Research Square

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Tendon graft reconstruction and transtibial rip-stop repair achieve higher ultimate failure loads than cross-tag rip-stop repair for complete medial meniscus posterior horn radial tears: a porcine biomechanical study

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Research Article

Keywords: biomechanics, meniscus repair, radial tear, tendon graft, transtibial pull-out

Posted Date: November 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11585840/v1

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Additional Declarations: No competing interests reported.

Abstract

Background

The mechanical performance of tendon graft reconstruction for complete radial meniscal tears remains poorly characterized. This study compared cross-tag rip-stop suture repair, rip-stop transtibial pull-out repair, and tendon graft reconstruction for a complete radial tear of the posterior horn of the medial meniscus. We hypothesized that tendon graft reconstruction would have a higher ultimate load to failure than both repair constructs.

Methods

Twenty-seven fresh porcine knees were randomly allocated to cross-tag rip-stop suture repair (CSR), rip-stop transtibial pull-out repair (RTR), or interposition tendon graft reconstruction (TGR) (n = 9 per group). Constructs were subjected to monotonic tensile loading to failure. Ultimate load to failure, stiffness, displacement at ultimate load, and failure mode were evaluated. Group differences were analyzed using Welch one-way analysis of variance and Games-Howell pairwise comparisons.

Results

Mean ultimate load to failure was 122.6 ± 32.2 N for CSR, 249.3 ± 93.3 N for RTR, and 334.7 ± 73.6 N for TGR ($p < 0.001$). Both RTR and TGR had significantly higher ultimate loads than CSR ($p = 0.008$ and $p < 0.001$, respectively), whereas TGR and RTR did not differ significantly ($p = 0.112$). Stiffness did not differ significantly among groups ($p = 0.082$). Mean displacement at ultimate load was 11.7 ± 4.0 mm for CSR, 21.9 ± 8.7 mm for RTR, and 22.3 ± 5.8 mm for TGR ($p < 0.001$). CSR failed exclusively by suture failure, whereas tibial fixation failure and meniscal tissue failure predominated in RTR and TGR, respectively.

Conclusions

Tendon graft reconstruction and rip-stop transtibial pull-out repair achieved higher time-zero ultimate loads to failure than cross-tag rip-stop suture repair. Tendon graft reconstruction showed the highest mean ultimate load to failure, although the difference from rip-stop transtibial pull-out repair was not statistically significant.

Level of Evidence:

Not Applicable, controlled laboratory study.

Background

The meniscus transmits tibiofemoral load, increases contact area and contributes to joint stability; its circumferential collagen fibers convert axial loading into hoop tension [1]. A complete radial tear disrupts this mechanism, as demonstrated by markedly reduced hoop strain in a cadaveric study of the medial meniscus [2]. Computational studies suggest that medial meniscal radial tears can increase local meniscal stress, with one model showing an approximately twofold increase in peak meniscal shear stress under static loading [3], although the effect depends on tear location and width [4].

Meniscal preservation has become increasingly common as more tears are considered repairable [5]. Systematic reviews report improved patient-reported outcomes after radial tear repair [6, 7], although one found complete healing in only 62% of repairs, partial healing in 30%, and no healing in 8% [6]. These findings support investigating constructs with improved initial mechanical stability.

Reinforced suture configurations and transtibial augmentation have been developed to improve the initial stability of radial tear repair. Cross-tag repair reduced cyclic displacement, whereas rebar reinforcement, using vertical sutures as rip-stops, increased load to failure and reduced suture cut-out [8, 9]. Transtibial augmentation has been reported to reduce gapping and increase load to failure [10], although an additional mechanical advantage over reinforced suture constructs has not been consistently demonstrated [11].

Tendon graft reconstruction provides a tissue bridge across a meniscal defect. In animal models, tendon autografts developed fibrocartilage-like characteristics following meniscal reconstruction [12, 13]. In a retrospective clinical study, gracilis autograft reconstruction of medial meniscus posterior root tears was associated with higher MRI-defined complete healing rates than transtibial pull-out repair [14]. However, the time-zero mechanical performance of a tendon graft bridging both sides of a complete posterior horn radial tear remains poorly characterized.

The purpose of this study was to compare time-zero ultimate load to failure, stiffness, displacement at ultimate load, and failure modes among cross-tag rip-stop suture repair (CSR), rip-stop transtibial pull-out repair (RTR), and interposition tendon graft reconstruction (TGR) for complete radial tears of the posterior horn of the medial meniscus. We hypothesized that TGR would have a higher ultimate load to failure than CSR and RTR.

Methods

Study design and ethics

This controlled laboratory study was conducted at the Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Nakhon Pathom, Thailand. All constructs were prepared and tested using specimens from the same source and the same testing machine and protocol. The Institutional Review Board of the Faculty of Medicine Vajira Hospital, Navamindradhiraj University, issued a certificate of exemption for this study (COE 038/2025 X).

