A Critical Biomechanical Evaluation of Foot and Ankle Soft Tissue Repair

Sara Mateen, DPM[a], Laura E. Sansosti, DPM, FACFAS[b],
Andrew J. Meyr, DPM, FACFAS[b,*]

KEYWORDS

- Mechanical testing • ATFL • Talocalcaneonavicular • Plantar metatarsophalangeal • Tendon repair • Ligamentous repair

KEY POINTS

- To understand the normal biomechanical forces extending through lower extremity soft tissue structures during physiologic function.
- To understand the biomechanical evaluation of repair techniques with mechanical testing.
- To recognize common limitations in the mechanical testing literature.
- To appreciate the difference between statistically significant and clinically significant differences in the biomechanical testing literature.

INTRODUCTION

History has demonstrated that, on balance, Sir Isaac Newton was full of it. An isolated eccentric who spent much of his time considering alchemy, the occult and doomsday prophecies, his initially groundbreaking discourses about “gravity” as an invisible and intangible force have long been demonstrated inaccurate by Albert Einstein and future generations of physicists.[1–8] Despite this, it is difficult to critically analyze the medical literature with respect to the biomechanical properties of lower extremity soft tissue repair without first understanding the unit of force for which he serves as an eponym:

- A “Newton (N)” is defined as the force required to accelerate 1 kg mass at a rate of 1 m/s^2, and
- A “Newton meter (Nm)” is a measurement of torque resulting from 1 N force applied to a 1-m moment arm.

---

[a] Temple University Hospital Podiatric Surgical Residency Program, Philadelphia, PA, USA; [b] Department of Podiatric Surgery, Temple University School of Podiatric Medicine, Philadelphia, PA, USA
* Corresponding author. TUSPM Department of Surgery, 148 North 8th Street, Philadelphia, PA 19107.
E-mail address: ajmeyr@gmail.com

Clin Podiatr Med Surg 39 (2022) 521–533
https://doi.org/10.1016/j.cpm.2022.02.011
podiatric.theclinics.com

Although these serve as among the most frequently cited outcome measures in mechanical testing investigations, they are neither easily conceptualized nor readily applicable in terms of clinical evaluation.

With that said, however, any foot and ankle surgeon is able to develop a better understanding of these units without having to dive too deeply into the principles of physics. In fact, it is not much more complicated than the more familiar formula: pressure = force/area. Put simply, higher forces and smaller areas lead to increased pressure. The Newton unit of force is somewhat more complex in that it involves the extra dimensions of speed and distance, but the general concept is the same. Higher weights, faster speeds, and greater distances of structure contraction/extension all lead to higher force when considering the Newton. The inherent value of the unit is that it is a more dynamic and responsive measure of force, and of course the foot and ankle is a very dynamic functional anatomic area with varying forces exerted through numerous anatomic structures and in a variety of clinical situations.

The objective of this review is to provide a practical critical assessment of the literature with respect to soft tissue repair techniques in the foot and ankle. We will first review the typical forces expected through anatomic structures during their normal function, and then use this as a guide to evaluate reconstruction techniques and protocols. We hope that this will also further allow critical readers to interpret the distinction between statistically significant and clinically significant differences in the literature. For example, statistically significant differences that would not be expected to affect medical decision-making might be argued to be of little clinical value. The specific anatomic structures of the Achilles tendon, anterior tibiofibular ligament, plantar metatarsophalangeal ligament (plantar plate or plantar pad), and calcaneonavicular ligament (spring ligament) will be reviewed.

ACHILLES TENDON

The Achilles tendon almost certainly represents the lion's share of the published literature with respect to the mechanical testing analysis of lower extremity soft tissue reconstruction, and we have hopefully progressed far beyond Hippocrates' description of "this tendon, if bruised or cut, causes the most acute fevers, induces choking, deranges the mind and at length brings death".[9] Generally considered the strongest and thickest tendon in the body, the length ranges between 11 and 26 cm with a width of 4.5 to 8.6 cm.[9,10] It is comprised primarily of type 1 collagen; however, type 3 collagen is more commonly found following rupture or injury.[9] Along the tendon's length, the fibers spiral up to 90°. This might contribute to increased strength, decreased buckling, and less deformation.[9,11] The longitudinally oriented fibers also allow for significant weight-bearing and physiologic stress.

The calcaneal insertion site of the tendon represents a relatively small footprint, only about 10% of the tendon itself, but its microstructural arrangement and properties allow for maximum attachment, an increased moment arm with smooth function, and dispersion of about 2 KN of force.[12] This capability is in large part due to the off-axis orientation of the fibers and a mineral concentration of up to 50%. The collagen fibers disperse stress locally, and mineralization increases stiffness to the area, which provides coordinated protection to the insertion and transfers stress to the tendon proper.[12]

