Journal of Biomechanics 151 (2023) 111520

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

Short communication

# Effect of polyester-based artificial tendons on movement biomechanics: A preliminary in vivo study

Patrick T. Hall [a,e], Caleb Stubbs [a], Alisha P. Pedersen [b], Caroline Billings [b], Stacy M. Stephenson [c], Cheryl B. Greenacre [d], David E. Anderson [b], Dustin L. Crouch [a,*]

[a] Department of Mechanical, Aerospace, and Biomedical Engineering, Tickle College of Engineering, University of Tennessee, 1512 Middle Drive, Knoxville, TN 37966, United States
[b] Department of Large Animal Clinical Sciences, College of Veterinary Medicine, University of Tennessee, 2407 River Drive, Knoxville, TN 37996, United States
[c] Division of Plastic & Reconstructive Surgery, Department of Surgery, University of Tennessee Graduate School of Medicine, 1924 Alcoa Highway, Knoxville, TN 37920, United States
[d] Department of Small Animal Clinical Sciences, College of Veterinary Medicine, University of Tennessee, 2407 River Drive, Knoxville, TN 37996, United States
[e] Exponent, 3440 Market Street, Suite 600, Philadelphia, PA 19104, United States

ARTICLE INFO

*Keywords:*
Prosthesis
Kinematics
Pressure
Animal
Orthopedics

ABSTRACT

Artificial tendons may be valuable clinical devices for replacing damaged or missing biological tendons. In this preliminary study, we quantified the effect of polyester-suture-based artificial tendons on movement biomechanics. New Zealand White rabbits underwent surgical replacement of either the Achilles (n = 2) or tibialis cranialis (TC, n = 2) biological tendons with artificial tendons. Once pre-surgery and weekly from 2 to 6 weeks post-surgery, we quantified hindlimb kinematics and ground contact pressures during the stance phase of hopping gait. Post-surgical movement biomechanics were either consistent or improved over time in both groups. However, the Achilles group had greater overall biomechanical and muscle deficits than the TC group. In the TC group, at 6 weeks post-surgery, foot angles were about 10° greater than those in healthy controls during the first 30 % of stance. At 6 weeks post-surgery, the Achilles group exhibited lesser (i.e., more dorsiflexed) ankle angles (minimum angle = 31.5 ± 9.4°) and vertical ground reaction forces (37.4 ± 2.6 %BW) during stance than those in healthy controls (65.0 ± 11.2° and 50.2 ± 8.3 %BW, respectively). Future studies are needed to quantify long-term biomechanical function with artificial tendons, the effect of artificial tendons on muscle function and structure, and the effect of formal rehabilitation.

## 1. Introduction

Biological tendons, the anatomical links between muscles and bones, transmit forces and store and release elastic potential energy. These functions are compromised following conditions such as acute tendon rupture (Leppilahti and Orava, 1998; Leppilahti et al., 1996; Nistor, 1981) and rotator cuff tear (Yamamoto et al., 2010). Amputation may also damage or remove part or all of the tendons (Early, 1999; Jones and Davidson, 1999), which may affect the success of emergent limb reconstruction methods (Clites et al., 2018; Hall et al., 2021). When direct tendon repair fails or is contraindicated, autologous tendon grafts may be used (Feibel and Bernacki, 2003), potentially leading to donor site morbidity.

One potential treatment for severely damaged or missing tendons is to replace them with an artificial tendon (Murray and Semple, 1979). One recent artificial tendon design consisted of braided strands of polyester microfiber suture (Melvin et al., 2011; Melvin et al., 2010; Melvin et al., 2012; Melvin et al., 2003). These previous studies showed that the muscle cells closely integrated with the polyester microfibers, with little scar tissue formation. This likely contributed to their observation that the resulting muscle-artificial tendon junction was stronger than the muscle itself. These outcomes were achieved up to 180 days post-surgery for attachment of the quadriceps muscle in goats, a high-load application (Melvin et al., 2012).

