Systematic Review

Proximal Hamstring Repairs Show Similar Load to Failure to Intact Hamstring Tendons: A Systematic Review and Meta-analysis of Biomechanical Investigations

James MacLeod, M.D., Michael S. Lee, B.A., Andrew Fallon, B.S.,
Stephen M. Gillinov, M.D., Nancy Park, M.D., Kevin Girardi, B.S., Jonas Vorbau, B.S.,
Jay Moran, M.D., Jessica M. Fritz, Ph.D., Anthony Nasser, Ph.D., Serkan Surucu, M.D., and
Andrew E. Jimenez, M.D.

Purpose: To review cadaveric studies evaluating the maximum load to failure after proximal hamstring repair with various numbers and sizes of anchors. **Methods:** The Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines were used when conducting this systematic review. PubMed, Cochrane Central Register of Controlled Trials (CENTRAL), and Scopus were queried in July 2024. Articles were included if they reported on the load to failure or maximum load in human cadavers undergoing proximal hamstring repair. Maximum load to failure was pooled among studies evaluating repairs compared with intact native hamstring tendons. The Biomechanics Objective Basic Science Quality Assessment Tool (BOBQAT) was used to score all articles. **Results:** Six studies reporting on 97 human cadaveric hemipelves undergoing open repair for proximal hamstring tears were included. The mean ages of cadavers ranged from 45.4 to 63.0 years. The mean maximum load to failure ranged from 183.3 to 1,164 N. Repairs showed no statistically significant difference in maximum load to failure when compared with native proximal hamstrings, with an effect size of −0.31 (95% confidence interval, −1.05 to 0.42; $P = .40$). **Conclusions:** Proximal hamstring repair shows a wide range of maximum loads to failure, with repaired hamstrings achieving loads to failure comparable to those of intact tendons. Repairs incorporating 3 or more anchors may improve load to failure. **Clinical Relevance:** Investigating the strength of proximal hamstring repair techniques can help surgeons identify which techniques may provide the strongest repair for patients. Proximal hamstring repairs show similar levels of load to failure compared with native hamstring tendons.

Proximal hamstring tears can be managed operatively or nonoperatively.[1-4] Operative treatment is recommended for tears of 2 or more tendons with significant retraction (>2 cm) and symptomatic injuries refractory to more than 6 months of nonoperative management.[5-7] Overall, the severity of the tear, clinical history, and level of retraction can be used to assess whether surgery is indicated. There have been a limited number of biomechanical investigations on factors that may maximize the strength of a proximal hamstring repair.[8,9] Anchor sizes,[10,11] numbers of anchors,[12,13] and operative techniques often differ between surgeons. Typically, 2 to 5 suture anchors, varying from 2.8 to 5.5 mm, are used to secure the torn hamstring to the ischium.[9,14] Studies have compared the effect of increased anchors on repair strength, with some showing significantly stronger repairs with more anchors.[9,15] Despite heterogeneity in repair techniques and technology,[7] reported patient outcomes are good.

A recent systematic review with 767 patients (96.5%) undergoing surgical management reported an over

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From the Department of Orthopaedic Surgery, Medical College of Wisconsin, Milwaukee, Wisconsin, U.S.A. (J. MacLeod, M.S.L., J.M.F.); Sacred Heart University, Fairfield, Connecticut, U.S.A. (A.F.); Department of Orthopaedics and Rehabilitation, Yale School of Medicine, New Haven, Connecticut, U.S.A. (S.M.G., N.P., K.G., J. Moran, S.S., A.E.J.); Quinnipiac University, Hamden, Connecticut, U.S.A. (J.V.); and University of Technology Sydney, Sydney, Australia (A.N.).

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Address correspondence to Andrew E. Jimenez, M.D., Department of Orthopaedics and Rehabilitation, Yale School of Medicine, 800 Howard Ave, First Floor, New Haven, CT 06519, U.S.A. E-mail: andrew.jimenez@yale.edu

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90% rate of patient satisfaction with a mean 85% rate of return of knee flexion strength compared with the contralateral leg.[16] Furthermore, multiple studies have shown return-to-sport rates of over 90%[17,18]—with 1 study reporting that 94.4% of athletes returned to the preinjury level[17]—as well as favorable postoperative patient-reported outcomes.[12,19] There has been little aggregate literature reporting on the maximum load to failure after proximal hamstring surgical repair and factors influencing repair success such as number and size of anchors used. Surgical technique is primarily dictated by surgeon comfort and experience.[7]

The purpose of this study was to review cadaveric studies evaluating the maximum load to failure after proximal hamstring repair with various numbers and sizes of anchors. It was hypothesized that proximal hamstring repair of complete hamstring tears in cadaveric specimens would result in similar loads to failure to intact tendons, regardless of repair technique.

Methods

This systematic review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines. This systematic review was prospectively registered in PROSPERO (CRD42024570826). PubMed, Cochrane Central Register of Controlled Trials (CENTRAL), and Scopus were queried for references on July 18, 2024. The following search strategy was used in PubMed: (hamstring OR biceps femoris OR semitendinosus OR semimembranosus) AND (repair) AND (cadaver OR biomechanic*). The detailed search strategy formatted and used for each database is recorded in Table 1. Articles were included in this systematic review if they reported on the load to failure or maximum load in human cadavers undergoing open proximal hamstring repair. Exclusion criteria included opinion articles, technique articles, reviews, infographics, in vivo studies, animal studies, and abstracts. All screening was performed using Covidence (Veritas Health Innovation, Melbourne, Australia). Titles and abstracts were reviewed by 2 independent authors (M.S.L., A.F.). A third independent author (A.E.J.), an orthopaedic surgeon specializing in hip preservation and sports medicine, resolved all conflicts. Titles and abstracts that met the inclusion criteria on initial screening underwent independent full-text review by M.S.L. and A.F. Any disagreements were resolved by a third independent reviewer (A.E.J.).

