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Review

Biomechanical properties of common graft choices for anterior cruciate ligament reconstruction: A systematic review

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ABSTRACT

Background: This systematic review explores the differences in the intrinsic biomechanical properties of different graft sources used in anterior cruciate ligament (ACL) reconstruction as tested in a laboratory setting.
Methods: Following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, two authors conducted a systematic review exploring the biomechanical properties of ACL graft sources (querying PubMed, Cochrane, and Embase databases). Using the keywords "anterior cruciate ligament graft," "biomechanics," and "biomechanical testing," relevant articles of any level of evidence were identified as eligible and included if they reported on the biomechanical properties of skeletally immature or mature ACL grafts solely and if the grafts were studied in vitro, in isolation, and under similar testing conditions. Studies were excluded if performed on both skeletally immature and mature or non-human grafts, or if the grafts were tested after fixation in a cadaveric knee. For each graft, failure load, stiffness, Young's modulus, maximum stress, and maximum strain were recorded.
Findings: Twenty-six articles were included. Most studies reported equal or increased biomechanical failure load and stiffness of their tested bone-patellar tendon-bone, hamstring, quadriceps, peroneus longus, tibialis anterior and posterior, Achilles, tensor fascia lata, and iliotibial band grafts compared to the native ACL. All recorded biomechanical properties had similar values between graft types.
Interpretation: Most grafts used for ACL reconstruction are biomechanically superior to the native ACL. Utilizing a proper graft, combined with a standard surgical technique and a rigorous rehabilitation before and after surgery, will improve outcomes of ACL reconstruction.

1. Introduction

Anterior cruciate ligament (ACL) tears are common injuries that can severely affect a patient's knee stability, mobility, and ability to play sports if not treated properly. Investigators have extensively studied risk factors, prevention strategies, treatment approaches, and outcomes (Anderson et al., 2016; Chalmers et al., 2014; Pappas et al., 2013; Posthumus et al., 2011). Each surgeon must strive to recreate the native knee's kinematics and articular loading as closely as possible in hopes of maximizing stability and mobility. A successful ACL reconstruction depends on the following factors: tunnel placement, graft type, graft preconditioning, femoral and tibial fixation, successful rehabilitation, and severity of associated pathologies. Multiple studies have explored the factors above, aiming to identify which combination of these factors will maximize patient outcomes (Brand et al., 2000; Claes et al., 2011; Lobb et al., 2012; Woo et al., 1998). Specifically, the biomechanical properties of the various available grafts have been extensively studied in hopes of finding the graft source that will best mirror native ACL biomechanics.

The ACL is a viscoelastic structure that functions as a primary stabilizer to prevent anterior tibial translation and a secondary stabilizer to prevent tibial rotation. It undergoes creep and relaxation, resulting in laxity after a certain amount of loading that returns to its original

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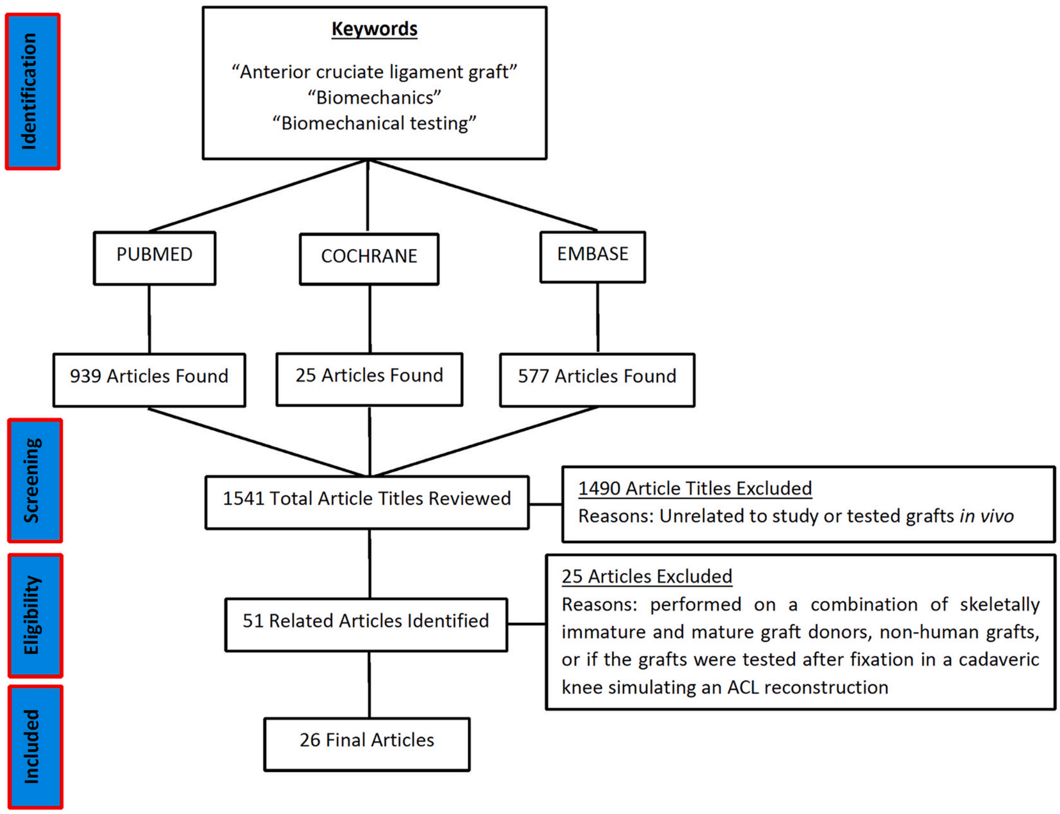