A major existing knowledge gap that precludes more widespread clinical translation of artificial tendons is their effect on movement biomechanics. Artificial tendons may have mechanical properties (e.g., stiffness) and length that differ from those of the biological tendons they

* Corresponding author.
*E-mail address:* dustin.crouch@utk.edu (D.L. Crouch).

https://doi.org/10.1016/j.jbiomech.2023.111520
Accepted 1 March 2023
Available online 6 March 2023

replace. Such differences could affect musculoskeletal and movement biomechanics based on well-known mathematical relationships (e.g., muscle–tendon force–length relationship) defined from empirical observations (Zajac, 1989). Potential biomechanical functional changes may induce changes in muscle structure (Stenroth et al., 2012), which would further affect function. Finally, how the artificial tendon integrates with muscle and surrounding tissues, including potential foreign body reactions (Holmdahl et al., 1997), may affect tendon sliding and force transmission.

The goal of this preliminary study was to quantify the effect of a suture-based artificial tendon on movement biomechanics in a rabbit model. We hypothesized that movement biomechanics would indicate impaired function immediately following surgery, with subsequent recovery toward pre-surgical levels by 6 weeks post-surgery.

## 2. Methods

The design of the artificial tendons (Fig. S1, see supplemental material) was based on the prostheses developed by Melvin, et al. (Melvin et al., 2011; Melvin et al., 2010). We used customized USP size 0 braided polyester suture cut to 12″ length and double-armed with swaged 3/8-circle taper point needles (0.028″ wire diameter) (RK Manufacturing Corp, Danbury, CT, USA). The sutures were grouped into bundles of 3 strands for the Achilles tendon and 2 strands for the TC tendon. The suture bundles were folded in half and braided. The braided section was coated in biocompatible silicone (BIO LSR M340, Elkem Silicones, Lyon, FR) to discourage buildup of fibrotic adhesions. The artificial tendons were cleaned and sterilized before surgery.

All animal procedures were approved by the University of Tennessee, Knoxville Institutional Animal Care and Use Committee. Four New Zealand White rabbits (16 weeks old, 3.40 ± 0.26 kg at the time of surgery) were divided into two equal groups to undergo surgical replacement of either the Achilles or TC biological insertion tendon with an artificial tendon. Under anesthesia, the respective biological tendon was excised from the muscle–tendon junction to the bony insertion point. The artificial tendon was sewn into the proximal end of the muscle as previously described (Melvin et al., 2010). We attached the artificial tendon to the bone using a suture anchor (Table S1) into either the superior aspect of the calcaneus (Achilles) or the lateral aspect of the talus (tibialis cranialis).

The limb was bandaged for about two weeks immediately post-surgery to protect the sutured incision and to partially immobilize the ankle during initial muscle–tendon healing and integration. To monitor the integrity of the artificial tendon in vivo, we performed radiography of the operated limb every other week, starting on the day of surgery. After bandages were removed, the rabbits were given pen time to promote limb use.

Each rabbit underwent 6 biomechanics testing sessions: once the week before surgery (W0) and at weeks 2–6 post-surgery (W2–W6). During each test session, we collected biomechanical data for up to five successful (i.e., hopping without stopping) trials of hopping along a runway. As previously described (Hall et al., 2022), we first recorded sagittal plane video and ground contact pressures synchronously from the operated limb at 60 Hz using a webcam (1080P HD Webcam, SVPRO) and pressure mat (Tekscan, Very HR Walkway 4; South Boston, MA), respectively.

From videos, we computed hindlimb ankle angles and foot angles (i.e., angle between foot and ground); angle definitions are shown in Fig. 1. Vertical ground reaction forces (vGRF) were extracted from the pressure mat data using proprietary software (Walkway, Tekscan, Inc., Norwood, MA, USA) and expressed as a percentage of body weight (%BW). Finally, we computed the stance duration as the length of time over which the total ground contact pressure for a given hindlimb was greater than zero. Biomechanical data were computed only for the stance phase of hopping since the low sampling frequency (60 Hz) of the video data precluded accurate marker tracking during swing phase.

