33. https://doi.org/10.1007/s00167-021-06826-y.

[3] Trojani C, Sbihi A, Djian P, Potel J-F, Hulet C, Jouve F, et al. Causes for failure of ACL reconstruction and influence of meniscectomies after revision. Knee Surg Sports Traumatol Arthrosc 2011;19:196–201. https://doi.org/10.1007/s00167-010-1201-6.

[4] Grassi A, Di Paolo S, Lucidi GA, Macchiarola L, Raggi F, Zaffagnini S. The Contribution of Partial Meniscectomy to Preoperative Laxity and Laxity After Anatomic Single-Bundle Anterior Cruciate Ligament Reconstruction: In Vivo Kinematics With Navigation. Am J Sports Med 2019;47:3203–11. https://doi.org/10.1177/0363546519876648.

[5] Dejour D, Pungitore M, Valluy J, Nover L, Saffarini M, Demey G. Preoperative laxity in ACL-deficient knees increases with posterior tibial slope and medial meniscal tears. Knee Surg Sports Traumatol Arthrosc 2019;27:564–72. https://doi.org/10.1007/s00167-018-5180-3.

[6] Wu WH, Hackett T, Richmond JC. Effects of Meniscal and Articular Surface Status on Knee Stability, Function, and Symptoms after Anterior Cruciate Ligament Reconstruction: A Long-term Prospective Study <sup/>. Am J Sports Med 2002;30:845–50. https://doi.org/10.1177/03635465020300061501.

[7] Wasserburger JN, Shultz CL, Hankins DA, Korcek L, Martin DF, Amendola A, et al. Long-term National Trends of Arthroscopic Meniscal Repair and Debridement. Am J Sports Med 2021;49:1530–7. https://doi.org/10.1177/0363546521999419.

[8] Herzog MM, Marshall SW, Lund JL, Pate V, Mack CD, Spang JT. Trends in Incidence of ACL Reconstruction and Concomitant Procedures Among Commercially Insured Individuals in the

United States, 2002-2014. Sports Health 2018;10:523–31. https://doi.org/10.1177/1941738118803616.

[9] Jacquet C, Pujol N, Pauly V, Beaufils P, Ollivier M. Analysis of the trends in arthroscopic meniscectomy and meniscus repair procedures in France from 2005 to 2017. Orthop Traumatol Surg Res 2019;105:677–82. https://doi.org/10.1016/j.otsr.2019.01.024.

[10] Canham W, Stanish W. A study of the biological behavior of the meniscus as a transplant in the medial compartment of a dog’s knee. Am J Sports Med 1986;14:376–9. https://doi.org/10.1177/036354658601400505.

[11] Wang D, Zhang B, Li Y, Meng X, Jiang D, Yu J-K. The Long-term Chondroprotective Effect of Meniscal Allograft Transplant: A 10- to 14-Year Follow-up Study. Am J Sports Med 2022;50:128–37. https://doi.org/10.1177/03635465211054022.

[12] Novaretti JV, Lian J, Sheean AJ, Chan CK, Wang JH, Cohen M, et al. Lateral Meniscal Allograft Transplantation With Bone Block and Suture-Only Techniques Partially Restores Knee Kinematics and Forces. Am J Sports Med 2019;47:2427–36. https://doi.org/10.1177/0363546519858085.

[13] Yoon KH, Lee HW, Park SY, Yeak RDK, Kim J-S, Park J-Y. Meniscal Allograft Transplantation After Anterior Cruciate Ligament Reconstruction Can Improve Knee Stability: A Comparison of Medial and Lateral Procedures. Am J Sports Med 2020;48:2370–5. https://doi.org/10.1177/0363546520938771.

[14] Zaffagnini S, Grassi A, Marcheggiani Muccioli GM, Benzi A, Serra M, Rotini M, et al. Survivorship and clinical outcomes of 147 consecutive isolated or combined arthroscopic bone plug free meniscal allograft transplantation. Knee Surg Sports Traumatol Arthrosc 2016;24:1432–9. https://doi.org/10.1007/s00167-016-4035-z.