Specimens and allocation

Twenty-seven fresh porcine knees from animals aged 5–6 months and weighing 100–120 kg were used, with one medial meniscus obtained from each knee. The specimens were assigned to CSR, RTR or TGR using simple randomization before construct preparation (n = 9 per group), then prepared and tested on the day they were received without freezing. They were kept moist with normal saline throughout preparation and testing.

Specimen preparation and tear model

Skin and periarticular soft tissues were removed, and the femur was disarticulated while preserving the meniscal attachments to the tibial plateau. The tibia was transected approximately 15 cm distal to the joint line for mounting in the testing machine (Fig. 1a), consistent with a previously described porcine testing model [15]. The anterior horn of the medial meniscus was divided to permit tensile loading across the posterior horn. A radial tear was created with a scalpel in the posterior horn, 10 mm from the center of the posterior root attachment [12], without excising meniscal tissue. The tear extended from the inner free edge to the meniscocapsular junction and was therefore classified as a complete radial tear [16]. All constructs were prepared by a single surgeon.

Cross-tag rip-stop suture repair (CSR)

The tear was repaired using an inside-out cross-tag configuration based on the technique described by Stender et al. [8]. Two vertical mattress sutures, one on each side of the tear, were placed to act as rip-stops. Two oblique sutures were then passed across the tear and over the vertical mattress sutures in a crossed configuration (Fig. 1b, c). All sutures were No. 2 – 0 FiberWire (Arthrex, Naples, FL, USA). The suture passes were positioned 5 mm from the tear margins and 3 and 6 mm from the peripheral meniscal rim.

Rip-stop transtibial pull-out repair (RTR)

The RTR construct combined the rebar principle described by Massey et al. [9] with transtibial cortical-button fixation adapted from Homan et al. [17]. One vertical reinforcing suture was placed on each side of the tear, parallel to the tear line and approximately 1 mm from the tear margin. A single horizontal No. 2 FiberWire suture (Arthrex, Naples, FL, USA) was passed across the tear and over the two vertical sutures, which acted as rip-stops against suture cut-through. A 6-mm transtibial tunnel was created from the anteromedial tibia to the tear site using an anterior cruciate ligament (ACL) tibial guide set at 55°. Both limbs of the horizontal suture were shuttled through the tunnel and secured over a 12-mm Suture Button (AR-8922; Arthrex) on the anteromedial tibial cortex under manual tension (Fig. 2a-c).

Interposition tendon graft reconstruction (TGR)

The TGR construct used a tendon graft passed through meniscal perforations on either side of the radial tear to bridge the tear. The technique was adapted from previously described porcine and clinical tendon-graft reconstruction techniques [12, 14]. An autologous flexor digitorum profundus tendon was harvested from the same porcine specimen and prepared to a uniform diameter of 3 mm. Both graft ends were whip-stitched with No. 2 FiberWire (Arthrex, Naples, FL, USA) (Fig. 3a). Two standardized 3-mm perforations were created in the meniscus, one on each side of the tear, 5 mm from the tear margin and 3–5 mm from the peripheral meniscal rim. Using an ACL tibial guide set at 55°, a 2.0-mm Kirschner wire was advanced from the anteromedial tibia to the tear site and over-reamed with a 6-mm reamer (Fig. 3b). The graft was passed through the two perforations to bridge the tear, and both graft limbs were delivered into the tibial tunnel (Fig. 3c). The graft was preloaded to 2 N and fixed with a 6 × 23-mm polyether ether ketone (PEEK) interference screw (AR-1360P; Arthrex). The screw was advanced within the tibial tunnel to lie immediately beneath the tibial plateau, with the fixation site located approximately 1 cm medial to the tibial tuberosity (Fig. 3d). The characteristics of the three constructs are summarized in Supplementary Table S1.

Biomechanical testing

All constructs were tested using the same protocol. The tibia was rigidly secured to the lower fixture of a universal testing machine (Cometech) equipped with a 20-kN load cell (model LRK-20KN; NTS Technology Co., Ltd.). The free anterior meniscal segment was clamped 10 mm from the tear using a clamping approach adapted from a previously described porcine testing model [15]. The posterior fragment remained attached to the tibia through the posterior root. Tensile loading was applied approximately perpendicular to the tibial plateau (Fig. 1a).

Each construct underwent monotonic tensile loading to failure at a crosshead displacement rate of 5 mm/min [9, 18]. Load and displacement data were recorded throughout testing. Ultimate load to failure (N), defined as the maximum load recorded before construct failure, was the primary outcome. Construct stiffness (N/mm) was calculated using ordinary least-squares linear regression of load against displacement between the first crossings of 20% and 80% of each specimen's ultimate load. Displacement at ultimate load (mm) was recorded using the machine encoder at each specimen's maximum load and represented overall construct displacement rather than direct tear-site gapping. Failure mode was determined by direct visual inspection, and the observed failure modes were categorized according to the component or interface at which failure occurred as suture failure, meniscal tissue failure, graft failure, tibial fixation failure, or tibial tunnel cut-through.

