A Novel Approach to Segmental Meniscus Repair – Can We Improve Biomechanical Performance of Meniscus Transplants and Reduce the Risk of Extrusion?

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INTRODUCTION: Menisci act to reduce friction for knee articular cartilage, perform an essential role in load bearing by dispersing mechanical stress, and are crucial for normal knee kinematics [1]. Meniscus extrusion, meniscal tears and excision of meniscal tissue have been shown to increase contact pressure in the tibiofemoral compartment, leading to accelerated osteoarthritis and other degenerative changes [2]. While meniscectomy often provides short-term symptom relief, its long-term effects on joint health are concerning [3]. Allograft meniscal transplantation is an option for adults but limited in pediatric patients due to donor scarcity and long-term survival concerns. Meniscus transplantation may also be at higher risk of secondary meniscus extrusion, and segmental meniscus transplantation may lower the risk of extrusion by preserving the menisco-tibial ligament complex tissues. Segmental meniscal transplantation could address these limitations; however, although various surgical repair techniques have been described, little is known about their biomechanical performance. The purpose of this study was to compare the biomechanical performance of two segmental repair techniques using cyclic loading and load to failure testing (**Fig.1**). We hypothesized that a novel suture technique will improve ultimate strength and resistance to cyclic fatigue compared to a recently described control technique.

METHODS: Twenty-four bovine meniscus explants (12 medial, 12 lateral) were prepared with a standardized segmental defect measuring approximately one-third of the meniscus length (12.6 ± 2.1 mm, **Fig. 1**). The defect was repaired using the native tissue. Two repair techniques were tested: 1) a novel technique that utilized two hashtag, two luggage tag suture patterns, and one vertical mattress suture and 2) a control technique that used four luggage tags, two horizontal and one vertical mattress suture repairs. To maintain shape of the menisci during testing, repaired specimens were mounted on custom 3D-printed PLA boards and secured with four 2.5 mm Kirschner wires. To allow for application of tensile forces on the excised segments, four additional LabralTape sutures were passed through the resected portion of the specimens. Alignment was carefully adjusted to ensure the load passed through the segment's center of mass along the desired axis. Quasi-static (n=6) and cyclic (n=6) uniaxial tension protocols were performed in universal test frames using custom jigs and grips. For the quasi-static experiments, specimens were loaded to failure at a rate of 1 mm/s. Cyclic tests consisted of 1000 loading cycles between 20 and 50 N, followed by a ramp to failure at 1 mm/s. Outcomes included stiffness, maximum force, and failure mode for all specimens, as well as plastic deformation and survival analysis for cyclic tests. Statistical analysis was performed using a one-way ANOVA with significance set at $p < 0.05$.

RESULTS: The novel repair technique demonstrated significantly higher maximum load to failure in both static (311.9 ± 26.2 N vs. 209.5 ± 82.6 N, $p = 0.0159$) and dynamic tests (339.0 ± 43.0 N vs. 181.0 ± 89.0 N, $p = 0.0029$) compared to the control group (**Fig. 2A**). Stiffness was not significantly different between groups in either test (not shown). During cyclic loading, plastic deformation increased significantly between 100 and 500 cycles in both groups, but no differences were observed across groups at any cycle count (**Fig. 2B**). Survival analysis showed that 33% of control specimens failed before completing 1000 cycles, whereas all novel repairs survived (**Fig. 2C**).

DISCUSSION: The results of this study confirmed our hypothesis that the novel repair provides superior biomechanical performance compared to the control technique. The significantly higher ultimate failure loads in both quasi-static and post cyclic testing suggest that this technique can better withstand forces experienced by the meniscus during routine knee loading. Although stiffness was not significantly different between groups, the ability of the novel repair to survive 1000 cycles without failure indicates that its suture configuration more effectively distributes load across the tissue. This study had several limitations. Repairs were performed in an open setting rather than arthroscopically which affects suture placement compared to clinical practice. In addition, cyclic loading was performed in uniaxial tension and does not capture the complex, multi-directional forces experienced in vivo. Future work should focus on in vivo validation, including biological integration at the graft host interface, as well as arthroscopic implementation to replicate surgical conditions.

SIGNIFICANCE/CLINICAL RELEVANCE: The novel repair technique for segmental meniscus transplantation provides stronger fixation and greater resistance to cyclic fatigue and could be performed while also preserving the native menisco-tibial ligament complex and reduce the risk of meniscus extrusion. This approach could expand surgical options for pediatric and adult patients who are poor candidates for total meniscal allograft transplantation by preserving native tissue and reducing long-term joint degeneration.

REFERENCES: [1] Mameri+, Curr. Rev. Musculoskelet. Med., 2022; [2] Caldwell+, Oper. Tech. Sports Med., 1994; [3] Ozeki+, Life, 2022.

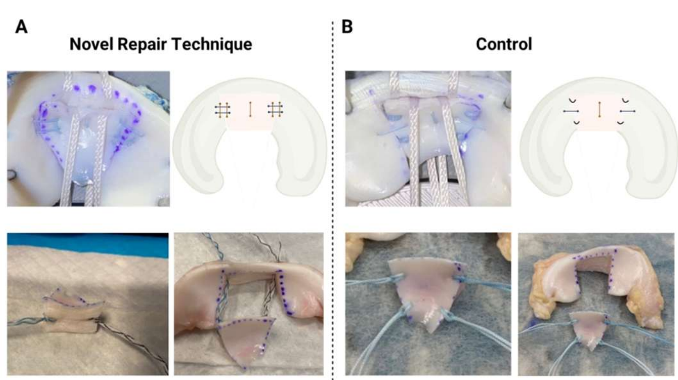

Figure 1: Two segmental meniscal repair techniques were evaluated. Left: Novel repair with two hashtag and two luggage tags. Right: Control repair with four luggage tags, two horizontal and one vertical mattress suture repairs.

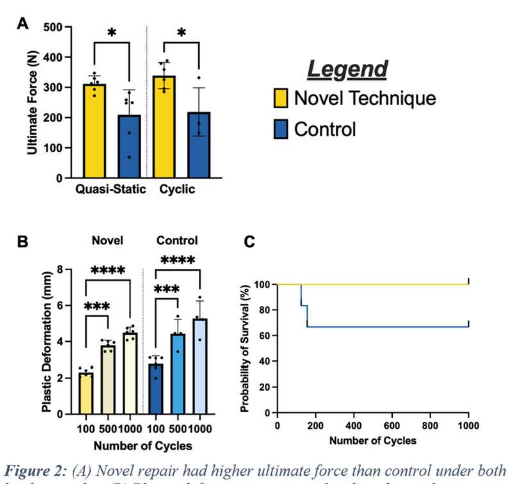

*Figure 2: (A) Novel repair had higher ultimate force than control under both loading modes. (B) Plastic deformation increased with cycles, with no group differences. (C) All novel repairs survived 1000 cycles; one-third of controls failed. p<0.05, ** p<0.01, *** p<0.001, **** p<0.0001*