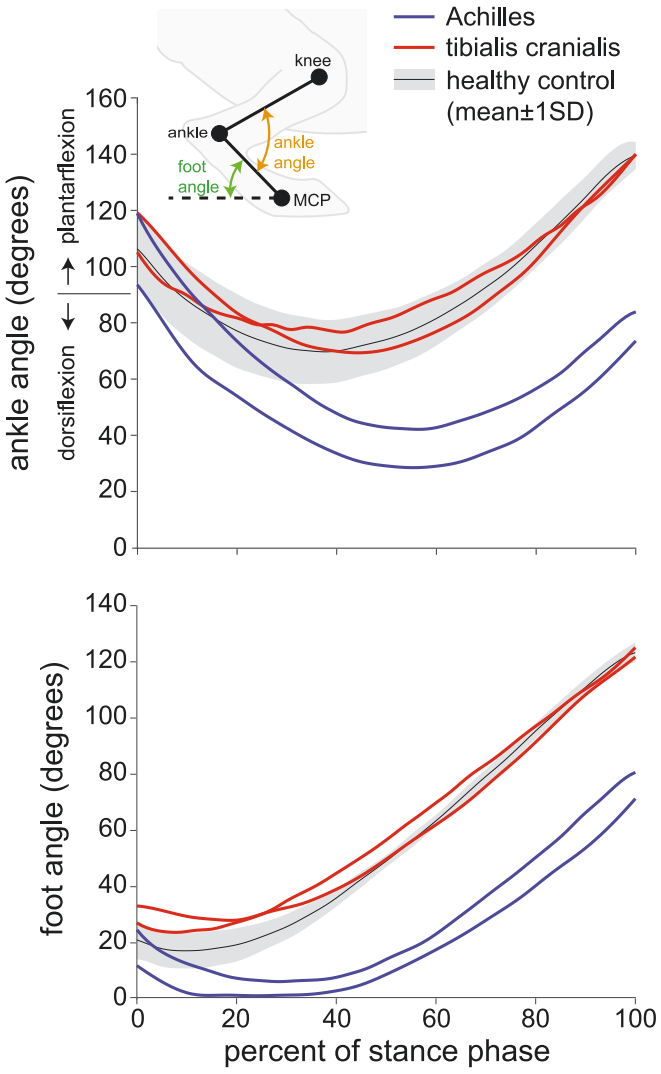


**Fig. 1.** Ankle (top) and foot (bottom) angles during the stance phase of hopping gait at 6 weeks post-surgery. Each curve represents the mean of 5 trials. Healthy control data from (Hall et al., 2022).

Due to our study's low sample size in this preliminary study, we qualitatively compared sample values and summary statistics (e.g., arithmetic means) between groups and among timepoints.

## 3. Results

Radiographs appeared to indicate that artificial tendons remained attached to the suture anchors. However, post-mortem dissection revealed that, in one rabbit in the Achilles group, the artificial tendon had separated from the suture anchor. There was substantial fibrous scar tissue around the anchor and distal end of the artificial tendon that appeared to anchor the artificial tendon to the bone (Fig. S2). Biomechanical results were similar between the two rabbits in the Achilles group and, therefore, are not distinguished by rabbit in this paper.

At 6 weeks post-surgery, foot angles in the TC group were about 10° larger than in healthy controls for the first 30 % of stance phase. The Achilles group had substantially smaller ankle and foot angles than the tibialis cranialis (TC) group and healthy controls (Fig. 1). Whereas the ankle was plantarflexed (>90°) after 70 % stance in the TC and healthy control groups, the ankle remained dorsiflexed throughout most of stance in the Achilles group. Despite remaining in a dorsiflexed posture, the ankle angle in the Achilles group increased (i.e., became less dorsiflexed) after about 55 % stance, compared to about 40 % stance in

healthy controls.