A fair amount is known about the physiologic stresses that occur through this tendon during normal function. Forces of approximately 3 KN have been reported during maximal isometric contractions, 2.6 KN during slow walking, 1 KN during cycling, and as high as 9 KN while running. This equates to approximately 12.5 times body weight or 11 KN/cm^2 when considering the cross-sectional area of the tendon.[9,10,13,14] Repetitive hopping can produce peak loads of 3.8 KN, unilateral hopping up to 5 KN, and squat jumping to 2.2 KN.[9,10,13] Ultrasonographic studies have demonstrated that maximal tendon forces range between 200 and 3800N, elongation values from 2 to 24 mm, Young modulus between 0.3 and 1.4 GPa, and stiffness of 17 to 760 N/mm.[10]

From a biomechanical perspective, the gastroc-soleus complex and Achilles tendon serve many purposes.[11] During the contact period of the gait cycle, it works to decelerate internal tibial rotation, and similarly during midstance, it decelerates anterior tibial advancement. It further acts to plantarflex the ankle joint to initiate heel off. Weakness or tightness of the complex might result in imbalances or gait cycle abnormalities, which in turn can lead to numerous ankle and foot pathologic conditions.[11] It is of course also one of the most prone tendons to rupture, largely in part due to the forces it is subject to and the relative paucity of blood supply to what has traditionally been referred to as the watershed region.[11] The incidence of Achilles tendon rupture has been reported across the literature as approximately 9.9 to 40 per 100,000 annually.[10,15] Tendons can typically stretch up to 4% before sustaining damage, but past this 4% threshold the collagen cross-links are disrupted and beyond 8% macroscopic rupture occurs.[9–11]

Backer and colleagues performed a review on 100 articles pertaining to Achilles tendon rupture and evaluated strength measurements following rupture healing.[15] Significant variability was noted with measurement style, patient positioning, angular velocity, repetitive measurements, and the use of warm-up sessions before obtaining outcomes. Results also varied across studies in terms of the reported unit of force versus direct percent comparisons to the unaffected limb. The authors concluded there is a lack of consensus on the optimal means of assessing strength following rupture. This is obviously important to consider as one views and interprets the published literature.

Sadoghi and colleagues performed a systematic review generally representative of the broader literature pertaining to initial strength analyses following end-to-end Achilles tendon repairs.[16] Eleven studies were incorporated into the analysis, and several different repair techniques were assessed including the familiar Krackow, Kessler, Bunnell, Ma-Griffith, triple bundle, and giftbox suture repairs among others. Reported tensile strengths ranged from 81 to 453 N with a mean of 222.7 N. The triple bundle technique had the highest tensile strength at 453 N, followed by the Bunnell (217.2 N), Krackow (172.7 N), giftbox (168 N), Kessler (167.7 N), and Ma-Griffith (149.5 N). Importantly, despite these apparent differences, the authors concluded that the variability in study design, sample size, and measurement techniques rendered a formal conclusion on construct superiority unfeasible.

With that said, this study provides a good example of a discussion of the difference between a statistically significant and clinically significant result. Although a statistically significant difference might easily be demonstrated between the triple bundle and Ma-Griffith techniques (453 N vs 149.5 N), for example, both groups would be expected to fail if the patient engaged in unprotected walking in the immediate postoperative period.[9,10,13,14] It is therefore reasonable to question if this statistically significant difference has any clinical significance if it does not affect postoperative medical decision-making.[14] All the described techniques would be expected to require immediate postoperative protected immobilization. A clinically significant difference, however, might be argued to be one that would allow for a faster functional recovery or change in prescribed postoperative rehabilitation protocols.

Several investigations have been published examining and comparing different end-to-end tendon repair techniques, but it seems fair to conclude that most constructs produce results with failure occurring in the ballpark of several hundred Newtons.[17–25] Even with graft augmentation, the highest observed mean load to failure we observed was 821 N.[20] Certainly, some techniques are likely to be “stronger” than the others, but the literature shows a theme of our ability to perform an end-to-end repair that is likely able to withstand forces that occur with nonweight-bearing range of motion, but that are likely to fail with unprotected weight-bearing mobilization.[9,10,13,14] Similar results are also observed when one considers tendon-to-bone repair and reattachment techniques.[14,26–35]

ANTERIOR TALOFIBULAR LIGAMENT

Injury to the lateral ankle ligaments also represents a commonly encountered pathologic condition and target for surgical repair. This most frequently occurs in inverted and plantarflexed positions with damage to the anterior talofibular ligament (ATFL) alone or in combination with the calcaneofibular ligament.[36]

Several investigations have provided insight into the normal expected forces through the ATFL. St. Pierre and colleagues found a mean tensile strength at failure of 206 N (range 58–556 N) with an equal distribution of the failure, occurring within the midsubstance of the ligament and at the talar insertion.[37] Viens and colleagues found an ultimate load to failure at 154 ± 63.7 N with a stiffness of 14.5 ± 4.4 N/mm in intact ATFL specimens.[38] Similarly, Waldrop and colleagues noted an ultimate failure load of 160.9 ± 72.2 N and a stiffness of 12.4 ± 4.1 N/mm in intact specimens.[39] Moreover, Tohyama and colleagues reported that 30 N of force should be applied during the anterior drawer testing to achieve a sufficient examination; otherwise, the amount of displacement required for the diagnosis of ankle instability might not occur.[40–42] These highlight another relative limitation of the mechanical testing literature in that protocols are only available with cadaveric methodology. In vivo measurement and testing to failure are not possible.

