

To What Degree is Spider Silk a Better Alternative to a Conventional Graft in Ligament Reconstruction Surgery?

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ABSTRACT

The purpose of this review is to evaluate synthetic spider silk as a potential ligament in anterior cruciate ligament (ACL) reconstruction surgery. Synthetic spider silk, produced using ion-doped and twisted hydrogel fibers, has high capabilities in tensile strength, damping capacity, toughness, stretchability, and Young's modulus, along with biocompatible properties. It surpasses the commonly used bone-tendon-bone (BTB) graft in tensile strength and stiffness, and the synthetic ligament augmentation reconstruction system (LARS) graft in tensile strength. Clinical trials are needed to fully assess the synthetic spider silk's viability as a reliable graft in ACL reconstruction. The lack of data on biomechanical properties is apparent in the current literature surrounding ACL grafts. Further research and trials need to be done on varying biomechanical properties (Stretchability, damping capacity, toughness, stiffness) in order to determine the best graft for ACL reconstruction surgery.

Keywords: Synthetic spider silk, Anterior cruciate ligament (ACL), Graft materials, Ligament reconstruction, Damping capacity, Bone-tendon-bone (BTB) graft, LARS synthetic graft, Hydrogel fibers

INTRODUCTION

In the past 15 years, amongst high school athletes, the incidence of anterior cruciate ligament (ACL) has increased by 25.9% (1-3). The current golden standard for treatment is surgical ligament reconstruction, which involves using either autograft or allograft. Using this golden standard, only 50% of athletes are able to return

to their previous level of play prior to the initial injury (4). Failure rates of the grafted ligament post reconstruction have been reported to be up to 40% in the literature using current techniques (4).

As allografts and autografts are not a perfect solution for ACL tears, the inclusion of spider silk as a material for ligament reconstruction surgery may be a viable alternative. Spider silk has been widely studied and accepted for its high tensile strength, stretchability, damping capacity, and toughness. Natural spider silk, however, is difficult to mass produce, as it cannot be recreated in a laboratory, and naturally harvesting from spiders is challenging due to costs and sustainability (5). Synthetic spider silk compounds would be more plausible for use in ligamentous repair as they are not limited by these factors. Synthetic spider silk may also

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be a better alternative to the current gold standard due to its strength, reliability, and durability. Synthetic spider silk formed from ion-doped and twisted core-sheath hydrogel fibers exhibit a tensile strength of 895 MPa, a stretchability of 43.3%, and a Young's modulus of 28.7 GPa (6). Comparatively, the patellar bone-to-bone (BTB) graft, one of the most common graft choices in ACL repair (7), has a max tensile strength of 36.9 MPa, a stiffness of 210-278 N/mm, a stretchability of 11.4 % and a Young's modulus of 225 to 337.8 MPa¹⁹.

This literature review aims to determine if the introduction of synthetic spider silk, specifically created from ion-doped and twisted hydrogel fibers, would be comparable as a graft to the current gold standard of allografts and autografts. The review will examine the properties of the material and the practicality of installation to determine if synthetic spider silk is a better alternative to the current gold standard.

METHODS AND MATERIALS

In this review, I screened for studies utilizing spider silk as a therapeutic intervention found on PubMed and Google Scholar. The inclusion criteria for studies on synthetic spider silk were that they provided detailed data on its biomechanical properties. The process to fabricate the synthetic silk had to be clearly explained with data that could be reliably analyzed. Additionally, the material needed to be feasible for potential integration into the body, meaning it was made from materials that could or have been used in biological applications, such as hydrogel fibers. A systematic approach was utilized to evaluate studies. Abstracts were read by the primary author and evaluated for inclusion criteria. Studies that met the inclusion criteria were included for a full text review. Full articles were evaluated, and only those that satisfied both inclusion and exclusion criteria were utilized for this review. Exclusion criteria included

studies that did not provide adequate biomechanical data or were not feasible for integration in the body. To provide better characterization of the viability of use of spider silk as a therapeutic intervention in ACL reconstruction, I chose to compare this to the widely accepted and utilized patellar bone-to-bone graft and Ligament augmentation and reconstruction system (LARS) synthetic grafts.

RESULTS

Limitations of Natural Spider Silk Feasibility

Natural spider silk is made of proteins with high concentrations of nonpolar and hydrophobic amino acids arranged in repetitive amino acid sequences, which form a material with high tensile strength and durability (8). However, the production of natural spider silk is limited by the cannibalistic tendencies of spiders, making them unsuitable for livestock breeding as they cannot be enclosed with one another. Another method of harvesting silk is through collecting egg sacks or milking, over 70 workers and \$500,000 worth of work are needed in order to produce 3.4m of spider silk textile (5).