Sample size

An a priori sample size calculation used published ultimate-load data for porcine tendon-graft root repair (176.9 ± 46.0 N) [19] and Rebar radial tear repair (124.1 ± 27.1 N) [9], yielding Cohen's d = 1.40. Using a

normal approximation for two independent means, two-sided α = 0.05, and 80% power, 8.03 specimens per group were required, rounded up to nine (n = 9 per group; 27 total).

Statistical analysis

Statistical analyses were performed using StataNow/SE version 19.5 (StataCorp LLC, College Station, TX, USA). Continuous outcomes are presented as mean ± standard deviation (SD), with individual observations. Within-group distributions were assessed using Q-Q plots and the Shapiro-Wilk test. Groups were compared using Welch one-way analysis of variance and prespecified Games-Howell pairwise tests. Pairwise mean differences are reported with multiplicity-adjusted 95% confidence intervals (CIs) and p values. Failure modes are summarized as counts and percentages. All tests were two-sided, with adjusted $p < 0.05$ considered statistically significant.

Results

All 27 constructs were included in the analysis, with nine specimens in each group. Ultimate load to failure, construct stiffness, and displacement at ultimate load are summarized in Table 1. Individual ultimate-load values are presented in Figure 4, and specimen-level data are provided in Supplementary Table S2.

Ultimate load to failure

Mean ultimate load to failure was 122.6 ± 32.2 N for CSR, 249.3 ± 93.3 N for RTR, and 334.7 ± 73.6 N for TGR (Welch ANOVA, $p < 0.001$). Compared with CSR, ultimate load was higher by 126.8 N for RTR (Games–Howell-adjusted 95% CI, 36.4 to 217.2 N; $p = 0.008$) and by 212.1 N for TGR (adjusted 95% CI, 139.8 to 284.5 N; $p < 0.001$). The mean difference between TGR and RTR was 85.4 N (adjusted 95% CI, −17.4 to 188.1 N; $p = 0.112$), which was not statistically significant (Table 1).

Stiffness

Mean construct stiffness was 15.6 ± 5.0 N/mm for CSR, 14.7 ± 4.2 N/mm for RTR, and 20.9 ± 6.4 N/mm for TGR. The overall difference was not statistically significant ($p = 0.082$). TGR exceeded RTR by 6.2 N/mm, although this difference was not statistically significant (adjusted 95% CI, −0.5 to 12.8 N/mm; $p = 0.071$). Neither comparison with CSR was statistically significant (Table 1).

Displacement at ultimate load

Mean displacement at ultimate load was 11.7 ± 4.0 mm for CSR, 21.9 ± 8.7 mm for RTR, and 22.3 ± 5.8 mm for TGR, with a significant overall difference ($p < 0.001$). Displacement was significantly greater than CSR by 10.3 mm for RTR ($p = 0.020$) and 10.7 mm for TGR ($p = 0.001$). TGR and RTR did not differ significantly (mean difference, 0.4 mm; $p = 0.992$). Adjusted 95% CIs are presented in Table 1.

Failure mode

All nine CSR specimens failed by suture failure. In the RTR group, three specimens (33.3%) had suture failure, one (11.1%) had meniscal tissue failure, four (44.4%) had tibial fixation failure, and one (11.1%) had tibial tunnel cut-through. In the TGR group, seven specimens (77.8%) had meniscal tissue failure through the graft-passage perforations, one (11.1%) had graft failure, and one (11.1%) had tibial fixation failure (Table 2).

Discussion

The principal finding was that rip-stop transtibial pull-out repair (RTR) and interposition tendon graft reconstruction (TGR) achieved significantly higher time-zero ultimate loads to failure than cross-tag rip-stop suture repair (CSR), with mean loads approximately 2.0 and 2.7 times that of CSR, respectively. TGR showed the highest mean ultimate load but did not significantly outperform RTR, partially supporting the hypothesis. Construct stiffness did not differ significantly among groups. RTR and TGR reached ultimate load at significantly greater machine-recorded displacement than CSR, without a significant difference between them. Predominant failure modes also differed by construct.

The mean ultimate load to failure of CSR (122.6 N) was comparable to that reported for Rebar repair (124.1 ± 27.1 N) [9]. Nakanishi et al. found that modified cross tie-grip repair reduced cyclic displacement without significantly increasing ultimate load compared with the original technique [18]. McFarlane et al. and Bachmaier et al. also demonstrated biomechanical benefits of reinforced suture configurations [20, 21]. Together with a systematic review [22], these findings support the role of reinforcement geometry in improving the mechanical performance of radial meniscal repairs.