When considering the biomechanical strength of differing fixation options for the ATFL, it is important to consider anatomic versus nonanatomic restoration, with or without supplemental augmentation.[43] A cadaveric study performed by Shoji and colleagues evaluated cadaveric specimens in terms of intact ATFL, injured ATFL, anatomic repair of the ATFL, and nonanatomic ATFL repair, for example.[44] The overall kinematic laxity of the anatomic repair was not statistically different from an intact ATFL, and in fact internal rotation laxity was significantly increased in the nonanatomic repair at 30° and 15° of plantarflexion versus an intact ATFL. This might point toward relative advantages of augmentation in addition to primary repair.

Viens and colleagues evaluated intact ATFLs relative to repair with either suture tape augmentation alone or Brostrom with suture tape augmentation.[38] Those with suture tape augmentation alone saw an ultimate load to failure of 315.5 ± 66.8 N and stiffness of 31.4 ± 9.9 N/mm compared with 250.8 ± 122.7 N and 21.1 ± 9.1 N/mm in the Brostrom plus augmentation group and 154 ± 63.7 N with stiffness of 14.5 ± 4.4 N/mm in the intact specimens. These results might indicate that, different than the Achilles tendon, surgical techniques for the ATFL might have the ability to achieve supraphysiologic loads to failure. Conversely, however, Waldrop and colleagues compared the traditional Brostrom and suture anchor repair techniques.[39] They noted an ultimate failure load of 160.9 ± 72.2 N and a stiffness of 12.4 ± 4.1 N/mm in the intact specimens but substantially less following the Brostrum (68.2 ± 27.8 N ultimate failure load; 6 ± 2.5 N/mm stiffness), suture anchor in the fibula (79.2 ± 34.3 N ultimate failure load; 6.8 ± 2.7 N/mm stiffness), and suture anchor in the talus (75.3 ± 45.6 N ultimate failure load; 6.6±4 N/mm).

Other investigations into the use of suture anchors have found more encouraging results. Cottom and colleagues evaluated 3 different arthroscopic techniques for lateral ankle repair with suture anchors.[45] The studied groups consisted of a single-row 2-suture anchor construct, double-row 4-anchor knotless construct, and double-row 3-anchor construct. Load to failure was observed at a mean of 156.43 ± 30.39 N, 206.62 ± 55.62 N, and 246.82 ± 82.37 N, with a statistically significant difference observed between the 2-anchor and 3-anchor constructs. These all seem to be more comparable to the load to failure findings of intact ATFLs.[37–39] Stiffness in the Cottom and colleagues investigation was measured at a mean of 12.10 ± 5.43 N/m, 13.40 ± 7.98 N/m, and 12.55 ± 4.0 N/m, respectively.[45]

These and other results are interesting from a critical analysis standpoint and likely carry clinical significance.[46–49] Because the strength of repairs with augmented techniques seems to reach physiologic or even supraphysiologic values, it might imply the ability to accelerate postoperative rehabilitation and weight-bearing protocols in some situations.

PLANTAR PLATE

The plantar metatarsophalangeal ligament (plantar plate or plantar pad) is a cup-shaped, intra-articular covering of the inferior aspect of the metatarsophalangeal joint (MPJ).[50,51] It is continuous with the joint capsule both medially and laterally effectively creating a fibrocartilaginous socket for the metatarsal head.[50] The primary composition is type 1 collagen with fibers oriented both longitudinally and interwoven, creating a strong structure to resist compressive and tensile loads.[50] Pauwel theory of “causal histogenesis” describes this collagen fibril orientation with the direction of the greatest tension able to withstand most tensile forces and support the windlass mechanism.[52]

The plantar plate plays a significant role with respect to inherent MPJ stability.[53–55] Pathologic condition in this anatomic area nearly always involves excessive dorsal translation of the proximal phalanx. Although it is easy to conceptualize the digit as actively rotating in a relatively dorsal direction on the metatarsal head, in fact during stance and propulsion the digit is firmly and statically in contact with the weight-bearing surface while the metatarsal head is the structure that effectively “moves.” It is admittedly challenging to recreate this functional movement with cadaveric mechanical testing protocols, as well as investigate an accurate physiologic construct considering the dynamic stabilization provided by the extrinsic tendons.