[15] González-Lucena G, Gelber PE, Pelfort X, Tey M, Monllau JC. Meniscal Allograft Transplantation Without Bone Blocks: A 5- to 8-Year Follow-Up of 33 Patients. Arthroscopy: The Journal of Arthroscopic & Related Surgery 2010;26:1633–40.

https://doi.org/10.1016/j.arthro.2010.05.005.

[16] Martelli S, Zaffagnini S, Bignozzi S, Lopomo N, Marcacci M. Description and validation of a navigation system for intra-operative evaluation of knee laxity. Comput Aided Surg 2007;12:181–8. https://doi.org/10.3109/10929080701387259.

[17] Lorbach O, Kieb M, Domnick C, Herbort M, Weyers I, Raschke M, et al. Biomechanical evaluation of knee kinematics after anatomic single- and anatomic double-bundle ACL reconstructions with medial meniscal repair. Knee Surg Sports Traumatol Arthrosc 2015;23:2734–41. https://doi.org/10.1007/s00167-014-3071-9.

[18] Spang JT, Dang ABC, Mazzocca A, Rincon L, Obopilwe E, Beynnon B, et al. The effect of medial meniscectomy and meniscal allograft transplantation on knee and anterior cruciate ligament biomechanics. Arthroscopy 2010;26:192–201. https://doi.org/10.1016/j.arthro.2009.11.008.

[19] Arno S, Hadley S, Campbell KA, Bell CP, Hall M, Beltran LS, et al. The effect of arthroscopic partial medial meniscectomy on tibiofemoral stability. Am J Sports Med 2013;41:73–9. https://doi.org/10.1177/0363546512464482.

[20] Watanabe Y, Van Scyoc A, Tsuda E, Debski RE, Woo SL-Y. Biomechanical function of the posterior horn of the medial meniscus: a human cadaveric study. Journal of Orthopaedic Science 2004;9:280–4. https://doi.org/10.1007/s00776-004-0781-8.

[21] Yammine K. Effect of partial medial meniscectomy on anterior tibial translation in stable knees: a prospective controlled study on 32 patients. BMC Sports Sci Med Rehabil 2013;5:17. https://doi.org/10.1186/2052-1847-5-17.

[22] Getgood A, LaPrade RF, Verdonk P, Gersoff W, Cole B, Spalding T, et al. International Meniscus Reconstruction Experts Forum (IMREF) 2015 Consensus Statement on the Practice of Meniscal Allograft Transplantation. Am J Sports Med 2017;45:1195–205. https://doi.org/10.1177/0363546516660064.

[23] Allen CR, Wong EK, Livesay GA, Sakane M, Fu FH, Woo SL-Y. Importance of the medial meniscus in the anterior cruciate ligament-deficient knee. J Orthop Res 2000;18:109–15.

https://doi.org/10.1002/jor.1100180116.

[24] Wieser K, Betz M, Farshad M, Vich M, Fucentese SF, Meyer DC. Experimental loss of menisci, cartilage and subchondral bone gradually increases anteroposterior knee laxity. Knee Surg Sports Traumatol Arthrosc 2012;20:2104–8. https://doi.org/10.1007/s00167-011-1799-z.

[25] Musahl V, Citak M, O'Loughlin PF, Choi D, Bedi A, Pearle AD. The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. Am J Sports Med 2010;38:1591–7. https://doi.org/10.1177/0363546510364402.

[26] Tang X, Marshall B, Wang JH, Zhu J, Li J, Smolinski P, et al. Lateral Meniscal Posterior Root Repair With Anterior Cruciate Ligament Reconstruction Better Restores Knee Stability. Am J Sports Med 2019;47:59–65. https://doi.org/10.1177/0363546518808004.