Across all test sessions, joint angle extrema were similar between the TC group and healthy controls (Fig. 2) except that minimum foot angles remained ~10° higher in the TC group than in healthy controls from 2 to 6 weeks post-surgery. In the Achilles group, the maximum ankle angle decreased by an average of 46 % from pre-surgery to 2 weeks post-surgery but recovered by 40 % from 2 to 6 weeks post-surgery. Maximum foot angle in the Achilles group decreased by an average of 45 % from pre-surgery to 2 weeks post-surgery and did not substantially recover by 6 weeks post-surgery.

By 6 weeks post-surgery, compared to healthy controls, net vertical ground reaction forces (vGRFs) were generally higher in the TC group and lower in the Achilles group throughout stance (Fig. 3). From pre-surgery to 2 weeks post-surgery, maximum vGRF decreased by 24 % and 56 %, on average, in the TC and Achilles groups, respectively (Fig. 4). Subsequently, from 2 to 6 weeks post-surgery, maximum vGRF increased by 39 % and 72 %, on average, in the TC and Achilles groups, respectively. At 6 weeks post-surgery, maximum vGRF was 10 % higher in the TC group (55.2 ± 18.2 %BW) than in healthy controls (50.2 ± 8.3 %BW). Conversely, maximum vGRF was 26 % lower in the Achilles group (37.4 ± 2.6 %BW) than in healthy controls.

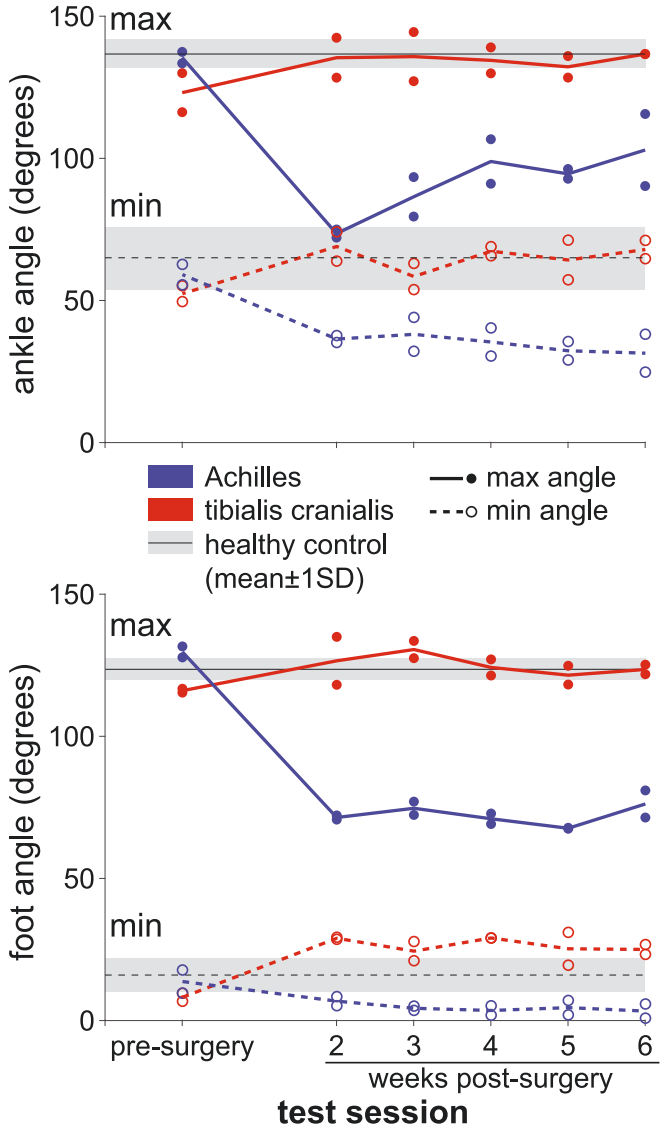


**Fig. 2.** Ankle (top) and foot (bottom) ankle extrema across pre- and post-surgery test sessions. Each point represents the mean of 4-5 trials. Lines represent the mean across rabbits in each group. Healthy control data from (Hall et al., 2022).