Bhatia and colleagues used cadaveric models to determine the anatomic restraints that counteract second MPJ dislocation.[56] About 37 ± 5.7 N of force was required to dislocate the MPJ with an intact capsule and plantar plate, whereas a mean force of 26 ± 5.32 N (range 22–34 N) was required to dislocate the second toe following division of the plantar plate and 20 ± 3.5 N (range 15–23 N) following sectioning of both the medial and lateral collateral ligaments. Division of both the plantar plate and collaterals resulted in dislocation after only 8 ± 4.74 N (range 5–10 N). Suero and colleagues measured and compared dorsal displacement of the proximal phalanx in isolation as well as in combination of sectioning the plantar plate and surrounding structures. The mean dorsal displacement of an intact MPJ was approximately 10.6 mm, but when both the plantar plate and the collateral ligaments were sectioned, there was a 63% increase in dorsal displacement.[57]

Indirect repair approaches not specifically addressing the anatomy might lead to inadequate results.[50,58,59] Highlander and colleagues reported that the Weil osteotomy without plantar plate repair had a 36% complication rate of floating toe deformity with a 15% recurrence rate.[60] This might indirectly point toward the need to address the plantar plate tear or disruption directly. Chalayon and colleagues compared intact sagittal plane stability of the lesser MPJ in terms of superior subluxation, dorsiflexion, and plantarflexion.[61] Overall, the mean stability of the lesser MPJs in terms of superior subluxation was 3.03 ± 0.93 N/mm, dorsiflexion was 2.07 ± 0.38 N/mm, and plantarflexion was 0.42 ± 0.06 N/mm. Disruption of the plantar plate significantly decreased stability by an average 23%.

Specific literature and materials testing plantar plate repair constructs are relatively limited. Finney and colleagues sought to assess 3 different suture configurations that might be used for plantar plate repairs (horizontal mattress, luggage-tag, and Mason-Allen suture techniques).[62] Specimens underwent cyclic loading followed by load to failure. No differences were observed in number of cycles leading to 2 mm of displacement (mattress: 19.2 ± 1.5; luggage-tag: 18.6 ± 2.9; Mason-Allen: 18.8 ± 2.0). Peak load to failure forces were reported as 115.53 ± 15.95 N for the horizontal mattress, 102.42 ± 19.33 N for the luggage-tag, and 89.96 ± 15.78 N for Mason-Allen techniques. This difference between the horizontal mattress and Mason-Allen techniques was found to be statistically significant. Displacement at failure was noted at 9.3±2 mm for the horizontal mattress, 8.1 ± 1.6 mm for the luggage-tag, and 7.6 ± 1.6 mm for the Mason-Allen techniques. The authors also measured stiffness of the constructs, which were 52.6 ± 2.8 N/mm, 50.3 ± 10.5 N/mm, and 53.9 ± 4.9 N/mm, respectively. Neither displacement nor stiffness between constructs was found to be statistically significant.

Although the horizontal mattress seemed to be superior in terms of load to failure in the Finney and colleagues study, the constructs performed similarly across other studied parameters and the clinical significance of a 25 N difference in this location is unclear.[62] This might be particularly true as the ∼90 N peak load to failure observed with the Mason-Allen technique could be considered supraphysiologic when considering the Bhatia and colleagues findings of 38 N for an intact joint.[56] One should certainly be careful directly comparing the results from 2 different studies implementing 2 different mechanical testing protocols, but the Finney and colleagues results seem to indicate that all repair techniques effectively doubled the “normal” load to failure observed in the intact joints of the Bhatia and colleagues investigation.[56,62]

SPRING LIGAMENT

Another soft tissue structure providing static support is the plantar calcaneonavicular ligament. More commonly referred to as the spring ligament complex (SLC), it is a thick triangular structure composed of at least 2 distinct ligamentous bands primarily connecting the sustentaculum tali of the calcaneus to the medial aspects of the navicular.[63–65] The superomedial calcaneonavicular ligament is a fibrocartilaginous band with collagen orientation able to withstand repetitive loads, whereas the inferomedial calcaneonavicular ligament contains organized longitudinal fibers able to resist tensile forces.[63] Although there is no direct attachment to the talus, this complex is in close anatomic proximity to the medial and plantar aspects of the talonavicular joint. This, in combination with the deltoid ligament, supports the head of the talus, provides static stability to the talar head and the talonavicular joint, supports the medial longitudinal arch, and provides kinetic coupling between the forefoot and the hindfoot.[63,66–69]

This has been an area of contemporary interest with respect to the diagnosis and treatment of posterior tibial tendon dysfunction (PTTD) and peritalar subluxation. Tears or attenuation of the SLC are commonly observed in those with PTTD, and

Table 1
Summative findings of biomechanics of lower extremity soft tissue procedures

Anatomic Area	Expected Physiologic Forces	Reviewed Repair Constructs	Conclusion?
Achilles tendon	Substantial variation is noted in expected physiologic forces depending on the specific activity[9,10,13,14]	Most repair techniques noted to fail at **>100 N** and **<1000 N**[14–16]	Reviewed repair constructs seem to range from supraphysiologic when considering nonweight-bearing range of motion, but infraphysiologic when considering weight-bearing activity
ATFL	Mean loads to ligament failure observed to range between **154** and **206N** in cadaveric methodologies[37–39]	Mean loads to failure observed to range between **68 N** and**315 N** in cadaveric methodologies examining multiple repair techniques[38,39]	Reviewed repair constructs seem to range from infraphysiologic to supraphysiologic
Plantar plate (plantar metatarsophalangeal ligament)	**37 ± 5.7 N** found to dislocate the second MPJ in a cadaveric methodology with an intact joint capsule and plantar plate[56]	Mean loads to failure observed to range between **90 N** and**116 N** in a cadaveric methodologies examining 3 different repair techniques[62]	Reviewed repair constructs seem supraphysiologic
Spring ligament (plantar calcaneonavicular ligament)	A mathematical model theorized approximate forces of **50 N** with 2-foot stance and **82 N** with single limb stance[80]	No direct analyses reviewed	This likely represents an interesting avenue for future investigation

some have proposed that this is likely the structure that fails first within the pathogenesis of peritalar subluxation, and its primary repair in flatfoot reconstructive surgeries has become more commonplace.[70–79]