Quality Assessment

The Biomechanics Objective Basic Science Quality Assessment Tool (BOBQAT) was used to score all articles.[20] The BOBQAT is a 15-item scoring system with a maximum score of 100 and has been shown to be a valid and reliable method of assessing the quality of biomechanical studies.[20] A score of 90 to 100 was designated excellent quality, and scores between 80 and 89 were deemed good quality.[20] This tool includes scoring based on the inclusion of a clear and answerable purpose, demographic characteristics, specimen condition, appropriate bone density, reproducible technique, appropriate outcome measures, appropriate loading conditions, appropriate load magnitude, cyclic loading, sample size calculation, proper statistical analysis, results consistent with methods, limitations considered, conclusions based on results, and disclosure of funding and potential conflicts. Two independent reviewers (A.F., J.MacLeod) graded all articles in the review. Scoring discrepancies were resolved by a third independent reviewer (S.S.), an orthopaedic surgery sports surgeon.

Data Extraction

Data extraction was performed using a premade Microsoft Excel sheet (Microsoft Office 2011; Microsoft, Redmond, WA). The following data were extracted: first author, year of publication, number of hemipelves, sex of hemipelves, mean age of hemipelves, operative technique, surgical approach, number of anchors, anchor size, type of anchor, suture technique, load to failure, anterior and posterior displacement, failure strain, failure location, mechanism of failure, stiffness,

Table 1. Article Search Strategies for Databases

Database	Search String	Results
PubMed	(hamstring OR biceps femoris OR semitendinosus OR semimembranosus) AND (repair) AND (cadaver OR biomechanic*)	174
Cochrane Central Register of Controlled Trials	1. (hamstring):ti,ab,kw OR (biceps femoris):ti,ab,kw OR (semitendinosus):ti,ab,kw OR (semimembranosus):ti,ab,kw 2. (repair):ti,ab,kw 3. (cadaver):ti,ab,kw OR (biomechanic*):ti,ab,kw	18
Scopus	(TITLE-ABS-KEY (hamstring) OR TITLE-ABS-KEY (biceps AND femoris) OR TITLE-ABS-KEY (semitendinosus) OR TITLE-ABS-KEY (semimembranosus) AND TITLE-ABS-KEY (repair) AND TITLE-ABS-KEY (cadaver) OR TITLE-ABS-KEY (biomechanic*))	198

ab, abstract; ABS, abstract; KEY, keyword; kw, keyword; ti, title.