RTR sustained a significantly higher ultimate load than CSR, consistent with Bhatia et al., who reported higher median failure loads for transtibial 2-tunnel than double horizontal mattress repair (196 vs 106 N), with less cyclic gapping [10]. However, Buckley et al. found no significant differences in failure load or cyclic gapping among transtibial, hybrid rip-stop, and hybrid-tunnel repairs, although vertical rip-stop sutures reduced meniscal tissue cut-through [11]. The RTR construct evaluated here follows a similar principle to the combined rip-stop and transtibial pull-out technique described by Homan et al. [17]. Its performance may reflect the larger suture caliber, reinforcement geometry, transtibial load path, and cortical-button fixation. Zhang et al. found that inside-out and transtibial rip-stop repairs restored tibiofemoral contact mechanics without significant differences between approaches [23]. Thus, RTR's higher tensile strength does not establish an advantage in contact mechanics.

TGR sustained a significantly higher ultimate load than CSR but did not significantly outperform RTR (334.7 ± 73.6 vs 249.3 ± 93.3 N). Wu et al. reported lower failure loads for tendon-graft root reconstruction than transtibial pull-out repair (176.9 ± 46.0 vs 258 ± 45 N), despite greater stiffness and lower elongation at failure [19]. Construct geometry may partly explain this difference: their graft passed through a single incision near the detached root, whereas ours bridged two perforations on opposite sides of the radial tear, potentially distributing load across two graft–meniscus interfaces. Interference-screw fixation may also contribute, given its improved primary stability in a porcine root repair model

[24]. However, differences in testing and fixation preclude attributing TGR performance specifically to the graft.

Despite the differences in ultimate load, construct stiffness did not differ significantly among the three groups. RTR and TGR reached ultimate load at greater machine-recorded displacement than CSR (21.9 ± 8.7 and 22.3 ± 5.8 vs 11.7 ± 4.0 mm, respectively). This displacement represented movement of the entire construct and could be influenced by deformation of the meniscal tissue, stretching of the sutures or graft, settling at the tissue–construct and tibial fixation interfaces, and movement within the testing system [25]. It therefore does not necessarily indicate greater gapping at the radial tear. In TGR, the interposition graft provided a continuous bridge across the tear and may have allowed some deformation to be accommodated by the graft and its fixation interfaces while maintaining continuity between the two sides of the tear. However, tear-site gapping was not measured directly.

Failure patterns differed according to construct design. All CSR specimens exhibited suture failure, which may reflect the smaller-caliber No. 2 – 0 suture material and reliance on a suture-only repair. In RTR, four specimens had tibial fixation failure and one had tibial tunnel cut-through. The rip-stop configuration and larger No. 2 suture may have protected the meniscus-suture interface, allowing the tibial fixation or tunnel wall to become the limiting component. The predominance of tibial fixation failure in RTR is consistent with the findings of Spannagel et al., who reported tibial fixation failure as the most common failure mode overall in porcine transtibial root repair constructs [24]. TGR failed predominantly through the meniscal tissue at the graft-passage perforations (7 of 9 specimens), identifying the graft–meniscus interface as the principal failure site in this construct. However, these mechanisms were not tested independently and should be interpreted descriptively.

Beyond initial mechanical strength, tendon graft reconstruction may provide a tissue bridge capable of integration and remodeling. Animal studies have demonstrated fibrocartilage-like remodeling of tendon autografts after meniscal reconstruction [12, 13]. A retrospective clinical study also associated gracilis autograft reconstruction of medial meniscus posterior root tears with higher MRI-defined complete healing rates and better patient-reported outcomes than transtibial pull-out repair [14]. However, these studies evaluated meniscal deficiency or root tears rather than the two-sided radial tear reconstruction tested here. The potential benefits of TGR for healing and cartilage protection cannot be determined from time-zero testing and require further in vivo investigation.

Limitations

This study has several limitations. First, a porcine model was used, limiting direct extrapolation to human tissue. Previous biomechanical testing of meniscal root repairs demonstrated greater cyclic displacement and lower cyclic stiffness in human than porcine specimens [26]. In addition, the absence of an intact control group prevented assessment of whether the tested constructs restored native meniscal strength. Second, time-zero testing does not account for tissue healing, graft integration, or remodeling; therefore, the observed mechanical differences may not reflect long-term repair

performance. Third, monotonic load-to-failure testing did not assess construct behavior under repeated loading. Crosshead displacement reflected overall construct deformation rather than direct tear-site gapping. Further testing should directly measure tear-site gapping under joint loading [27] and assess meniscal extrusion [28]. Fourth, the constructs differed in suture caliber, repair configuration, and fixation method. The observed biomechanical differences therefore reflect the performance of the complete constructs, and the individual contributions of graft interposition, rip-stop reinforcement, and tibial fixation could not be determined. The constructs also differed in load path: RTR and TGR incorporated direct tibial fixation, whereas CSR relied on sutures spanning the tear and the retained posterior root attachment. The constructs were evaluated under tensile loading, which did not reproduce physiological hoop loading. Finally, the small sample size may have limited the ability to detect differences between RTR and TGR. The absence of a statistically significant difference in ultimate load to failure should therefore not be interpreted as evidence of equivalence.

