Meniscus Tear Gapping under Physiological Knee Loading: Considerations For Postoperative Rehabilitation

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INTRODUCTION: Meniscal tears alter the tibiofemoral contact mechanics and are a known risk factor for the onset of post-traumatic knee joint osteoarthritis [1]. In light of the current paradigm shift toward meniscus-preserving treatments, arthroscopic suture repair has become the preferred approach [2]. However, the reported failure rates remain high (14.8–21.8%) [3], and the underlying causes and risk factors are still poorly understood. Critical meniscus gapping (>1.5 mm) in response to extensive knee joint loading during the early postoperative phase can impair the healing process [4,5]. Consequently, adequate rehabilitation is essential for successful meniscus repair. Yet, there is no consensus on the optimal postoperative rehabilitation protocols for different tear types, particularly regarding unrestricted versus conservative loading regimens [6]. Notably, there is no objective data identifying biomechanical differences between rehabilitation-related and normal daily movement activities. Therefore, the objective of this ex-vivo study was to investigate the biomechanical effects of common radial and circumferential medial meniscus tear patterns before and after suture repair under physiological daily and crutch-assisted gait exercises.

METHODS: Based on a priori sample size calculation, 31 intact human knee joints (approved by the Ethics Committee) were assigned to three meniscal tear groups: radial tear (RT, n = 13, 7 male / 6 female, age: 54 ± 9 yrs., BMI: 23 ± 3 kg/m^2), longitudinal tear (LT, n = 8, 5 male / 3 female, age: 54 ± 9 yrs., BMI: 24 ± 4 kg/m^2), and bucket-handle tear (BHT, n = 10, 2 male / 8 female, age: 57 ± 11 yrs., BMI: 26 ± 6 kg/m^2). Specimens were prepared for biomechanical testing using an established dynamic knee joint simulator (Fig. 1) [7]. Six movements were simulated via active muscle force application: daily exercises (gait, gait with imposed 10° ankle rotation (GaitR), standing up (StandUp) and sitting down (SitDown)), and rehabilitation-related movements (four-point crutch gait under 30% (CG30) and 50% (CG50) body weight). The muscle profiles of the eight most relevant knee-spanning muscles were obtained in advance from a combined motion analysis and inverse dynamic study involving thirteen volunteers. Each knee was tested in three conditions: intact, ruptured, and repaired. Following a posteromedial capsulotomy, medial meniscus tears (RT, LT, BHT) were artificially induced and subsequently repaired by an experienced orthopaedic surgeon using the all-inside repair technique with certified surgical implants. Knee kinematics were recorded using a motion tracking system, while tibiofemoral contact pressure (CP) and contact area (CA) were assessed using pressure-sensitive films. Tantalum beads were inserted pairwise adjacent to the tear to measure the change in distance between marker pairs (gapping/compression) via roentgen stereophotogrammetric analysis [4]. Normally distributed data were analyzed using repeated-measures one-way ANOVA followed by Tukey's multiple comparisons test. Non-normally distributed data were analyzed using the Friedman test, applying Dunn's post hoc correction whenever necessary. A p-value of ≤ 0.05 was considered statistically significant.

RESULTS: Overall, knee joint kinematics were not affected by tear pattern or meniscal condition. Tibial external rotation during crutch-assisted movements (CG30, CG50) was on average 49% lower than during daily movements (Gait, GaitR, SitDown), irrespective of the meniscal condition. Tibiofemoral contact mechanics were largely unaffected in the LT and BHT group. In contrast, a significant increase in CP (Gait, GaitR SitDown: +30%; $p \leq 0.025$; Fig. 2A) and a decrease in CA (Gait, StandUp, SitDown: −26%; $p \leq 0.039$; Fig. 2B) were found in the RT group when comparing the ruptured versus intact state. Interestingly, CG30 and CG50 movements showed no effect on contact mechanics. Suture repair restored the contact parameters to near-intact levels (CP: $p \leq 0.023$, CA: $p \leq 0.031$). Meniscus gapping, evaluated as the mean of three marker pairs, was highest in the RT group, reaching up to 1.93 mm (SitDown, Fig. 3A), whereas the LT group showed a tear compression of up to −0.54 mm (Fig. 3B). Suture repair significantly reduced RT gapping to below the critical threshold (CG30, CG50, GRot; $p \leq 0.047$). BHT exhibited both gapping (≤ 1.3 mm) and compression (≥ -1.4 mm) during deep flexion exercises in the ruptured state.