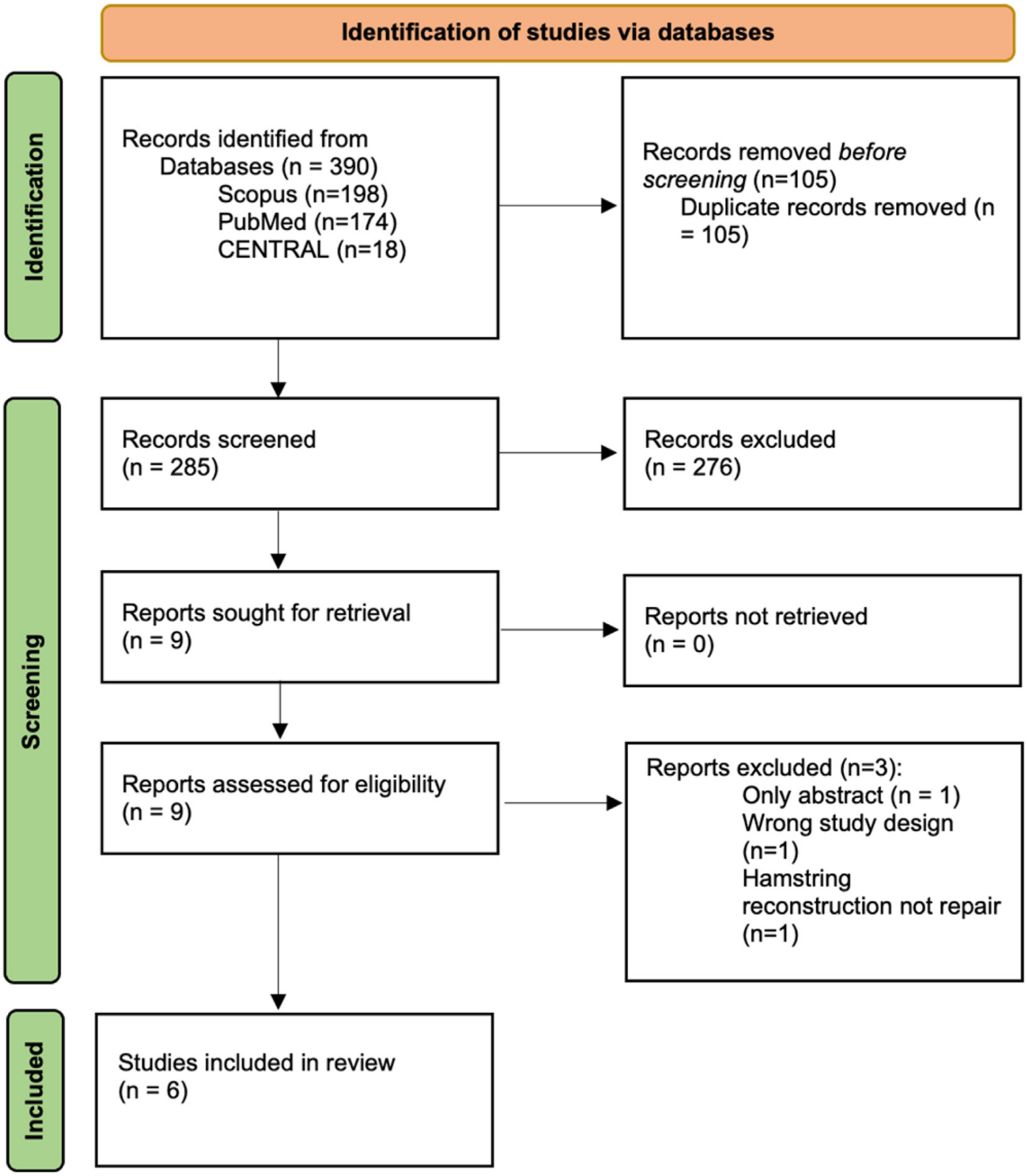


Fig 1. Article selection flowchart. (CENTRAL, Cochrane Central Register of Controlled Trials.)

cycling methodology, and type of suture used. Data were extracted by 2 independent authors (A.F., J.MacLeod). Discrepancies in extracted data were resolved by a third independent reviewer (A.E.J.).

Statistical Analysis

Meta-analysis was performed, and standard mean differences were calculated for load to failure of hamstring repairs compared with native hamstrings. The hamstring repair technique with the highest load to failure within studies was used for comparison. Mean load to failure and standard deviation were extracted from comparative studies reporting on anchor number and size, but these data were not pooled. Statistical analysis was performed in RevMan (version 5.4 [2020 release]; The Cochrane Collaboration, London, England). The random-effects model was chosen to incorporate study-based heterogeneity into the summative calculations. Heterogeneity was evaluated with the I^2 statistic using the cutoffs from the *Cochrane Handbook for Systematic Reviews of Interventions*.[21] The level of statistical significance was defined as $P < .05$.

Results

Study Selection

Querying PubMed, CENTRAL, and Scopus yielded 390 studies. After duplicates were removed, 285 articles

Table 2. Study Characteristics

Study	Study Subgroups	Hemipelves	Sex	Mean Age, yr	BOBQAT Score
Campbell et al.,[15] 2017	(1) Three 2.8-mm anchors (2) Five 2.8-mm anchors (3) Three 5.5-mm anchors (4) Five 5.5-mm anchors (5) Intact hamstring	21 hemipelves comprising 3 repairs with three 2.8-mm anchors, 5 repairs with five 2.8-mm anchors, 3 repairs with three 5.5-mm anchors, 5 repairs with five 5.5-mm anchors, and 5 intact hamstrings	"Even gender split"	62.5 (49-67)	93
Gerhardt et al.,[22] 2019	(1) Repair with knotted sutures (2) Repair with knotless sutures (3) Intact hamstring	17 hemipelves, comprising 5 all-knotted repairs, 6 all-knotless repairs, and 6 intact hamstrings	17 male	— (52-89)	93
Harvey et al.,[24] 2015	(1) Specimen at 0° (2) Specimen at 45° (3) Specimen at 90°	24 hemipelves, comprising 8 repairs at 0°, 8 repairs at 45°, and 8 repairs at 90°	NR	NR	93
Otto et al.,[23] 2020	(1) Titanium suture anchor (2) All-suture anchor	18 hemipelves, comprising 9 repairs with titanium suture anchors and 9 repairs with all-suture anchors	8 male and 10 female	63.0 ± 10.4	100
Ryan et al.,[8] 2019	Open repair	10 hemipelves, consisting of 10 open repairs	5 male and 5 female	45.4 (39-51)	90
Hamming et al.,[9] 2015	(1) Two small anchors (2.9 mm) (2) Two large anchors (5.5 mm) (3) Five small anchors (2.9 mm) (4) Native hamstring	24 hemipelves, comprising 6 repairs with 2 small anchors, 6 repairs with 2 large anchors, 6 repairs with 5 small anchors, and 6 native hamstrings	24 male	54.5 (34-63)	90

NOTE. Data are reported as mean ± standard deviation (range).
BOBQAT, Biomechanics Objective Basic Science Quality Assessment Tool; NR, not reported.

underwent title and abstract screening, with 9 studies advancing to full-text review. Of the 9 studies that underwent full-text review, 6 were included in the systematic review.[8,9,15,22-24] All included studies were cadaveric studies and assigned Level V evidence based on previous guidelines.[25] The article selection process is detailed in Figure 1.