Comparison of Natural vs Synthetic Spider Silk Properties

To address the limitations of natural silk production, a synthetic silk has been developed using ion-doped and twisted hydrogel fibers. This synthetic silk exhibits a tensile strength of 895 MPa, stretchability of 43.3%, a damping capacity of 95%, a toughness of 370 MJ⁻³, and Young's modulus of 28.7 GPa (Table 1) (6).

A study conducted by Woo *et al.* recorded the tensile properties of knee cadavers from three groups: young (22 to 35), middle-aged (40 to 50), and older (60 to 97), and found that as age advanced, mechanical properties such as linear stiffness, ultimate load, and energy absorbed weakened.

Table 1. Properties of Anterior Cruciate Ligament (ACL) Grafts by Graft Type

| Property | Synthetic Silk | Bone-Patellar-Bone Graft | LARS Synthetic Graft |
|----------------------------------|----------------------|--------------------------|----------------------|
| Tensile Strength | 895 MPa | 33.4 MPa | 117 MPa |
| Stretchability/Elongation | 43.30% | 11.40% | NA |
| Young's Modulus/Stiffness | 28.7 GPa | 225–337.8 MPa | NA |
| Toughness | 370 MJ ⁻³ | NA | NA |
| Damping Capacity | 95% | NA | NA |

Current ACL Gold Standard Grafts' Properties

A bone patellar tendon bone (BTB) graft, a commonly used graft in ACL reconstruction⁷, was reported to have a tensile strength of 1581-1784 N, with a cross-sectional area of 48.4 mm², resulting in a 32.7 to 36.9 MPa, stretchability of 11.4%, and Young's modulus of 225 to 337.8 MPa¹⁹ (Table 1).

The LARS is a type of synthetic graft often used in ligamentous reconstruction. This synthetic graft is formed from terephthalic polyethylene polyester fibers designed to follow the anatomic structure of an ACL. Available studies report a tensile strength of 2300 N and a diameter of 5mm, resulting in a tensile strength of 117 MPa⁹ and overall mechanical failure rates of 33.3% (10). However, no values were reported for Young's modulus, stretchability, damping capacity, or toughness. The graft is considered desirable for its shorter surgical time, fewer postoperative complications, reduced morbidity at the harvest site, faster postoperative recovery, and lower incidence of postoperative arthrofibrosis; however, it should be noted that 40% of patients were unable to return to the same level of sport as before reconstruction (11).

DISCUSSION

Synthetic Spider Silk favorability over Natural Spider Silk

Natural spider silk is a strong compound in terms of strength and durability, with high elastic potential and high stress and strain levels; however, it is unsustainable to produce. Collecting naturally spun spider silk comes with challenges. Spiders are cannibalistic; therefore, they cannot be enclosed with each other, creating difficulties for large-scale production. Collecting spider silk through milking or collecting egg sacks is also unsustainable, as over \$500,000 and 70 workers are needed to produce 3.4m of textile, which is neither labor nor cost-effective (5). These diminishing returns make it less practical to use in ligament reconstruction. The difficulties associated with naturally harvesting spider silk have led researchers to develop methods for producing synthetic silk in a laboratory, which is not reliant on the challenges of natural silk production.

Synthetic spider silk constructed from ion-doped and twisted hydrogel fibers has been cited to be favorable in medical applications due to its capable mechanical properties. This synthetic silk is made from hydrogel fibers, which are a biocompatible material due to their similar molecular properties to native human tissues

(12). Hydrogels are being integrated into the medical field through scaffolds and, in theory, would be a suitable material simply in terms of compatibility. However, it is important to note that there are no fully understood implications of any mounted immune response this material may cause or the effects of long-term biodegradability after integration.

Woo *et al.* (13) performed a study on younger (22 to 35), middle (40 to 50), and older (60 to 97) cadaver knees to determine their tensile properties. It was found that the linear stiffness, ultimate load, and energy absorbed decreased significantly with advanced age groups. The lower tensile capacities make older individuals more susceptible to ACL rupture (14). In contrast, and in the case of the synthetic silk graft, the higher linear stiffness, ultimate load, and energy absorbed make it less likely to rupture.

In the case of synthetic silk, it displays a tensile strength of 895 MPa, similar to stainless steel, 860 MPa, and titanium, 900 MPa (15). Tensile strength is important because it models how much stress a graft can withstand. This elevated tensile strength allows the graft to withstand large amounts of load and energy, resulting in lower chances of rupture with strenuous activity, jumping, landing, and taking direct forces (16). The synthetic silk has an elevated toughness of 370 MJ³. Toughness is the total amount of energy a material can absorb before it fractures (17). It serves as a marker of a graft's capacity to deal with multidirectional forces.

