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Procedia Structural Integrity 68 (2025) 106–111

Structural Integrity Procedia

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European Conference on Fracture 2024

Comparative evaluation of surgical methods in the treatment of chronic irreparable supraspinatus tears: a biomechanical study

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Abstract

Chronic irreparable supraspinatus (SSP) tears are frequently treated using tensor fascia lata (TFL); however, these grafts are prone to recurrent ruptures. A TFL scaffold with seeded mesenchymal stem cells (MSCs) may increase the mechanical strength of the regenerated tendon. In this experimental study the above hypothesis is evaluated and the healing qualities of the MSC embedded scaffold are compared against the ones repaired with only a TFL allograft, from a biomechanical perspective. A number of skeletally mature male rabbits were used to create a chronic retracted SSP tear model. A tendon defect was created at the right shoulder of each specimen and was reconstructed six weeks later using a TFL allograft either with or without MSCs embedded. The rabbits were sacrificed twelve weeks after the operation and their biomechanical evaluation was based on the tendon's ultimate failure load and stiffness of each group. The results of the biomechanical analysis revealed that the MSC group demonstrated a higher tensile strength than the TFL group. The values of the mean ultimate failure load and the mean stiffness of both TFL and MSC groups were significantly lower compared to the respective values obtained for the intact rotator cuff (RC) group. It seems that bone marrow MSCs increased the mechanical strength of the supraspinatus tendon; however, the stiffness was similar between the operated groups in rabbit models. Based on the results, it could be stated that rotator cuff regeneration using MSCs appears as a promising approach; nonetheless, additional clinical evidence is required, before definite conclusions are drawn.

Keywords: Chronic supraspinatus tear; rotator cuff; tensor fascia lata; mesenchymal stem cell; biomechanics

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10.1016/j.prostr.2025.06.029

1. Introduction

Rotator cuff (RC) tears are among the most common injuries afflicting the shoulder, and clinical intervention is often required (Yokoya et al., 2012). While most RC tears heal with excellent results after open or arthroscopic repair, some chronic retracted tears cannot be repaired due to muscle atrophy or fatty degeneration (Yildiz et al., 2019). Despite advances in surgical treatment options, large rotator cuff tears remain a challenge for orthopaedic surgeons (Varvitsiotis et al., 2014). Using allografts as the tensor fascia lata (TFL) appears promising in addressing these complex tears (Mihata et al., 2012; Yildiz et al., 2019; Varvitsiotis et al., 2014); however, there is still no standard treatment method with optimal outcomes. A critical limitation of TFL scaffolds is their primary role as mechanical reinforcement, lacking the biological capacity for tissue regeneration resulting often in scar tissue formation and a recurrent tear (Varvitsiotis et al., 2014). The introduction of tissue engineering in the medical field, and specifically the utilization of non-differentiated progenitor cells of musculoskeletal tissues to regenerate soft and hard tissues (Bruder et al., 1994; Caplan, 1991; Wakitani et al., 1994) offers a potential solution.

The purpose of this study is to investigate the possibility of a mechanically and histologically enhanced restoration of a full-thickness RC tear with TFL allografts (Fig. 1a), using stem cells derived from synovial membranes compared to TFL alone. In the present research protocol, it is proposed that the combination of TFL allograft with stabilized MSCs from synovial membranes can improve tendon restoration. To test this hypothesis, a rabbit model of RC defects was established (Fig. 1b). Rabbits were treated with a TFL scaffold embedded with or without seeded MSCs, and the biomechanical response of their tendons was studied.