Study Characteristics

Six studies reporting on 97 human cadaveric hemipelves undergoing repair of proximal hamstring tears were included.[8,9,15,22-24] Two studies used hemipelvis pairs from the same donors.[8,23] Five studies performed open proximal hamstring repair,[9,15,22-24] and one study performed open and endoscopic proximal hamstring repair[8]; only the open repairs from the latter study were included in this analysis. The mean ages of cadavers ranged from 45.4 years[8] to 63 years.[23] Among the 5 studies reporting sex, there were 50 male and 23 female hemipelves undergoing repair and 15 male and 2 female intact hamstring hemipelves.[8,9,22-24] The BOBQAT scores for all studies were 90 or higher out of a possible 100.[20] Scores ranged from 90[8,9] to 100.[23] Study characteristics are reported in Table 2.

Proximal Hamstring Repair Characteristics

The number of anchors used in hamstring repairs ranged from 2 anchors[9] to 5 anchors.[15] In studies comparing numbers of anchors used, mean load to failure ranged from 284.7 N[15] to 502.4 N[15] for 3 or fewer anchors and from 183.3 N[15] to 1,164 N[9] for more than 3 anchors; pooling was not reported because of high heterogeneity ($I^2 = 81\%$) (Appendix Fig 1). Anchor sizes in hamstring repairs ranged from 2.6 mm[23] to 5.5 mm.[9,15,22,23] In studies comparing sizes of anchors used, mean load to failure ranged from 183.3 N[15] to 799.64 N[23] for small anchors (<3 mm) and from 490.8 N[15] to 573.27 N[23] for large anchors (>5 mm); pooling was not reported because of high heterogeneity ($I^2 = 78\%$) (Appendix Fig 2). Four studies used knotted anchors,[9,15,23,24] whereas 2 studies used knotted and knotless anchors.[8,22] Details regarding surgical technique are reported in Table 3.

Load to Failure

Load to failure ranged from 183.3 N[15] to 1,164 N[9] (Fig 2). Some studies compared the load to failure of surgically repaired hamstrings with native hamstrings[9,15,22] and/or evaluated the effects of anchor size[9,15,23] and number of anchors[9,15] on load to failure. Load-to-failure values are listed in Table 4, and cycling methodology is recorded in Table 5.

Pooled repairs with the highest loads to failure in comparative studies showed no statistically significant difference in maximum load to failure when compared with native proximal hamstrings, with an effect size of

Table 3. Characteristics of Anchors and Sutures Used in Repair

Study	No. of Anchors	Size of Anchor	Knotted or Knotless Anchors	Suture Technique and Anchor Placement	Type of Suture
Campbell et al.,[15] 2017	(1) Three anchors (2) Five anchors (3) Three anchors (4) Five anchors	(1) 2.8 mm (2) 2.8 mm (3) 5.5 mm (4) 5.5 mm	Knotted	Modified Krackow with triangle in groups 1 and 3 (3 anchors) and X configuration in groups 2 and 4 (5 anchors)	Nonabsorbable No. 2 UHMWPE sutures (Ultrabraid; Smith & Nephew, Andover, MA)
Gerhardt et al.,[22] 2019	(1) Three anchors (knotted) (2) Four anchors (knotless)	(1) 5.5 mm (knotted) (2) 4.75 mm (knotless)	(1) Knotted (2) Knotless	Krackow with (1) triangle and (2) rectangle	(1) Knotted: 1.3-mm-wide UHMWPE nonabsorbable suture (SutureTape; Arthrex, Naples, FL) (2) Knotless: 2.0-mm-wide UHMWPE nonabsorbable suture (FiberTape; Arthrex), as well as UHMWPE nonabsorbable braided suture (No. 2 FiberWire; Arthrex)
Harvey et al.,[24] 2015	3 anchors	2.9 mm	Knotted	Krackow with equal spacing on anatomic footprint	No. 2 Orthocord (DePuy Mitek, Raynham, MA) with 4 throws on each side of tendon
Otto et al.,[23] 2020	3 anchors	2.6 mm for all-suture anchor and 5.5 mm for titanium anchor	Knotted	Krackow with inline placement	Titanium anchor: No. 2 FiberWire All-suture anchor: 1.3-mm SutureTape loaded into each all-suture anchor
Ryan et al.,[8] 2019	4 anchors	3.0 mm (n = 2) and 3.75 mm (n = 2)	Knotted (n = 2) and knotless (n = 2)	Double row with diamond configuration	No details on suture itself; 2 double-loaded 3.0-mm PEEK (polyether ether ketone) suture anchors (Arthrex) and two 3.75-mm PEEK knotless screw-in anchors (Arthrex)
Hamming et al.,[9] 2015	(1) Two small anchors (2) Two large anchors (3) Five small anchors	(1) 2.9 mm (2) 5.5 mm (3) 2.9 mm	Knotted	Modified Kessler with line in groups 1 and 2 and Y shape in group 3	Nonabsorbable No. 2 UHMWPE sutures (Ultrabraid) in all groups

UHMWPE, ultrahigh-molecular-weight polyethylene.