Conclusions

Rip-stop transtibial pull-out repair and interposition tendon graft reconstruction achieved higher time-zero ultimate loads to failure than cross-tag rip-stop suture repair for complete radial tears of the posterior horn of the medial meniscus. Interposition tendon graft reconstruction showed the highest mean ultimate load to failure, although the difference from rip-stop transtibial pull-out repair was not statistically significant.

Declarations

Ethics approval and consent to participate

This study used porcine knees obtained from a commercial supplier after the animals had died. No live animals were used, and no animals were killed specifically for this study. The Institutional Review Board of the Faculty of Medicine Vajira Hospital, Navamindradhiraj University, issued a Certificate of Exemption for this study (COE 038/2025 X). Consent to participate was not applicable because the study did not involve human participants.

Consent for publication

Not applicable.

Availability of data and materials

Specimen-level biomechanical data are provided in Supplementary Table S2. Additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Authors' contributions

VW: Conceptualization, methodology, investigation, writing – original draft, writing – review and editing, and supervision. KJ: Conceptualization, methodology, investigation, formal analysis, visualization, writing – original draft, and writing – review and editing. IT and NK: Methodology, investigation, data curation, formal analysis, and writing – original draft. BC: Investigation and data curation. PA, CS, and NR: Resources and data curation. CSr: Supervision. All authors read and approved the final manuscript.

Acknowledgements

Not applicable.

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Tables

Table 1. Biomechanical outcomes

Outcome	CSR (n = 9)	RTR (n = 9)	TGR (n = 9)	Overall p
Ultimate load to failure (N)	122.6 ± 32.2	249.3 ± 93.3	334.7 ± 73.6	<0.001*
Stiffness (N/mm)	15.6 ± 5.0	14.7 ± 4.2	20.9 ± 6.4	0.082
Displacement at ultimate load (mm)	11.7 ± 4.0	21.9 ± 8.7	22.3 ± 5.8	<0.001*

Pairwise comparison	Load difference, N (adjusted 95% CI)	Adjusted p	Stiffness difference, N/mm (adjusted 95% CI)	Adjusted p	Displacement difference, mm (adjusted 95% CI)	Adjusted p
RTR − CSR	126.8 (36.4 to 217.2)	0.008*	−0.8 (−6.5 to 4.8)	0.923	10.3 (1.7 to 18.8)	0.020*
TGR − CSR	212.1 (139.8 to 284.5)	<0.001*	5.3 (−1.7 to 12.4)	0.152	10.7 (4.6 to 16.8)	0.001*
TGR − RTR	85.4 (−17.4 to 188.1)	0.112	6.2 (−0.5 to 12.8)	0.071	0.4 (−8.7 to 9.5)	0.992

Values are mean ± SD. Overall p values for ultimate load, stiffness, and displacement at ultimate load were obtained using Welch ANOVA. Pairwise comparisons used Games–Howell tests with multiplicity-adjusted 95% CIs and p values within each outcome. CI = confidence interval; CSR = cross-tag rip-stop suture repair; RTR = rip-stop transtibial pull-out repair; SD = standard deviation; TGR = tendon graft reconstruction.

*Statistically significant at $p < 0.05$; pairwise p values were adjusted using the Games–Howell method.

Table 2. Failure modes

Failure mode	CSR (n = 9)	RTR (n = 9)	TGR (n = 9)
Suture failure	9 (100.0)	3 (33.3)	0 (0.0)
Meniscal tissue failure	0 (0.0)	1 (11.1)	7 (77.8)
Graft failure	n/a	n/a	1 (11.1)
Tibial fixation failure	n/a	4 (44.4)	1 (11.1)
Tibial tunnel cut-through	n/a	1 (11.1)	0 (0.0)

Values are n (%). Failure modes were summarized descriptively. CSR = cross-tag rip-stop suture repair; RTR = rip-stop transtibial pull-out repair; TGR = tendon graft reconstruction; n/a = not applicable

(component absent in the construct).