With that said, it is a structure that is difficult to evaluate in isolation, both with respect to normal function and following surgical reconstruction. Cheung and colleagues concluded that force loaded on the SLC was approximately 50 N during 2-foot balance and gait, and that this increases to 82 N with single limb stance.[80] Huang and colleagues performed a cadaveric study to assess the significance of the plantar fascia, long and short plantar ligaments, and the spring ligament in maintaining arch stability.[81] Specimens were loaded to 230 N, 460 N, and 690 N with sequential sectioning of the aforementioned structures in various orders. Failure occurred at 920N when all 3 structures were sectioned. The observed decrease in arch height was greatest following sectioning of the plantar fascia regardless of order of release. This was followed by the plantar ligaments and, finally, the spring ligament. Stiffness decreased by 25%, 10%, and 2% following sectioning of the plantar fascia, plantar ligaments, and spring ligament, respectively.

Cifuentes-De la Portilla and colleagues evaluated different flatfoot arthrodesis and visualized the different stresses on osseous and cartilaginous structures following each procedure.[82–84] The highest stresses occurred at the navicular and the authors largely contributed this to the spring ligament. In an earlier study by the same authors, the biomechanical forces of each isolated joint following rearfoot arthrodesis were assessed. The talonavicular joint arthrodesis generated a significant stress reduction in comparison to the subtalar joint fusion, indirectly providing evidence to the importance of this anatomic area and supporting structures.[83]

Biomechanical testing of the SLC represents an interesting avenue for future investigations because very few have attempted this. However, Aynardi and colleagues did find significant difference in failure properties between traditional spring ligament repair and repair augmented with FiberTape[85] (**Table 1**).

CLINICS CARE POINTS

- The triple bundle technique for end to end repair of the Achilles tendon offers the highest tensile strength at 453 N compared to other techniques such as a the Bunnell, Krackow, Kessler, gift box, and Ma-Griffith.
- However, it is important to differentiate between statistically significance and clinical significance as it pertains to post-operative protocol with Achilles tendon repair.
- When considering ATFL repair, it is important to identify and consider anatomic versus nonanatomic repair and also with and without augmentation with allograft.
- Suture anchors in ATFL repair have had encouraging results and likely carry clinical significance.
- The plantar plate plays a significant role in MPJ stability along with the capsule and collateral ligaments.
- It is important to consider indirect versus direct repair of the plantar plate as it can affect recurrence rate.
- The spring ligament in combination with the deltoid ligament provide static stability to the talar head and talonavicular joint.
- Attenutation to this structure can result in the pathogenesis of peritalar subluxation and restoration of this ligament can aid in flatfoot reconstruction.

DISCLOSURE

All authors have no financial disclosures to report.

REFERENCES

1. Newton I. Observations upon the prophecies of Daniel, and the apocalypse of St. John. Glascow (United Kingdom): Good Press; 2019. p. 1–105.
2. Dry S. The Newton papers: the strange and true odyssey of Isaac Newton's manuscripts. Cary (NC): Oxford University Press; 2014.
3. Chambers J. The metaphysical world of Isaac Newton: alchemy, prophecy, and the search for lost knowledge. Merrimac (MA): Destiny Books; 2018. p. 1–408.
4. Gates J, Pelletier C. Proving Einstein right: the Daring expeditions that changed how we look at the universe. New York: PublicAffairs; 2019.
5. Stanley M. Einstein's war: how relativity triumphed amid the vicious nationalism of world war 1. London (United Kingdom): Penguin Audio; 2019.
6. Robinson A. The last man who knew everything: Thomas young, the anonymous polymath who proved Newton wrong, explained how we see, cured the sick, and deciphered the Rosetta stone, among other feats of genius. Serbia: Pi Press; 2005. p. 1–304.
7. Bauer LA. Resume of observations concerning the solar eclipse of May 29, 1919, and the Einstein effect. Science 1920;51:301–11.
8. Chant CA. Einstein displacement on the plates taken by the Canadian party at the Australian eclipse. Science 1923;57:469.
9. Doral NM, Alam M, Bozkurt M, et al. Functional anatomy of the Achilles tendon. Knee Surg Sports Traumatol Arthrosc 2010;18:638–43.
10. Winnicki K, Ochala-Klos A, Rutowicz B, et al. Functional anatomy, histology and biomechanics of the human Achilles tendon – a comprehensive review. Ann Anat 2020;229:151461.
11. Dayton P. Anatomic, vascular, and mechanical overview of the Achilles tendon. Clin Podiatr Med Surg 2017;34:107–13.
12. Sadeghi S, Taghizadeh H. Microstructural modeling of Achilles tendon biomechanics focusing on bone insertion site. Med Eng Phys 2020;78:48–54.
13. Joseph MF, Lillie KR, Bergeron DJ, et al. Achilles tendon biomechanics in response to acute intense exercise. J Strength Cond Res 2014;28:1181–6.
14. Lakey E, Kumparatana P, Moon DK, et al. Biomechanical comparison of all-soft suture anchor single-row vs double-row bridging construct for insertional Achilles tendinopathy. Foot Ankle Int 2020;42:215–23.
15. Backer HC, Yenchak AJ, Trofa DP, et al. Strength measurement after Achilles tendon repair. Foot Ankle Spec 2019;12:471–9.
16. Sadoghi P, Rosso C, Valderrabano V, et al. Initial Achilles tendon repair strength-synthesized biomechanical data from 196 cadaver repairs. Int Orthop 2012;36:1947–51.
17. Wu Z, Hua Y, Li H, et al. Biomechanical comparison of three methods for distal Achilles tendon reconstruction. Knee Surg Sports Traumatol Arthrosc 2015;23:3756–60.
18. Tian J, Rui R, Xu Y, et al. Achilles tendon rupture repair: biomechanical comparison of the locking block modified Krackow technique and the Giftbox technique. Injury 2020;51:559–64.
19. Tian J, Rui Y, Xu Y, et al. A biomechanical comparison of Achilles tendon suture repair techniques: locking block modified Krackow, Kessler, and percutaneous