DISCUSSION: This study is the first that quantifies the gapping behavior of typical medial meniscus tears and their surgical repair under physiologically simulated daily and rehabilitation-related movements. The main finding was that instable RTs reached critical gapping levels (>1.5 mm) during deep flexion exercises, whereas suture repair reduced gapping below this threshold. However, isolated analysis of the inner marker pairs revealed gap sizes of up to 9.7 mm during normal daily movements, with five specimens remaining above the critical threshold even after repair. This indicates unstable fixation, which becomes particularly evident under full weight-bearing deep flexion exercises, highlighting the importance of conservative rehabilitation. None of the tear patterns altered the knee kinematics, suggesting that active muscle force simulation stabilized the joint effectively. LT and BHT did not affect the tibiofemoral contact mechanics, whereas RT significantly increased CP during deep flexion. In summary, LT and BHT seem to allow for non-restrictive rehabilitation, whereas RT may require a more conservative protocol with partial weight-bearing (crutch-assisted gait) and limited flexion range to preserve suture stability. Limitations include the ex vivo setting, which does not account for biological healing, and the artificial tear application.

SIGNIFICANCE/CLINICAL RELEVANCE: Our findings provide a biomechanical baseline for developing a tear-specific rehabilitation protocol, enabling more precise and evidence-based post-surgical weight-bearing recommendations to reduce suture repair failure rates and thus improve patient recovery.

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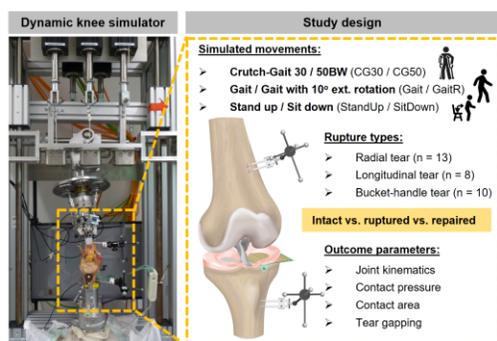
Fig. 1: Study design. The biomechanical effects of different medial meniscus tear patterns (radial, longitudinal, and bucket-handle) were assessed before and after all-inside suture repair. Outcomes included knee joint kinematics, tibiofemoral contact mechanics, and meniscus gapping behaviour. Daily activities and rehabilitation-relevant movements were simulated in an established dynamic knee joint simulator with active muscle control.
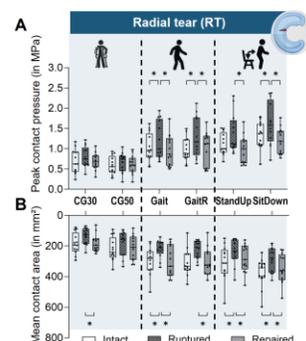
Fig. 2: Tibiofemoral contact pressure (A) and contact area (B) of radial tears. Box plots display minimum, maximum, median, and interquartile range for the different movement scenarios. Statistical differences were assessed using repeated-measures one-way ANOVA (p < 0.05).
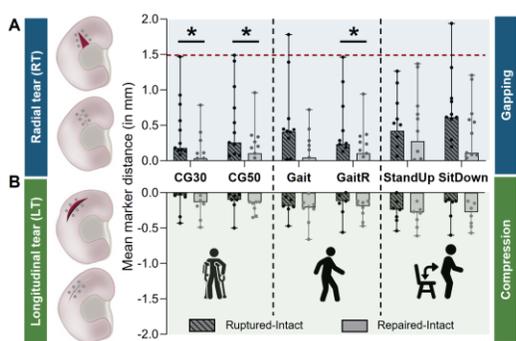
Fig. 3: Gapping behaviour in radial (A) and longitudinal (B) meniscus tears. Bar charts display median ± minimum/maximum values for the different movement scenarios. Gapping was quantified as the mean marker distance across all three marker pairs relative to the intact state. Statistical differences were assessed using the Wilcoxon test for non-parametric data (p < 0.05).