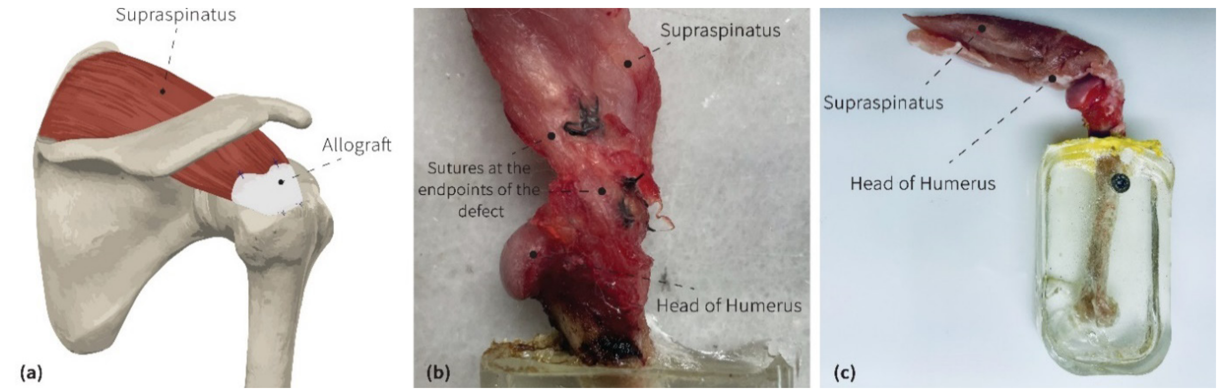

Fig. 1. (a) Illustration of the supraspinatus, scapula and proximal humerus, highlighting the location of the TFL allograft, either with or without seeded mesenchymal stem cells (MSCs), used to repair the small full-thickness defect at the SSP tendon insertion; (b) Healed SSP muscle specimen after repair with TFL allograft (secured to the humeral head with 3.0 nylon sutures); (c) Typical specimen embedded in resin.

Nomenclature

SSP	Supraspinatus
RC	Rotator Cuff
TFL	Tensor Fascia Lata
MSC	Mesenchymal Stem Cells

2. Materials and Methods

2.1. Ethical statement

The experimental subjects consisted of non-endangered rabbits, maintained in accordance with all relevant legislative requirements regarding living conditions, feeding, and euthanasia. Throughout the experimental procedures, all surgical interventions were performed under general anaesthesia. Euthanasia was conducted humanely via intravenous administration of a lethal dose of pentobarbital sodium, also under general anaesthesia. The study was conducted in accordance with the ethical guidelines of The General Directorate of Agricultural Economy and Veterinary Medicine of the Attica Region.

2.2. Surgical model and study design

Twelve shoulders were harvested from eleven mature male rabbits, with mass between 4 kg and 5 kg, for biomechanical testing. The remaining ones were used for histological analysis. An initial 6 mm RC defect was surgically created in the right shoulder of each animal and subsequently repaired with either a TFL allograft, which is considered a xenograft in rabbits or a TFL scaffold seeded with MSCs. The twelve specimens were categorized into three groups: a control group with an intact supraspinatus tendon (n=6), a TFL group (n=3), and an MSC group (n=3). The experimental protocol involved a three-stage process: (1) creation of a supraspinatus tear, (2) surgical reconstruction, (3) biomechanical evaluation of the healed shoulder specimens.

2.3. Specimen harvesting and preparation

At 12 weeks postoperatively, shoulders were harvested, preserving the scapula, humerus, and supraspinatus complex, while the surrounding soft tissues were removed. Specimens were then wrapped in wet gauze, sealed in individual plastic bags, and stored at -20 °C until biomechanical testing.

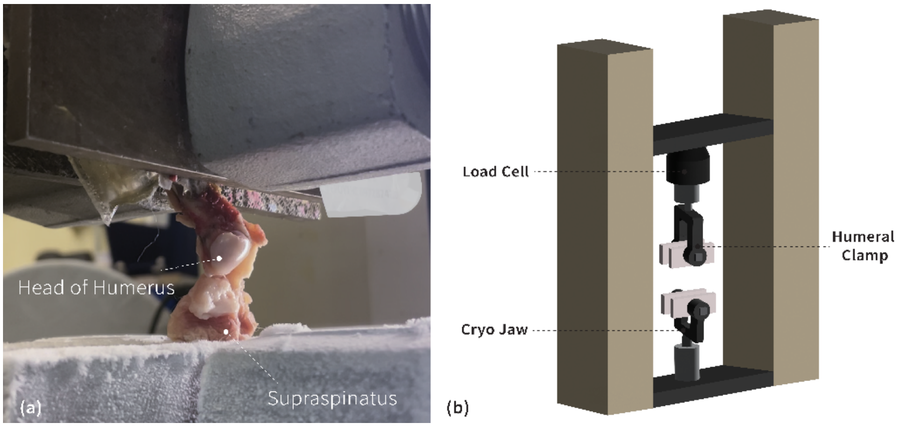

Fig. 2. (a) Typical specimen on the loading frame just before a typical test. The upper clamp is used for securing the humeral end of the specimen, whereas the lower one was submerged into liquid nitrogen for holding the SSP muscle; (b) Schematic illustration of the MTS loading frame.

2.4. Morphological assessment

After extraction, each shoulder was subjected to macroscopic evaluation to identify any gross evidence of incomplete healing, structural defects, or other abnormalities within the repaired tissues.

2.5. Biomechanical protocol

On the same day as the extraction surgery, half of the specimens were selected for biomechanical testing. The specimens were thawed in a water bath, and the supraspinatus-humerus complexes were re-wrapped in moistened gauze to prevent dehydration. Ligaments and tendons are typically tested in isolation using specialized grips for soft tissues, or specimens are prepared with bony attachments (Gordon et al., 2017). In the current study, the bony insertion of the supraspinatus tendon on the humerus head was preserved. The scapula was removed, and the humerus was then embedded in resin (Fig. 1c) for secure fixation at the materials testing machine (Fig. 2). The other end of the specimen, including the supraspinatus muscle, was secured using a cryo-clamp made of a low thermally conductive metal and submerged in liquid nitrogen to prevent slippage.