Achilles repair system with early rehabilitation program in vitro bovine model. Arch Orthop Trauma Surg 2020;140:1775–82.

20. Magnussen RA, Glisson RR, Moorman CT. Augmentation of Achilles tendon repair with extracellular matrix xenograft. Am J Sports Med 2011;39(7):1522–7.
21. Wagner P, Wagner E, Lopez M, et al. Proximal and distal failure site analysis in percutaneous Achilles tendon rupture repair. Foot Ankle Int 2019;40:1424–9.
22. McCoy BW, Haddad SL. The strength of Achilles tendon repair: a comparison of three suture techniques in human cadaver tendons. Foot Ankle Int 2010;31: 701–5.
23. Carmont MR, Kuiper JH, Silbernagel KG, et al. Tendon end separation with loading in an Achilles tendon repair model: comparison of non-absorbable vs. absorbable sutures. J Exp Orthop 2017;4:26.
24. Nguyen TP, Keyt LK, Herfat S, et al. Biomechanical study of a multifilament stainless steel cable crimp system versus a multistrand ultra-high molecular weight polyethylene polyester suture Krackow technique for Achilles tendon rupture repair. J Foot Ankle Surg 2020;59:86–90.
25. Cottom JM, Baker JS, Richardson PE, et al. Evaluation of a new knotless suture anchor repair in acute Achilles tendon ruptures: a biomechanical comparison of three techniques. J Foot Ankle Surg 2017;56:423–7.
26. Yammine K, Assi C. Efficacy of repair techniques of the Achilles tendon: a meta-analysis of human cadaveric biomechanical studies. Foot 2017;30:13–20.
27. Leung KS, Chong WS, Chow DHK, et al. A comparative study on the biomechanical and histological properties of bone-to-bone, bone-to-tendon, and tendon-to-tendon healing. An Achilles tendon-calcaneus model in goats. Am J Sports Med 2015;43(6):1413–21.
28. Boin MA, Dorweiler MA, McMellen CJ, et al. Suture-only repair versus suture anchor-augmented repair for Achilles tendon ruptures with a short distal stump. Orthop J Sports Med 2017;5(1). 2325967116678722.
29. Beitzel K, Mazzocca AD, Obopilwe E, et al. Biomechanical properties of double- and single-row suture anchor repair for surgical treatment of insertional Achilles tendinopathy. Am J Sports Med 2013;41(7):1642–8.
30. Awogni D, Chauvette G, Lemieux ML, et al. Button fixation technique for Achilles tendon reinsertion: a biomechanical study. J Foot Ankle Surg 2014;53:141–6.
31. Pilson H, Brown P, Stitzel J, et al. Single-row versus double-row repair of the distal Achilles tendon: a biomechanical comparison. J Foot Ankle Surg 2012;51:762–6.
32. Cox JT, Shorten PL, Gould GC, et al. Knotted versus knotless suture bridge repair of the Achilles tendon insertion. Am J Sports Med 2014;42(11):2727–33.
33. Fanter NJ, Davis EW, Baker CL. Fixation of the Achilles tendon insertion using suture button technology. Am J Sports Med 2012;40(9):2085–91.
34. Drakos MC, Gott M, Karnovsky SC, et al. Biomechanical analysis of suture anchor vs tenodesis screw for FHL transfer. Foot Ankle Int 2017;38(7):797–801.
35. Hembree WC, Tsai MA, Parks BG, et al. Comparison of suture-based anchors and traditional bioabsorbable anchors in foot and ankle surgery. J Foot Ankle Surg 2017;56:3–7.
36. McKeon BP, Heming JF, Fulkerson J, et al. The Krackow stitch: a biomechanical evaluation of changing the number of loops versus the number of sutures. Arthroscopy 2006;22:33–7.
37. St. Pierre RK, Rosen J, Whitesides TE, et al. The tensile strength of the anterior talofibular ligament. Foot Ankle 1983;4:83–5.