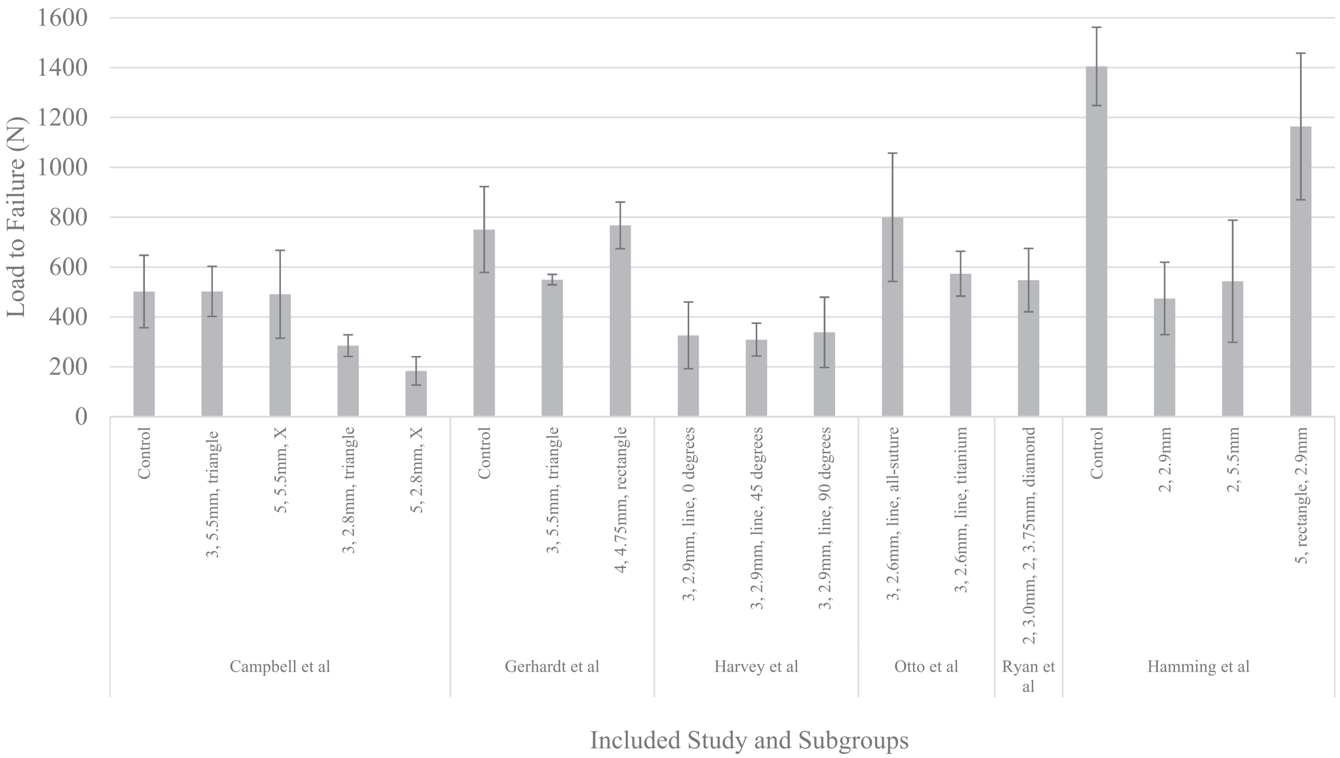


Fig 2. Load to failure of all native (control) and repaired hamstring subgroups by study, including number of anchors and size of anchors. Error bars display standard deviations.

−0.31 (95% confidence interval, −1.05 to 0.42; $P =$ .40) and heterogeneity (I^2) of 0%, as shown in Figure 3. These subgroups were reported in the studies by Campbell et al.,[15] with repairs using three 5.5-mm anchors (502.4 ± 100.6 N; range, 394-610 N); Gerhardt et al.,[22] with repairs using four 4.75-mm knotless anchors (767.18 ± 93.50 N); and Hamming et al.,[9] with repairs using five 2.9-mm anchors (1,164 ± 294 N). In terms of repair characteristics, the lowest mean load to failure (183.3 N; range, 118-220 N) was seen in hamstring repairs using five 2.8-mm anchors via an X suture configuration.[15]

Displacement

Six studies reported anterior displacement,[8,9,15,22-24] and one study reported posterior displacement.[23] Because the site of hamstring tendon attachment is large, displacement can be reported from the most anterior site of repair and/or the most posterior site.[23] Mean anterior displacement ranged from 2.39 mm[24] to 32.64 mm.[9] Posterior displacement values for all-suture anchors and titanium anchors were 5.87 mm and 5.23 mm, respectively.[23] Displacement values are recorded in Table 4.

Mechanism and Location of Failure

Four studies reported mechanisms of failure for surgical hamstring repair.[22-24] One study reported that all failures occurred at the tendon—bone—suture anchor interface,[15] whereas another study reported that 17 of 24 repairs failed because of knot or suture failure.[24] One study reported that 4 of 5 knotted anchor hamstring repairs failed at the footprint whereas 5 of 6 hamstring repairs using knotless anchors failed at the musculotendinous junction.[22] Failure characteristics are listed in Table 6.