The elevated damping capacity of 95% demonstrates that synthetic silk dissipates mechanical energy well. This energy dissipation minimizes the accumulation of stress, increasing a material's fatigue resistance (18). Having better fatigue resistance is crucial because ligaments are subject to thousands of repeated cycles every day, from walking to athletic movements like running, jumping, and pivoting. Young's modulus is a measurement of stiffness. The silk possesses an extremely high stiffness of 28.7 GPa. This high stiffness is stiff enough to stabilize the joint, and paired with a high stretchability of 43.3%, avoids being too rigid. The silk is able to stretch under dynamic loads without snapping. This high stiffness and stretchability improve load distribution and reduce stress concentration, leading to a more reliable graft.

Comparative Analysis of other common graft types

To compare the properties of the synthetic silk to the patellar BTB graft, a comparative analysis was conducted. The BTB graft is only able to withstand a maximum of 36.7 tensile force applied, and has a stretchability

of 11.4% (19). Thus, the synthetic silk graft, in theory, should withstand up to 2680% (Synthetic Spider Silk Tensile Strength/BTB Graft Tensile strength=895MPa /33.4MPa=26.8) more force and elongate 3.8 (Synthetic Spider Silk Stretchability / BTB Graft Stretchability = 43.3% / 11.4% = 3.8) times as long as the BTB graft. This higher tensile strength means that the graft is able to withstand higher forces being applied to it, therefore making it less susceptible to rupture. The increased stretchability, or elongation, allows the graft to deform more before breaking, potentially absorbing more force and distributing forces across the tissue, also making it less susceptible to rupture.

The LARS graft offers surgical convenience and reduced complications, but for younger athletes, synthetic silk may be a better alternative. LARS synthetic graft significantly falls short in terms of tensile strength compared to the synthetic silk, 117 to 895 MPa. Additionally, the LARS graft lacks available data on other mechanical properties such as toughness, stretchability, stiffness, and damping capacity. In contrast, synthetic silk provides a good biomechanical profile: its high toughness allows resistance from multidirectional forces, its damping capacity increases fatigue resistance, and its stiffness and stretchability, while much higher than a native ACL, may offer functional advantages in energy absorption and load distribution, all leading to a high performing graft and surpassing the LARS graft.

Limitations

While the biomechanical properties and strengths of synthetic spider silk are promising, there are still key limitations. The lack of in vivo studies, immunogenicity concerns, biodegradation, and long-term biological tissue integration need further research and investigation to evaluate the material's true potential for clinical application. Clinical trials are needed, and clinical outcomes must also be monitored and followed up with to fully assess its viability as a reliable graft in ACL reconstruction. Throughout my research, a gap in current literature on ACL graft biomechanical metrics is apparent, particularly for BTB and LARS grafts. Tensile strength is often reported; however, other mechanical properties such as toughness, damping capacity, stretchability, and stiffness are underreported or absent. These properties are important in understanding a graft's real-world performance under multidirectional and repetitive loading conditions, and allow for better analysis of ACL function. For example, without data on toughness, it is impossible to determine how well a

graft material will resist failure from different stresses, such as torsion and impact. Similarly, damping capacity shows how effectively a graft can absorb and dissipate mechanical energy, which reduces cumulative stress and increases fatigue resistance; however, this metric is seldom measured in traditional graft studies. The lack of uniform testing protocols makes cross-comparisons difficult and limits depth. This lack of standardization ultimately limits the ability to optimize graft selection based on patient profile, such as athletes vs. elderly patients. Closing these gaps in biomechanical metrics would increase our understanding of what makes an ideal graft material and enables a more objective comparison of new technologies such as synthetic spider silk.

CONCLUSION

The incidence of ACL rupture in high school athletes has risen by 25.9% in the past 20 years. The gold standard of ligament reconstruction has failure rates up to 40%. Synthetic spider silk created from ion-doped and twisted hydrogel fibers has favorable properties in tensile strength, toughness, damping capacity, and Young's modulus for use in ACL reconstruction. Synthetic spider silk has more promising biomechanical properties than what current grafts are available; however, research is needed on its overall efficacy and viability in clinical trials. Additionally, the currently used grafts, such as the BTB graft and LARS synthetic grafts mechanical properties need to be further investigated in order to create a more objective comparison of different graft types.

CONFLICT OF INTERESTS

The author declares that there are no conflicts of interest regarding the publication of this article.