Specimens were subjected to uniaxial tensile loading at a crosshead speed of 20 mm/min until failure, as described by Funakoshi et al. (2005), to determine the ultimate failure load of the supraspinatus repair. The experimental setup improvised ensured that the tendon remained aligned with the loading direction throughout the test. It is mentioned here that the specimens were monitored with a camera during their loading.

In contrast to other studies (Yildiz et al., 2019; Yokoya et al., 2012), a preloading cycle was omitted to simulate a sudden injury scenario and to mitigate potential confounding factors related to the use of cryo-clamps. Specifically, we aimed to avoid failure occurring within frozen tissue regions, which could introduce brittle failure.

3. Results

3.1. Gross evaluation

Studying the videos and the photos taken during loading (Fig. 3), it can be said that macroscopically, all samples from both groups, TFL and MSC, demonstrated complete healing at the glenoid and humeral sites. No defects were observed at any point along the graft-to-bone interface on either side. As regards the failure mode of the specimens, musculotendinous ruptures and ruptures at the tendon insertion were observed in the specimens of the control and TFL group. On the contrary, ruptures only at the insertion were detected in the specimens of the MSC group.

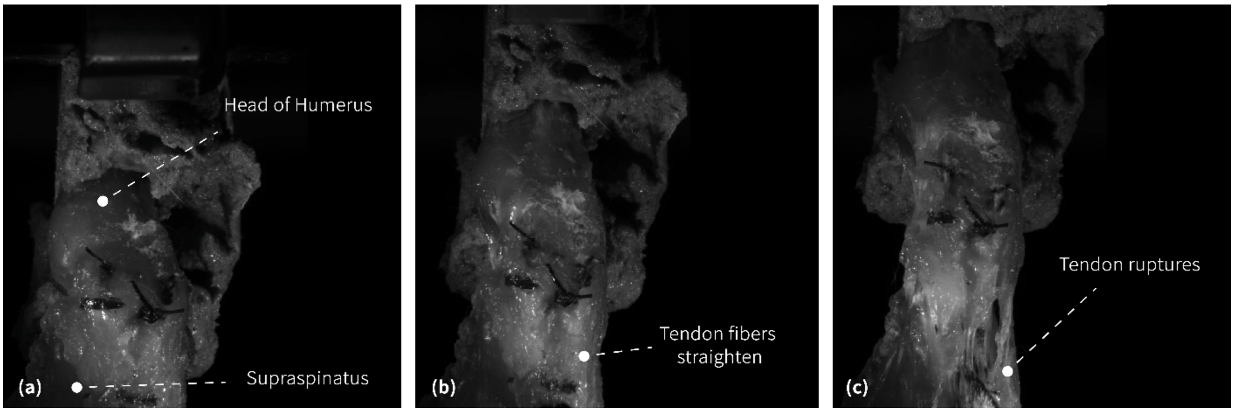

Fig. 3. Tensile testing of the supraspinatus-humerus complex. (a) Initial position prior to loading. (b) During loading, tendon fibers straighten and receive tensile load. (c) Progressive fiber tearing, initiating in thinner fibers until complete tendon rupture. Notably, no sample exhibited tendon freezing at the rupture site.

3.2. Mechanical Properties

The mechanical behaviour of the specimens during loading was examined and is shown in the corresponding Force-Displacement diagrams. Their behaviour appears to be compatible with the characteristic pattern of ligaments and tendons as shown in Fig.4. The initial part immediately after the application of a tensile load has a curved, concave upward shape and it is usually described as a “toe region”. Afterwards, the curve enters a linear region when all the collagen fibers are straightened, and the load distribution is uniform. As we approach higher loads, some ruptures of individual fibers are observed, and we end up in a second non-linear region where the maximum strength of the remaining tendon fibers is recorded before total rupture.

The means, the standard deviations (SD) and the medians of the maximum load, displacement at the instant of maximum load and stiffness of each group are recapitulated in Table 1. As it might be expected, the maximum load attained by both TFL and MSC groups are significantly lower compared to the control group and the same is true for their stiffness. However, comparing the two experimental groups against the control one, it is interesting to observe that although both groups have approximately the same stiffness, the MSC group attains about 50% higher maximum load compared to the TFL group. The control group of non-operated specimens served as a baseline, demonstrating the expected mechanical behaviour of an intact supraspinatus tendon under tensile load.