38. Viens NA, Wijdicks CA, Campbell KJ, et al. Anterior talofibular ligament ruptures, part 1: biomechanical comparison of augmented Broström repair techniques with the intact anterior talofibular ligament. Am J Sports Med 2014;42:405–11.
39. Waldrop NE 3rd, Wijdicks CA, Jansson KS, et al. Anatomic suture anchor versus the Brostrom technique for anterior talofibular ligament repair: a biomechanical comparison. Am J Sports Med 2012;40:2590–6.
40. Tohyama H, Yasuda K, Ohkoshi Y, et al. Anterior drawer test for acute anterior talofibular ligament injuries of the ankle. How much load should be applied during the test? Am J Sports Med 2003;31:226–32.
41. Fujii T, Luo ZP, Kitaoka HB, et al. The manual stress test may not be sufficient to differentiate ankle ligament injuries. Clin Biomech 2000;15:619–23.
42. Phisitkul P, Chaichankul C, Sripongsai R, et al. Accuracy of anterolateral drawer test in lateral ankle instability: a cadaveric study. Foot Ankle Int 2009;30:690–5.
43. Lohrer H, Bonsignore G, Dorn-Lange N, et al. Stabilizing lateral ankle instability by suture tape - a cadaver study. J Orthop Surg Res 2019;14:175.
44. Shoji H, Teramoto A, Sakakibara Y, et al. Kinematics and laxity of the ankle joint in anatomic and nonanatomic anterior talofibular ligament repair: a biomechanical cadaveric study. Am J Sports Med 2019;47:667–73.
45. Cottom JM, Baker JS, Richardson PE, et al. A biomechanical comparison of 3 different arthroscopic lateral ankle stabilization techniques in 36 cadaveric ankles. J Foot Ankle Surg 2016;55:1229–33.
46. Li H, Zhao Y, Hua Y, et al. Knotless anchor repair produced similarly favourable outcomes as knot anchor repair for anterior talofibular ligament repair. Knee Surg Sports Traumatol Arthrosc 2020;28:3987–93.
47. Jung HG, Kim TH, Park JY, et al. Anatomic reconstruction of the anterior talofibular and calcaneofibular ligaments using a semitendinosus tendon allograft and interference screws. Knee Surg Sports Traumatol Arthrosc 2012;20:1432–7.
48. Choi HJ, Kim DW, Park JS. Modified Broström procedure using distal fibular periosteal flap augmentation vs anatomic reconstruction using a free tendon allograft in patients who are not candidates for standard repair. Foot Ankle Int 2017;38:1207–14.
49. Giza E, Shin EC, Wong SE, et al. Arthroscopic suture anchor repair of the lateral ligament ankle complex. Am J Sports Med 2013;41:2567–72.
50. Camasta C. Plantar plate repair of the second metatarsophalangeal joint. In: Southerland JT, Boberg JS, Downey MS, et al, editors. McGlamry's comprehensive textbook of foot and ankle surgery. 4th Edition. Philadelphia (PA): Lippincott Williams & Wilkins; 2013. p. 187–201.
51. Maas NM, van der Grinten M, Bramer WM, et al. Metatarsophalangeal joint stability: a systematic review on the plantar plate of the lesser toes. J Foot Ankle Res 2016;9:32.
52. Petersen W, Tillmann B. Structure and vascularization of the cruciate ligaments of the human knee joint. Anat Embryol (Berl) 1999;200:325–34.
53. Fleischer AE, Hshieh S, Crews RT, et al. Association between second metatarsal length and forefoot loading under the second metatarsophalangeal joint. Foot Ankle Int 2018;39:560–7.
54. Landorf KB, Ackland CA, Bonanno DR, et al. Effects of metatarsal domes on plantar pressures in older people with a history of forefoot pain. J Foot Ankle Res 2020;13:18.
55. Coughlin MJ. Second metatarsophalangeal joint instability in the athlete. Foot Ankle 1993;14:309–19.