Figures

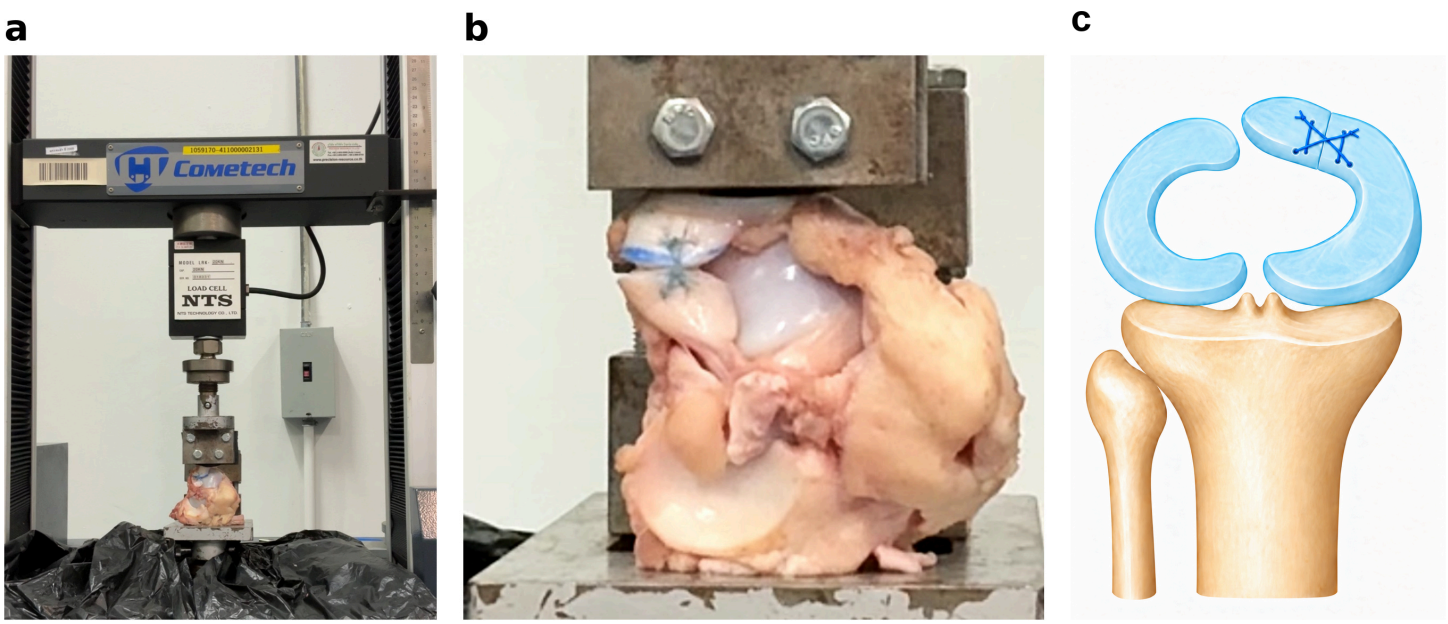

Figure 1

Biomechanical testing setup and cross-tag rip-stop suture repair. (a) Tibial fixation and meniscal clamping for tensile loading to failure. (b) Cross-tag rip-stop suture repair of a complete radial tear of the posterior horn of the medial meniscus mounted in the testing fixture. (c) Schematic illustration of the cross-tag rip-stop suture configuration.