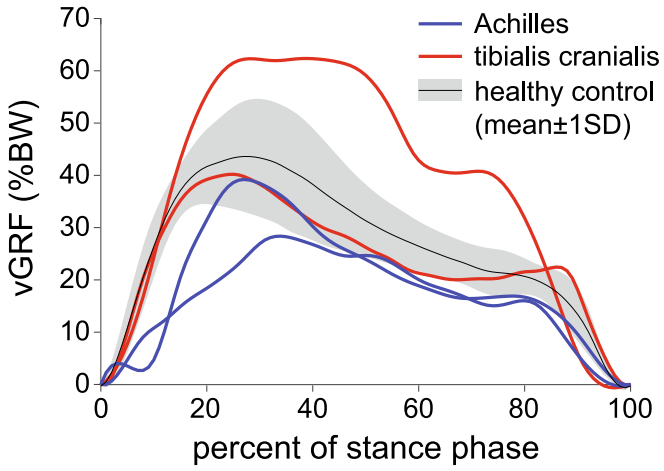


**Fig. 3.** Net vertical ground reaction force (vGRF) during the stance phase of hopping gait at 6 weeks post-surgery. Each curve represents the mean of 5 trials for one rabbit. Healthy control data from (Hall et al., 2022).

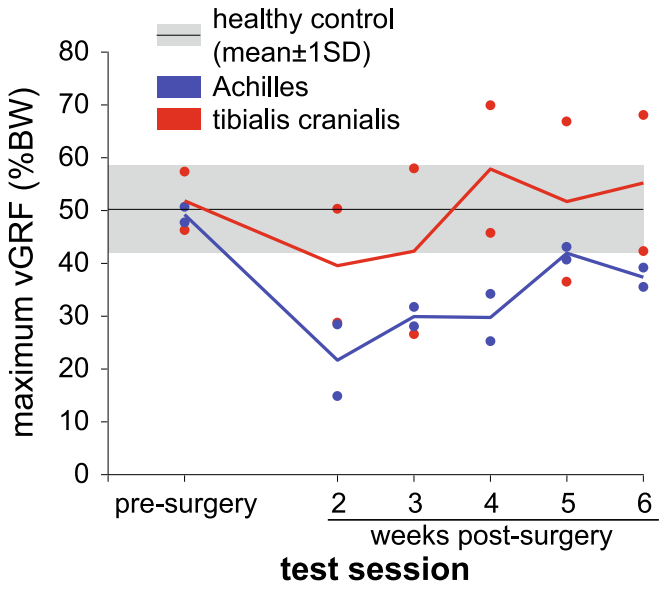


**Fig. 4.** Maximum vertical ground reaction force (vGRF) across pre- and post-surgery test sessions. Each point represents the mean of 4-5 trials for one rabbit. Lines represent the mean across rabbits in each group. Healthy control data from (Hall et al., 2022).

On average, for both groups, stance duration remained lesser post-surgery compared to pre-surgery values (Fig. S3). However, the mean stance duration for both groups remained within ± 1 standard deviation across all test sessions.

## 4. Discussion

Consistend with our hypothesis, rabbits in the Achilles group exhibited biomechanical impairment from W0 to W2 followed by some biomechanical recovery from W2 to W6. Conversely, rabbits in the tibialis cranialis (TC) group exhibited near-normal locomotor biomechanics across test sessions. One likely explanation for the difference between groups is that the mechanical load is expected to be greater in the Achilles tendon than in the TC tendon during stance. This is because ankle plantarflexion torque, typically generated by the triceps surae-Achilles muscle–tendon unit (Lieber and Blevins, 1989), contributes to

body weight support and forward propulsion during stance.

Differences in mechanical properties between artificial and biological tendons are unknown but have critical implications for both movement biomechanics and muscle architecture. For example, with more compliant tendons, muscles experience greater excursion during contraction, distorting the muscle–tendon force–length relationship (Zajac, 1989). In humans, higher tendon stiffness is associated with greater muscle mass and muscle fiber length, though a causal relationship has not yet been established (Stenroth et al., 2012). Artificial tendons provide a unique opportunity to investigate acute and chronic effects of tendon stiffness and to tune tendon stiffness based on patient-specific needs.