56. Bhatia D, Myerson MS, Curtis MJ, et al. Anatomical restraints to dislocation of the second metatarsophalangeal joint and assessment of a repair technique. J Bone Joint Surg Am 1994;76:1371–5.
57. Suero EM, Meyers KN, Bohne WH. Stability of the metatarsophalangeal joint of the lesser toes: a cadaveric study. J Orthop Res 2012;30:1995–8.
58. Ford LA, Collins KB, Christensen JC. Stabilization of the subluxed second metatarsophalangeal joint: flexor tendon transfer versus primary repair of the plantar plate. J Foot Ankle Surg 1998;37:217–22.
59. Sung W. Technique using interference fixation repair for plantar plate ligament disruption of lesser metatarsophalangeal joints. J Foot Ankle Surg 2015;54:508–12.
60. Highlander P, VonHerbulis E, Gonzalez A, et al. Complications of the Weil osteotomy. Foot Ankle Spec 2011;4:165–70.
61. Chalayon O, Chertman C, Guss AD, et al. Role of plantar plate and surgical reconstruction techniques on static stability of lesser metatarsophalangeal joints: a biomechanical study. Foot Ankle Int 2013;34:1436–42.
62. Finney FT, Lee S, Scott J, et al. Biomechanical evaluation of suture configurations in lesser toe plantar plate repairs. Foot Ankle Int 2018;39:836–42.
63. Rule J, Yao L, Seeger LL. Spring ligament of the ankle: normal MR anatomy. Am J Roentgenol 1993;161:1241–4.
64. Lin YC, Kwon JY, Ghorbanhoseini M, et al. The hindfoot arch: what role does the imager play? Radiol Clin North Am 2016;54:951–68.
65. Davis WH, Sobel M, DiCarlo EF, et al. Gross, histological, and microvascular anatomy and biomechanical testing of the spring ligament complex. Foot Ankle Int 1996;17:95–102.
66. Van Boerum DH, Sangeorzan BJ. Biomechanics and pathophysiology of flat foot. Foot Ankle Clin 2003;8:419–30.
67. Reeck J, Felten N, McCormack AP, et al. Support of the talus: a biomechanical investigation of the contributions of the talonavicular and talocalcaneal joints, and the superomedial calcaneonavicular ligament. Foot Ankle Int 1998;19(10):674–82.
68. Masaragian HJ, Massetti S, Perin F, et al. Flatfoot deformity due to isolated spring ligament injury. J Foot Ankle Surg 2020;59:469–78.
69. Bastias GF, Dalmau-Pastor M, Astudillo C, et al. Spring ligament instability. Foot Ankle Clin 2018;23:659–78.
70. Deland JT, de Asla RJ, Sung IH, et al. Posterior tibial tendon insufficiency: which ligaments are involved? Foot Ankle Int 2005;26:427–35.
71. Kelly M, Masqoodi N, Vasconcellos D, et al. Spring ligament tear decreases static stability of the ankle joint. Clin Biomech 2019;61:79–83.
72. Myerson MS, Thordarson DB, Johnson JE, et al. Classification and nomenclature: progressive collapsing foot deformity. Foot Ankle Int 2020;41:1271–6.
73. Thordarson DB, Schmotzer H, Chon J, et al. Dynamic support of the human longitudinal arch. A biomechanical evaluation. Clin Orthop Relat Res 1995;316:165–72.
74. Thordarson DB, Schmotzer H, Chon J. Reconstruction with tenodesis in an adult flatfoot model. A biomechanical evaluation of four methods. J Bone Joint Surg Am 1995;77:1557–64.
75. Tryfonidis M, Jackson W, Mansour R, et al. Acquired adult flat foot due to isolated plantar calcaneonavicular (spring) ligament insufficiency with a normal tibialis posterior tendon. Foot Ankle Surg 2008;14:89–95.

76. Pasapula C, Devany A, Fischer NC, et al. The resistance to failure of spring ligament reconstruction. Foot (Edinb) 2017;33:29–34.
77. Pasapula C, Devany A, Magan A, et al. Neutral heel lateral push test: the first clinical examination of spring ligament integrity. Foot (Edinb) 2015;25:69–74.
78. Flores DV, Mejía Gómez C, Fernández Hernando M, et al. Adult acquired flatfoot deformity: anatomy, biomechanics, staging, and imaging findings. Radiographics 2019;39:1437–60.
79. Ellis SJ, Williams BR, Wagshul AD, et al. Deltoid ligament reconstruction with peroneus longus autograft in flatfoot deformity. Foot Ankle Int 2010;31:781–9.
80. Cheung JT, Zhang M, An KN. Effects of plantar fascia stiffness on the biomechanical responses of the ankle-foot complex. Clin Biomech 2004;19:839–46.
81. Huang CK, Kitaoka HB, An KN, et al. Biomechanical evaluation of longitudinal arch stability. Foot Ankle 1993;14:353–7.
82. Cifuentes-De la Portilla C, Pasapula C, Larrainzar-Garijo R, et al. Finite element analysis of secondary effect of midfoot fusions on the spring ligament in the management of adult acquired flatfoot. Clin Biomech 2020;76:105018.
83. Cifuentes-De la Portilla C, Larrainzar-Garijo R, Bayod J. Analysis of the main passive soft tissues associated with adult acquired flatfoot deformity development: a computational modeling approach. J Biomech 2019;84:183–90.
84. Cifuentes-De la Portilla C, Larrainzar-Garijo R, Bayod J. Analysis of biomechanical stresses caused by hindfoot joint arthrodesis in the treatment of adult acquired flatfoot deformity: a finite element study. Foot Ankle Surg 2020;26:412–20.
85. Aynardi MC, Saloky K, Roush EP, et al. Biomechanical evaluation of spring ligament augmentation with the FiberTape device in a cadaveric flatfoot model. Foot Ankle Int 2019;40:596–602.