REFERENCES

1. Beck NA, Lawrence JTR, Nordin JD, DeFor TA, *et al.* ACL Tears in School-Aged Children and Adolescents Over 20 Years. *Pediatrics*. 2017; 139 (3): e20161877. doi:10.1542/peds.2016-1877
2. Institute A. Analysis: Serious knee injury among teen athletes grows 26%. November 27, 2023. Accessed May 30, 2025. <https://projectplay.org/news/2023/11/22/analysis-serious-knee-injury-among-teen-athletes-grows-26>
3. Maheshwer B, Paliobeis A, Halkiadakis P, Konda S, *et al.* Anterior Cruciate Ligament Tears in the Adolescent

- Population: Injury Demographics and Risk of Reinjury Among High School Athletes. *J Pediatr Orthop.* 2023; 43 (10): 591-597. doi:10.1097/BPO.0000000000002505
4. Boyd E, Endres NK, Geeslin AG. Postoperative healing and complications based on anterior cruciate ligament reconstruction graft type. *Ann Jt.* 2024; 9: 30. doi:10.21037/aoj-24-3
 5. Ramezaniaghdam M, Nahdi ND, Reski R. Recombinant Spider Silk: Promises and Bottlenecks. *Front Bioeng Biotechnol.* 2022;10:835637. doi:10.3389/fbioe.2022.835637
 6. Dou Y, Wang ZP, He W, *et al.* Artificial spider silk from ion-doped and twisted core-sheath hydrogel fibres. *Nat Commun.* 2019; 10 (1): 5293. doi:10.1038/s41467-019-13257-4
 7. Dhammi IK, Rehan-Ul-Haq, Kumar S. Graft choices for anterior cruciate ligament reconstruction. *Indian J Orthop.* 2015; 49 (2): 127-128. doi:10.4103/0019-5413.152393
 8. Römer L, Scheibel T. The elaborate structure of spider silk. *Prion.* 2008; 2 (4): 154-161. doi:10.4161/pri.2.4.7490
 9. Parchi PD, Ciapini G, Paglialunga C, *et al.* Anterior Cruciate Ligament Reconstruction with LARS Artificial Ligament—Clinical Results after a Long-Term Follow-Up. *Joints.* 2018; 6 (2): 75-79. doi:10.1055/s-0038-1653950
 10. Tulloch SJ, Devitt BM, Porter T, *et al.* Primary ACL reconstruction using the LARS device is associated with a high failure rate at minimum of 6-year follow-up. *Knee Surg Sports Traumatol Arthrosc Off J ESSKA.* 2019; 27 (11): 3626-3632. doi:10.1007/s00167-019-05478-3
 11. Moretti L, Garofalo R, Cassano GD, *et al.* Anterior Cruciate Ligament Reconstruction with LARS Synthetic Ligament: Outcomes and Failures. *J Clin Med.* 2025; 14 (1): 32. doi:10.3390/jcm14010032
 12. Chen G, Yang Z, Pan H, *et al.* A Review of Hydrogel Fiber: Design, Synthesis, Applications, and Futures. *Chem Rev.* Published online May 30, 2025. doi:10.1021/acs.chemrev.5c00159
 13. Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med.* 1991; 19 (3): 217-225. doi:10.1177/036354659101900303
 14. Aging and Tendon Health | OKC Orthopedics. <https://okcorthopedics.com/blog/geriatric-orthopedics/aging-tendon-health-tips/> (accessed on 2024-6-6)
 15. Young's Modulus of Elasticity – Values for Common Materials. Accessed June 6, 2025. https://www.engineeringtoolbox.com/young-modulus-d_417.html
 16. Noyes FR, Butler DL, Grood ES, Zernicke RF, Hefzy MS. Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. *J Bone Joint Surg Am.* 1984; 66 (3): 344-352. <https://doi.org/10.2106/00004623-198466030-00005>
 17. Engineer TE. Understanding Material Strength, Ductility and Toughness. November 19, 2020. <https://efficientengineer.com/material-strength-ductility-toughness/> (accessed on 2025-6-6)
 18. Zhang J, Perez RJ, Lavernia EJ. Documentation of damping capacity of metallic, ceramic and metal-matrix composite materials. *J Mater Sci.* 1993; 28 (9): 2395-2404. doi:10.1007/BF01151671
 19. Banovetz MT, Kennedy NI, LaPrade RF, Engebretsen L, Moatshe G. Biomechanical considerations for graft choice in anterior cruciate ligament reconstruction. *Annals of Joint.* 2023; 8: 17. doi:10.21037/aoj-22-50