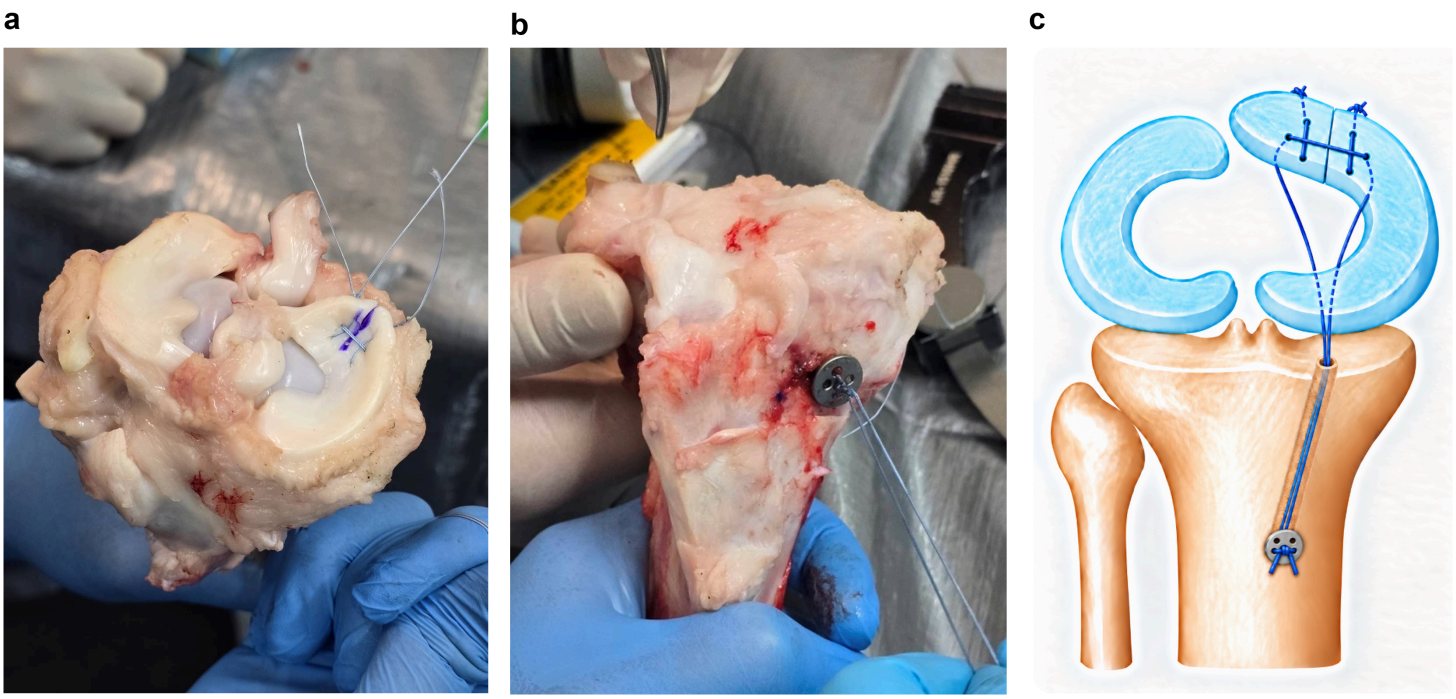

Figure 2

Rip-stop transtibial pull-out repair. (a) A vertical rip-stop suture on each side of the radial tear, with a horizontal suture spanning the tear over both reinforcing sutures. (b) Both limbs of the horizontal suture passed through a 6-mm tibial tunnel and secured over a cortical button on the anteromedial tibia. (c) Schematic illustration of the repair configuration and tibial fixation.

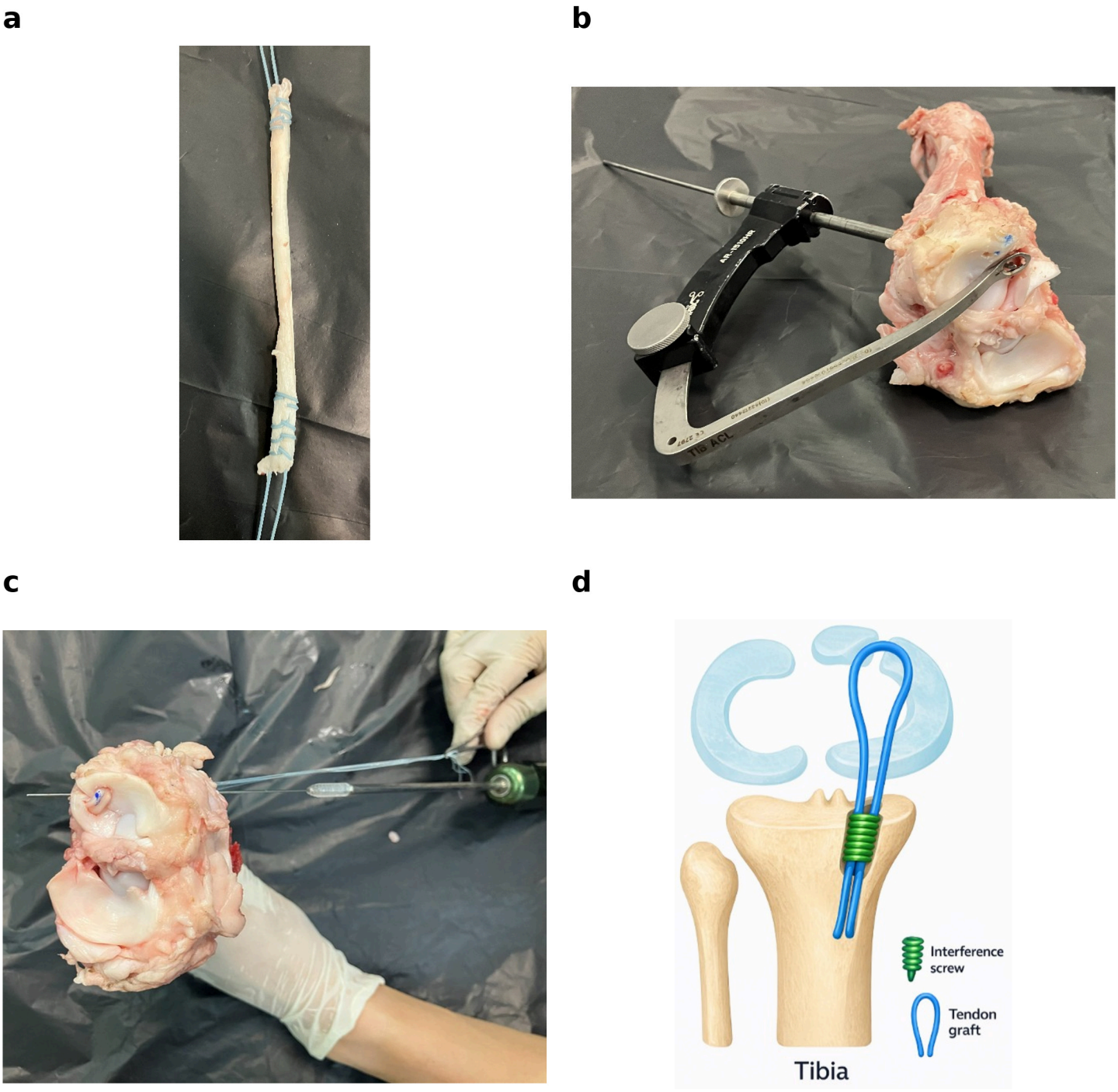

Figure 3

Interposition tendon graft reconstruction. (a) Flexor digitorum profundus tendon graft prepared to a diameter of 3 mm with whip-stitched ends. (b) Transtibial tunnel preparation using an ACL tibial guide. (c) Graft passed through meniscal perforations on either side of the tear before tibial fixation. (d) Schematic showing the graft bridging the radial tear and secured in a transtibial tunnel with an interference screw.