[27] Smith PA, Bezold WA, Cook CR, Krych AJ, Stuart MJ, Wijdicks C, et al. Kinematic Analysis of Lateral Meniscal Oblique Radial Tears in the Anterior Cruciate Ligament-Deficient Knee. Am J Sports Med 2021;49:3898–905. https://doi.org/10.1177/03635465211052521.

[28] Zaffagnini S, Di Paolo S, Stefanelli F, Dal Fabbro G, Macchiarola L, Lucidi GA, et al. The biomechanical role of meniscal allograft transplantation and preliminary in-vivo kinematic evaluation. J Exp Orthop 2019;6:27. https://doi.org/10.1186/s40634-019-0196-2.

[29] Zaffagnini S, Urrizola F, Signorelli C, Grassi A, Di Sarsina TR, Lucidi GA, et al. Current use of navigation system in ACL surgery: a historical review. Knee Surg Sports Traumatol Arthrosc 2016;24:3396–409. https://doi.org/10.1007/s00167-016-4356-y.

[30] Lopomo N, Signorelli C, Rahnemai-Azar AA, Raggi F, Hoshino Y, Samuelsson K, et al. Analysis of the influence of anaesthesia on the clinical and quantitative assessment of the pivot shift: a multicenter international study. Knee Surg Sports Traumatol Arthrosc 2017;25:3004–11. https://doi.org/10.1007/s00167-016-4130-1.

[31] Koh YG, Kim YS, Kwon OR, Heo DB, Tak DH. Comparative Matched-Pair Analysis of Keyhole Bone-Plug Technique Versus Arthroscopic-Assisted Pullout Suture Technique for Lateral Meniscal Allograft Transplantation. Arthroscopy 2018;34:1940–7.

https://doi.org/10.1016/j.arthro.2018.01.053.

[32] Stone KR. Editorial Commentary: Meniscus Transplantation With or Without Bone Blocks: If You Don't Have to Break It, Don't. Arthroscopy: The Journal of Arthroscopic & Related Surgery 2018;34:1948–9. https://doi.org/10.1016/j.arthro.2018.03.024.

[33] Ambra LF, Mestriner AB, Ackermann J, Phan AT, Farr J, Gomoll AH. Bone-Plug Versus Soft Tissue Fixation of Medial Meniscal Allograft Transplants: A Biomechanical Study. Am J Sports Med 2019;47:2960–5. https://doi.org/10.1177/0363546519870179.

[34] Grassi A, Di Paolo S, Coco V, Romandini I, Filardo G, Lucidi GA, et al. Survivorship and Reoperation of 324 Consecutive Isolated or Combined Arthroscopic Meniscal Allograft Transplants Using Soft Tissue Fixation. Am J Sports Med 2023;51:119–28. https://doi.org/10.1177/03635465221131522.

[35] Lopomo N, Bignozzi S, Martelli S, Zaffagnini S, Iacono F, Visani A, et al. Reliability of a navigation system for intra-operative evaluation of antero-posterior knee joint laxity. Computers in Biology and Medicine 2009;39:280–5. https://doi.org/10.1016/j.compbiomed.2009.01.001.

[36] Signorelli C, Bonanzinga T, Lopomo N, Marcheggiani Muccioli GM, Bignozzi S, Filardo G, et al. Do pre-operative knee laxity values influence post-operative ones after anterior cruciate ligament reconstruction?: Knee laxity after ACL reconstruction results. Scand J Med Sci Sports 2013;23:e219–24. https://doi.org/10.1111/sms.12059.

[37] Zaffagnini S, Bignozzi S, Martelli S, Imakiire N, Lopomo N, Marcacci M. New intraoperative protocol for kinematic evaluation of ACL reconstruction: preliminary results. Knee Surg Sports Traumatol Arthr 2006;14:811–6. https://doi.org/10.1007/s00167-006-0057-2.