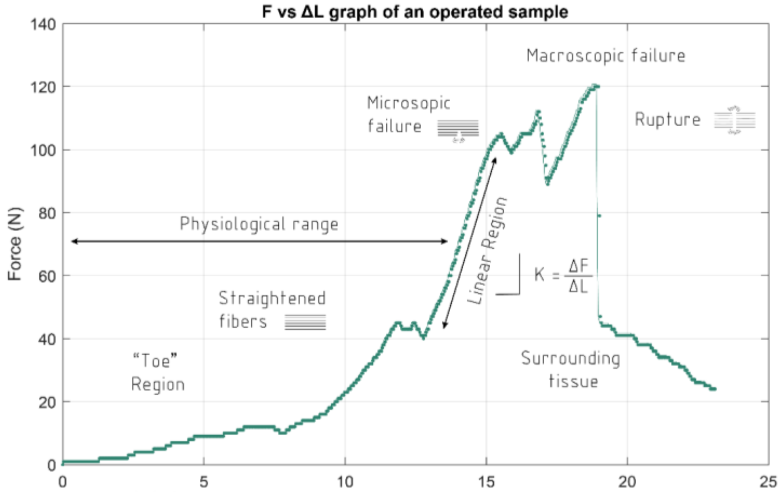

Fig. 4. Typical (for most ligaments and tendons) force-displacement plot.

As anticipated, a difference in stiffness by approximately 10% was observed between the control group and both study groups, reflecting the increased vulnerability of repaired tendons to rupture compared to intact ones. However, the repair method, whether with or without MSCs, did not appear to influence stiffness. Furthermore, Group MSC specimens demonstrated increased elongation until failure compared to Group TFL (Fig. 5). This may be attributed to inherent differences in elasticity between muscle tissue and the scar tissue formed at the suture site, influenced potentially by the presence of MSCs. A histological evaluation is necessary to confirm this preliminary result.

Table 1. Results of the biomechanical testing.

Group	Failure load [N]	Displacement [mm]	Stiffness [N/mm]
Non-Operated (Control)			
Mean	494.3	5.4	227.8
SD	116.9	2.5	59.7
Median	491.0	4.7	222.7
TFL Group			
Mean	104.9	7.5	33.1
SD	35.7	3.3	4.4
Median	99.1	8.6	30.9
MSC Group			
Mean	142.3	15.4	33.2
SD	26.8	6.4	5.9
Median	135.0	15.4	29.8

4. Discussion and Conclusions

The Group TFL, where SSP ruptures were repaired using fascia lata allografts, and Group MSC, where MSCs were incorporated into the repair, showed distinct mechanical properties compared to the control group. Notably, Group MSC specimens exhibited higher average tensile fracture load than the TFL Group, suggesting a potential improvement in mechanical strength and a decreased risk of re-tears following repair. This could highly impact the postoperative life of patients in everyday tasks. However, it is noted that the maximum load values are affected by geometric characteristics of the tendons such as cross-section area and morphology and should not be interpreted in isolation.

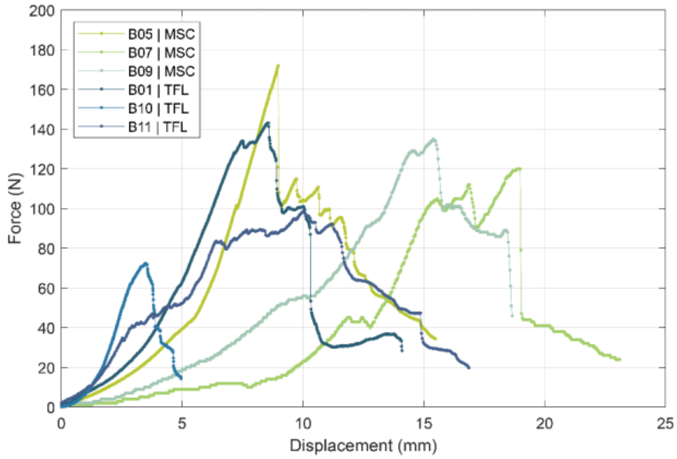

Fig. 5. Force - Displacement graphs of all operated samples.

In conclusion, this preliminary study suggests that the incorporation of MSCs during supraspinatus tendon repair may enhance tensile load and increase elongation until failure, potentially offering improved mechanical properties and a lower risk of re-tears. However, the mechanical properties of the reconstructed specimens remain inferior to the intact tendon. Results from the literature, also, suggest that the reconstructed shoulder cannot withstand the same loads as the intact RC; both in a sudden injury scenario as described in the present study or with preloading cycle as described in the works of Yildiz et al. (2019); Yokoya et al. (2012). In any case, additional experiments and further research are necessary, in order to gain a thorough overview and in-depth understanding of the underlying damage mechanisms and, in parallel, to assess the long-term clinical implications of this approach.

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