Foreign body reactions can induce the formation of a fibrous, collagenous capsule (Noskovicova et al., 2021) that could interfere with the function of implanted devices, like the artificial tendon, that move relative to surrounding tissues. In our study, ex vivo dissection of one rabbit in the Achilles group revealed fibrotic tissue that appeared to fuse the artificial tendon to the flexor digitorum insertion tendon proximal to the ankle joint. In the other rabbits, qualitatively, the fibrosis was not as severe. Future studies are needed to quantify (1) the extent of fibrosis, (2) the effect of fibrosis on in vivo muscle–tendon mechanics, and (3) the effectiveness of strategies to reduce fibrosis.

A potential confounding factor was that, in one rabbit in the Achilles group, the artificial tendon separated from the suture anchor sometime after surgery. From radiographs, it is unclear when separation occurred since the suture connecting the artificial tendon to the anchor is radiolucent. The separation did not seem to affect biomechanical outcomes since they were qualitatively similar between the two rabbits in the Achilles group. The similarity in outcomes may have been due to the scar tissue which, despite the anchor failure, mechanically linked the artificial tendon with the suture anchor and bone. Suture anchor failure is undesirable, so additional testing is needed to identify the mechanism of failure and prevention strategies.

Our study had several other limitations. First, though we had multiple tendon sizes available (in 2 mm increments) during surgery, we did not have a way to adjust the length of the artificial tendon intraoperatively; this may have led to a length mismatch between the artificial tendon and the replaced biological tendon. Second, since our sample size was small, we chose to perform qualitative, rather than statistical, comparisons; however, data were consistent between rabbits in each group. Third, due to hardware limitations, we measured biomechanics only from the operated hindlimb and only during stance phase. In future studies, we plan to upgrade our equipment to permit simultaneous bilateral data collection of both stance and swing phases of gait. Finally, the scope and duration of the study was limited to biomechanics up to 6 weeks post-surgery. To support clinical translation, future studies are needed to investigate other important aspects of artificial tendons, such as mechanical properties, long-term in vivo viability, possible effects of pain on biomechanics, biochemical tissue-material interactions, and effects on muscle force production.

In conclusion, our preliminary results showed, promisingly, that rabbits with an artificial tendon either maintained or recovered locomotor function. In future studies, we plan to (1) measure function for longer duration, (2) quantify the effect of artificial tendons on muscle force and architecture, and (3) implement structured rehabilitation to improve functional recovery. Our results can inform the development and clinical translation of artificial tendons for patients with irreparable tendon pathologies and defects.

## CRediT authorship contribution statement

**Patrick T. Hall:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Caleb Stubbs:** Writing – review & editing, Methodology, Investigation. **Alisha P. Pedersen:** Writing – review & editing, Investigation. **Caroline Billings:** Writing – review & editing, Investigation. **Stacy M. Stephenson:** Writing – review & editing, Conceptualization. **Cheryl B. Greenacre:** Writing – review & editing, Methodology, Investigation, Conceptualization. **David E. Anderson:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Dustin L. Crouch:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

National Institutes of Health, United States (K12HD073945), National Science Foundation, United States (Award number 1944001). Thanks to the University of Tennessee Office of Laboratory Animal Care and lab animal facility staff for assisting with animal care; and to Elkem Silicones for donating the silicone used for the artificial tendons.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2023.111520.