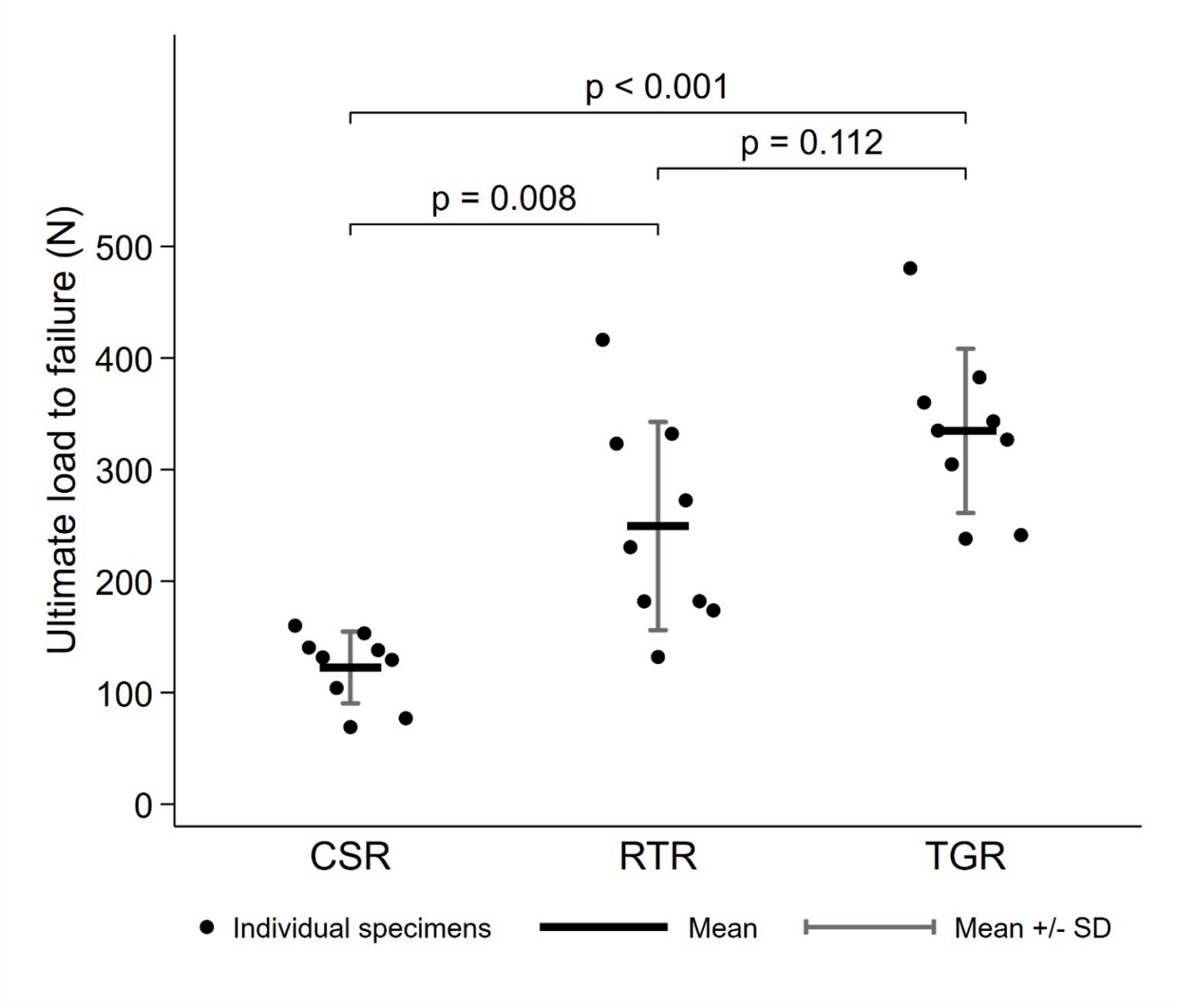

Figure 4

Ultimate load to failure by construct. Points represent individual specimens (n = 9 per group); horizontal bars and error bars indicate mean ± standard deviation. Brackets indicate Games–Howell-adjusted P values.

CSR = cross-tag rip-stop suture repair; RTR = rip-stop transtibial pull-out repair; TGR = tendon graft reconstruction.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryTableS2.docx
- SupplementaryTableS1.docx