Discussion

The main findings of this study were as follows: (1) Proximal hamstring repair shows a wide range of maximum loads to failure, with repaired hamstrings achieving comparable loads to failure to intact tendons. (2) Repairs with the highest loads to failure incorporated 3 or more anchors. However, pooled analysis of anchor size and number was not possible because of low sample size and high heterogeneity. Results confirmed the primary hypothesis that proximal hamstring repairs of complete hamstring tears would show mean loads to failure similar to those of the native hamstring tendons. Additionally, the findings do not indicate an optimal anchor size, nor do they indicate that increasing the number of anchors beyond 3 definitively results in superior repair, so surgeons should use their clinical judgment and personal preference when making these decisions. Quality

Table 4. Location and Force of Failure in Study Groups

Study	Study Subgroup	Load to Failure	Anterior Displacement	Posterior Displacement
Campbell et al.,[15] 2017	(1) 2.8-mm anchors (n = 3) (2) 2.8-mm anchors (n = 5) (3) 5.5-mm anchors (n = 3) (4) 5.5-mm anchors (n = 5)	(1) Three (triangle) 5.5 mm: 502.4 ± 100.6 N (394-610 N) (*P* = .95) (2) Five (X configuration) 5.5 mm: 490.8 ± 176.3 N (255-650 N) (*P* = .87) (3) Three (triangle) 2.8 mm: 284.7 ± 43.4 N (245-331 N) (*P* < .05) (4) Five (X configuration) 2.8 mm: 183.3 ± 56.7 N (118-220 N) (*P* < .05) (5) Control: 501.8 ± 145.3 N (401-723 N)	(1) Three (triangle) 2.8 mm: initial gap formation of 3.29 mm (1.36-4.84 mm); mean, 10.3 mm (4-16 mm) after cyclical loading (2) Five (X configuration) 2.8 mm: initial gap, 3.27 mm (1.5-5.1 mm); 9.9 mm after loading (6.3-17 mm) (3) Three (triangle) 5.5 mm: 58 cycles to gap formation with initial gapping of 0.60 mm (0-2.9 mm); 5.7 mm (2.7-8 mm) after cyclic loading (4) Five (X configuration) 5.5 mm: 110 cycles to gap formation with initial gap of 0.44 mm (0-2.18 mm); 5.6 mm after cyclic loading (2.4-8.7 mm)	NR
Gerhardt et al.,[22] 2019	(1) Knotted (2) Knotless (3) Control	(1) Knotted: 549.56 ± 20.74 N (2) Knotless: 767.18 ± 93.50 N (*P* = .248 vs control, *P* = .024 vs knotted) (3) Control: 750.58 ± 172.22 N	All constructs survived initial cyclic loading (1) Knotted: 15.12 ± 6.30 mm (*P* = .005 vs control and knotless) (2) Knotless: 5.75 ± 3.13 mm (*P* = .866 vs control) (3) Control: 5.33 ± 2.66 mm	NR
Harvey et al.,[24] 2015	(1) 0° (n = 8) (2) 45° (n = 8) (3) 90° (n = 8)	No significant differences (1) 0°: 326 ± 134 N (2) 45°: 309 ± 66 N (3) 90°: 338 ± 131 N	(1) 0°: 2.39 mm (2) 45°: 3.03 mm (3) 90°: 4.19 mm	NR
Otto et al.,[23] 2020	(1) All-suture anchor (2) Titanium suture anchor	(1) All-suture anchor: 799.64 ± 257.1 N (*P* = .008) (2) Titanium suture anchor: 573.27 ± 89.9 N	(1) All-suture: 6.60 ± 2.2 mm after 1,500 cycles (2) Titanium suture anchor: 5.49 ± 1.1 mm (*P* = .260) after 1,500 cycles	(1) All-suture anchor: 5.87 ± 2.08 mm (2) Titanium suture anchor: 5.23 ± 1.37 mm (*P* = 678)
Ryan et al.,[8] 2019	Open	Open: 547.4 ± 127.0 N Cycles to failure: 119 ± 32 N	Failure displacement Open: 12.7 ± 5.15 mm (authors noted that there was no displacement before failure)	NR
Hamming et al.,[9] 2015	(1) Two small anchors (n = 6) (2) Two large anchors (n = 6) (3) Five small anchors (n = 6) (4) Control (n = 6)	(1) Two small: 474 ± 145 N, with 81 ± 39 cycles to failure (2) Two large: 543 ± 245 N, with 98 ± 70 cycles to failure (3) Five small: 1,164 ± 294 N, with 259 ± 80 cycles to failure (4) Intact: 1,405 ± 157 N, with 326 ± 43 cycles to failure	(1) Two small: 7.36 ± 4.71 mm at 50th cycle (25-200 N), 21.99 ± 6.67 at maximum cyclic load (2) Two large: 6.52 ± 3.92 mm at 50th cycle (25-200 N), 20.11 ± 7.86 at maximum cyclic load (3) Five small: 4.44 ± 2.72 mm at 50th cycle (25-200 N), 32.64 ± 7.99 at maximum cyclic load (4) Intact: 1.14 ± 0.57 mm at 50th cycle (25-200 N), 22.34 ± 6.51 mm at maximum cyclic load	NR

NOTE. Data are reported as mean ± standard deviation (range).
NR, not reported.

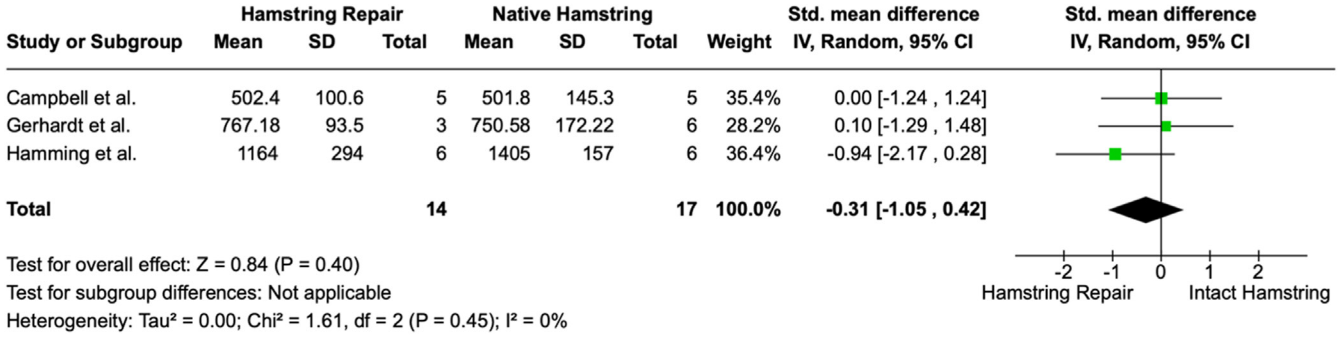
Table 5. Cycling Methodology and Measurement Methods of Studies