## References

Clites, T.R., Herr, H.M., Srinivasan, S.S., Zorzos, A.N., Carty, M.J., 2018. The Ewing amputation: the first human implementation of the agonist-antagonist myoneural interface. Plast. Reconstr. Surg. Glob. Open 6, e1997.
Early, J.S., 1999. Transmetatarsal and midfoot amputations. Clin. Orthopaed. Relat. Res. ® 361, 85–90.
Feibel, J.B., Bernacki, B.L., 2003. A review of salvage procedures after failed Achilles tendon repair. Foot AnkleClin 8, 105–114.
Hall, P.T., Bratcher, S.Z., Stubbs, C., Rifkin, R.E., Grzeskowiak, R.M., Burton, B.J., Greenacre, C.B., Stephenson, S.M., Anderson, D.E., Crouch, D.L., 2021. Fully implanted prostheses for musculoskeletal limb reconstruction after amputation: an in vivo feasibility study. Ann. Biomed. Eng. 49, 1012–1021.
Hall, P., Stubbs, C., Anderson, D.E., Greenacre, C., Crouch, D.L., 2022. Rabbit hindlimb kinematics and ground contact kinetics during the stance phase of gait. PeerJ 10, e13611.
Holmdahl, L., Risberg, B., Beck, D.E., Burns, J.W., Chegini, N., diZerega, G.S., Ellis, H., 1997. Adhesions: pathogenesis and prevention-panel discussion and summary. Eur. J. Surg. Suppl. 56–62.
Jones, L., Davidson, J., 1999. Save that arm: a study of problems in the remaining arm of unilateral upper limb amputees. Prosthet. Orthot. Int. 23, 55–58.
Leppilahti, J., Orava, S., 1998. Total Achilles tendon rupture. Sports Med. 25, 79–100.
Leppilahti, J., Puranen, J., Orava, S., 1996. Incidence of Achilles tendon rupture. Acta Orthopaedica Scandinavica 67, 277–279.
Lieber, R.L., Blevins, F.T., 1989. Skeletal muscle architecture of the rabbit hindlimb: functional implications of muscle design. J. Morphol. 199, 93–101.
Melvin, D.B., Klosterman, B., Gramza, B.R., Byrne, M.T., Weisbrode, S.L., Litsky, A.S., Clarson, S.J., 2003. A durable load bearing muscle to prosthetic coupling. Asaio J. 49, 314–319.
Melvin, A., Litsky, A., Mayerson, J., Witte, D., Melvin, D., Juncosa-Melvin, N., 2010. An artificial tendon with durable muscle interface. J. Orthop. Res. 28, 218–224.
Melvin, A., Litsky, A., Mayerson, J., Stringer, K., Melvin, D., Juncosa-Melvin, N., 2011. An artificial tendon to connect the quadriceps muscle to the Tibia. J. Orthop. Res. 29, 1775–1782.
Melvin, A.J., Litsky, A.S., Mayerson, J.L., Stringer, K., Juncosa-Melvin, N., 2012. Extended healing validation of an artificial tendon to connect the quadriceps muscle to the Tibia: 180-day study. J. Orthop. Res. 30, 1112–1117.
Murray, G.A., Semple, J.C., 1979. A review of work on artificial tendons. J. Biomed. Eng. 1, 177–184.
Nistor, L., 1981. Surgical and non-surgical treatment of Achilles Tendon rupture. A prospective randomized study. J. Bone Joint Surg. Am. 63, 394–399.
Noskovicova, N., Schuster, R., van Putten, S., Ezzo, M., Koehler, A., Boo, S., Coelho, N. M., Griggs, D., Ruminski, P., McCulloch, C.A., Hinz, B., 2021. Suppression of the fibrotic encapsulation of silicone implants by inhibiting the mechanical activation of pro-fibrotic TGF-beta. Nat. Biomed. Eng. 5, 1437–1456.

Stenroth, L., Peltonen, J., Cronin, N.J., Sipila, S., Finni, T., 2012. Age-related differences in Achilles tendon properties and triceps surae muscle architecture in vivo. J. Appl. Physiol. 1985 (113), 1537–1544.

Yamamoto, A., Takagishi, K., Osawa, T., Yanagawa, T., Nakajima, D., Shitara, H., Kobayashi, T., 2010. Prevalence and risk factors of a rotator cuff tear in the general population. J. Shoulder Elbow Surg. 19, 116–120.

Zajac, F.E., 1989. Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control. Critical Rev Biomed Eng 17, 359–411.