Study	Cycling Methodology and Measurement Methods
Campbell et al.,[15] 2017	Cyclic axial loading, 150 and 350 N, with 1-Hz frequency; up to 500 cycles Gap formation assessed using digital photography and ImageJ (National Institutes of Health, Bethesda, MA) analysis after initial 250-N load was applied and again at conclusion of cyclic loading Specimens then loaded to failure at 33 mm/s
Gerhardt et al.,[22] 2019	10-N preload applied before cyclic loading Sinusoidal function, 20 and 200 N, with 0.5-Hz frequency; 100 cycles Tendon displacement measured before post-cyclic loading Specimens then loaded to failure at 33 mm/s
Harvey et al.,[24] 2015	5-N preload held for 5 s Cyclically loaded, 10-125 N, with 1-Hz frequency; 1,500 cycles Specimens loaded at constant rate of 120 mm/min, and failure determined if displacement exceeded 3 mm
Otto et al.,[23] 2020	5-N preload held for 5 s Cyclically loaded, 10-125 N, with 1-Hz frequency; 1,500 cycles Load to failure performed after last cycle at constant rate of 120 mm/min.
Ryan et al.,[8] 2019	Nominal 1-N manual preload Cyclically ramped, 0 and 200 N, 50 cycles, followed by 50 cycles, 200 and 400 N Pattern of increasing 200-N load ranges repeated until specimen failed
Hamming et al.,[9] 2015	Preload cycle, 10-100 N, to estimate cyclic stiffness After preload, cyclic loading, 25 N, with 1-Hz frequency increased by 200 N every 50 cycles, to a maximum of 1,600 N

assessment scores were high for all included studies, with BOBQAT scores ranging from 90[8,9] to 100.[23]

Our review found that surgically repaired hamstrings showed similar loads to failure to native intact hamstring tendons. The effect size was −0.31 (95% confidence interval, −1.05 to 0.42; $P = .40$) with heterogeneity of $I^2 = 0\%$. These results are similar to the findings of a recent article reporting that pectoralis major tendon repairs with acellular dermal matrix augmentation have similar loads to failure to intact pectoralis major tendons.[26] However, the literature is not consistent across tendon sites given that a recent systematic review reporting on triceps repairs observed that intact tendons have higher loads to failure.[27] It is important to note that one-third of the comparative studies in our review reported negative effect sizes, nonsignificantly favoring higher loads to failure in native tendons.

Load to failure varied between different proximal hamstring repair techniques. Our study reported a range in load to failure from 183.3 N[15] to 1,164 N[9] for hamstring repairs. The lowest load to failure, 183.3 N (range, 118-220 N), was seen in hamstring repairs using five 2.8-mm anchors via an X suture configuration.[15] The study by Campbell et al.[15] found that hamstring repairs using three or five 2.8-mm anchors resulted in significantly lower loads to failure when compared with native hamstrings and hamstrings repaired with 5.5-mm anchors. Smaller anchor sizes have been previously associated with lower loads to failure.[28] A recent study comparing the sizes of anchors in biceps tenodesis found that 2.6-mm anchors resulted in significantly higher loads to failure than 1.9- and 1.6-mm anchors.[28] However, it is also important to note that the highest mean load to failure, 1,164 ± 294 N, was seen in hamstring repairs



	Hamstring Repair			Native Hamstring				Std. mean difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Campbell et al.	502.4	100.6	5	501.8	145.3	5	35.4%	0.00 [-1.24 , 1.24]
Gerhardt et al.	767.18	93.5	3	750.58	172.22	6	28.2%	0.10 [-1.29 , 1.48]
Hamming et al.	1164	294	6	1405	157	6	36.4%	-0.94 [-2.17 , 0.28]
Total			**14**			**17**	**100.0%**	**-0.31 [-1.05 , 0.42]**

Test for overall effect: Z = 0.84 (P = 0.40)
Test for subgroup differences: Not applicable
Heterogeneity: Tau² = 0.00; Chi² = 1.61, df = 2 (P = 0.45); I² = 0%

Fig 3. Forest plot depicting comparative studies reporting hamstring load to failure of native hamstring and best-performing repair. The subgroups were reported in the studies by Campbell et al.,[15] with repairs using three 5.5-mm anchors; Gerhardt et al.,[22] with repairs using four 4.75-mm knotless anchors; and Hamming et al.,[9] with repairs using five 2.9-mm anchors. (CI, confidence interval; IV, inverse variance; Random, random effects; SD, standard deviation; Std, standardized.)

Table 6. Characteristics of Failures

Study	Study Subgroup	Failure Strain	Mechanism and Location of Failure	Stiffness
Campbell et al.,[15] 2017	(1) 2.8-mm anchors (n = 3) (2) 2.8-mm anchors (n = 5) (3) 5.5-mm anchors (n = 3) (4) 5.5-mm anchors (n = 5)	NR	Repairs: all failures at tendon—bone—suture anchor interface Control: all failures at musculotendinous junction	NR
Gerhardt et al.,[22] 2019	(1) Knotted (2) Knotless (3) Control	NR	(1) Knotted: 4 of 5 at footprint and 1 of 5 due to suture anchor pullout (2) Knotless: 5 of 6 at musculotendinous junction and 1 of 6 from footprint	NR
Harvey et al.,[24] 2015	(1) 0° (n = 8) (2) 45° (n = 8) (3) 90° (n = 8)	NR	Knot/suture failure in 17 of 24 and anchor pullout in 6 of 24	NR
Otto et al.,[23] 2020	(1) All-suture anchor (2) Titanium suture anchor	NR	(1) All-suture anchor: soft-tissue tearing (n = 3), mid-suture section (n = 6) (2) Titanium suture anchor: anchor pullout (n = 2), suture-anchor interface (n = 7)	(1) All-suture anchor: 33.67 ± 8.99 N/mm (*P* = .374) (2) Titanium suture anchor: 37.09 ± 8.11 N/mm
Ryan et al.,[8] 2019	Open	0.81 ± 0.70 mm/mm	NR	NR
Hamming et al.,[9] 2015	(1) Two small anchors (n = 6) (2) Two large anchors (n = 6) (3) Five small anchors (n = 6) (4) Control (n = 6)	NR	NR	(1) Two small: 45 ± 10 N/mm at first cycle (25-200 N), 91 ± 22 at 50th cycle (25-200 N) (2) Two large: 49 ± 14 N/mm at first cycle (25-200 N), 89 ± 24 at 50th cycle (25-200 N) (3) Five small: 47 ± 17 N/mm at first cycle (25-200 N), 99 ± 13 at 50th cycle (25-200 N) (4) Intact: 104 ± 47 N/mm at first cycle (25-200 N), 127 ± 48 at 50th cycle (25-200 N)

NOTE. Data are reported as mean ± standard deviation (range).
NR, not reported.

using five 2.9-mm anchors.[9] Beyond anchor size, differing placement locations, methods of suture passage, and suture configurations may influence repair strength as described in the previously mentioned X placement technique.[15] These results show that anchor size may not influence load to failure and further research is needed to assess whether there is benefit in using more anchors during hamstring repair. Assessment of anchor-specific performance was limited by anchor type not being controlled for, especially given that load to failure was measured at time zero, which could prevent anchor integration or not account for loosening with time.

Our review found that the hamstring repair groups with the highest loads to failure incorporated 3 or more anchors. These subgroups were reported in the studies by Campbell et al.,[15] with repairs using three 5.5-mm anchors; Gerhardt et al.,[22] with repairs using four 4.75-mm knotless anchors; and Hamming et al.,[9] with repairs using five 2.9-mm anchors. Hamming et al. compared repairs using 2 anchors, repairs using 5 anchors, and intact hamstrings. They found significantly higher loads to failure in the 5-anchor repair group and native hamstring group compared with the 2-anchor repair group. A previous review found that a greater number of anchors was associated with higher load to failure in triceps repair.[29] One study included in our systematic review showed a significant effect size of −2.75 (95% confidence interval, −4.50 to −0.99), favoring higher loads to failure with more anchors,[9] whereas one study reported that the number of anchors did not influence repair strength for 2.8-mm and 5.5-mm anchors.[15] These results show that further studies are necessary to determine whether extra anchors result in superior repair strength but that some of the literature supports using 3 or more anchors for hamstring repair.

Future reviews should seek opportunities to pool hamstring repair technique variables with minimal heterogeneity. Additionally, further analysis is warranted to determine whether the conclusions of this review hold across different surgical techniques, given that the number of anchors, anchor material, and size of anchors may influence the load to failure of repair differently depending on surgical technique.

Limitations

This review is not without limitations. First, the sample sizes and number of studies included were low, limiting the power of the findings. Second, attempted pooling of data by number and size of anchors used resulted in few studies and high heterogeneity values, and thus, this was not reported. Additionally, interpreting load-to-failure values for cadaveric hamstring studies is limited by several factors. Hamstring tissue is viscoelastic, which causes it to be rate-dependent, and studies used various cycling methodologies, including different initial preloads and numbers of cycles, which may influence load to failure. Muscle size can vary in patients, and the sex and average age of hemipelves could affect strength. In fact, intact hemipelves used in this study were disproportionately male, which could increase load to failure for this group (i.e., control group). Moreover, studies did not uniformly account for age in their statistical analyses. All hamstrings were loaded statically, which is not representative of the multidirectional dynamic loading experienced by surgically repaired hamstrings in patients. Finally, variability in cadaveric preparation and differences between specimens may influence bone quality and soft-tissue characteristics, which could influence results, although all included studies were deemed high quality by the BOBQAT scoring method, which includes these factors.[20]

Conclusions

Proximal hamstring repair shows a wide range of maximum loads to failure, with repaired hamstrings achieving loads to failure comparable to those of intact tendons. Repairs incorporating 3 or more anchors may improve load to failure.

Disclosures

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