Fig. 1. Risk of bias assessment using RoBANS tool. All studies included in the systematic review were assessed for selection bias (due to patient selection and confounding factors), performance bias, detection bias, attrition bias, and reporting bias. A red plus sign indicates high study bias, while a green minus sign indicates low study bias. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stiffness after a period of rest. Previous studies have quantified the ultimate failure load of the native ACL as 2160 ± 157 Newtons (N), while mean ACL stiffness was 242 ± 28 N/mm (Woo et al., 1991; Woo et al., 1999). These values decreased with age and axis of loading. Forces on the ACL in situ have been reported during walking as 169 N, ascending stairs as below 100 N, and descending stairs as 445 N. Due to this as well as the fact that maximum failure load in older ACL cadaveric specimens being reported as 496 ± 85 N, it has been hypothesized that graft ultimate failure loads must be higher than this to serve as a suitable ACL replacement (Marieswaran et al., 2018).

Multiple studies have explored various graft sources, and there is consensus that various graft sources can be successfully utilized to reproduce native ACL biomechanics. However, there is no consensus on which graft source is the most biomechanically superior when compared to each other. The purpose of this systematic review is to explore the differences in the intrinsic biomechanical properties of different graft sources used in ACL reconstruction as tested in a laboratory setting. The authors hypothesize that there are multiple ACL graft sources that, when biomechanically tested in vitro, will produce similar biomechanical properties that can be successfully used to reproduce native ACL biomechanics.

2. Methods

The authors conducted a systematic review of articles exploring the biomechanical properties of ACL graft sources. This review follows a protocol decided upon previously by the primary and senior author and detailed below. This protocol is not published online, nor is the systematic review officially registered. However, PROSPERO and PubMed were queried to confirm that no previous systematic reviews on this topic have been published. Following PRISMA guidelines, PubMed, Cochrane, and Embase databases were queried for relevant articles (Fig. 2). Using the keywords (with no limits) "anterior cruciate ligament graft" in isolation and in combination with "biomechanics" or "biomechanical testing," 1541 related titles were identified and screened for pertinence. After review of each article by two authors, 51 related biomechanical articles were found and eligible for inclusion, excluding 1490 unrelated articles. Studies of any level of evidence and sample size, regardless of graft source (cadaver), graft type, testing conditions, or when the graft was tested after harvest, were eligible for inclusion. Studies performed in any country and published in any year were also eligible for inclusion. The 1490 unrelated articles almost exclusively did not study the biomechanical properties of ACL grafts, while a few articles studied the clinical outcomes of in vivo grafts. Articles were included if they reported on the biomechanical properties of skeletally immature or mature ACL grafts solely (without combining the results of both types of grafts in a way they cannot be distinguished), if the grafts (which could be from any source) were studied in vitro, if they were studied in isolation without being attached to cadaver knees, and if all the grafts were all studied under the same testing conditions. Studies were excluded if testing was performed and outcomes were reported on a combination of skeletally immature and mature graft donors in a way that the data could not be stratified between the two graft types, if testing was performed on non-human grafts, or if the grafts were tested after fixation in a cadaveric knee simulating an ACL reconstruction.

In total, 26 articles were included in our study after independent review by two authors (Table 1). Each study was analyzed for graft sources studied, graft preparation details, and testing conditions. Graft types studied include bone-patellar tendon-bone, hamstring, quadriceps, peroneus longus, tibialis anterior and posterior, Achilles, tensor fascia lata, and iliotibial band grafts. For each graft type, graft details, diameter and area, failure load in Newtons (N), stiffness in Newton/millimeters (N/mm), Young's Modulus in Megapascals (MPa), maximum stress in Megapascals (MPa), and maximum failure strain in

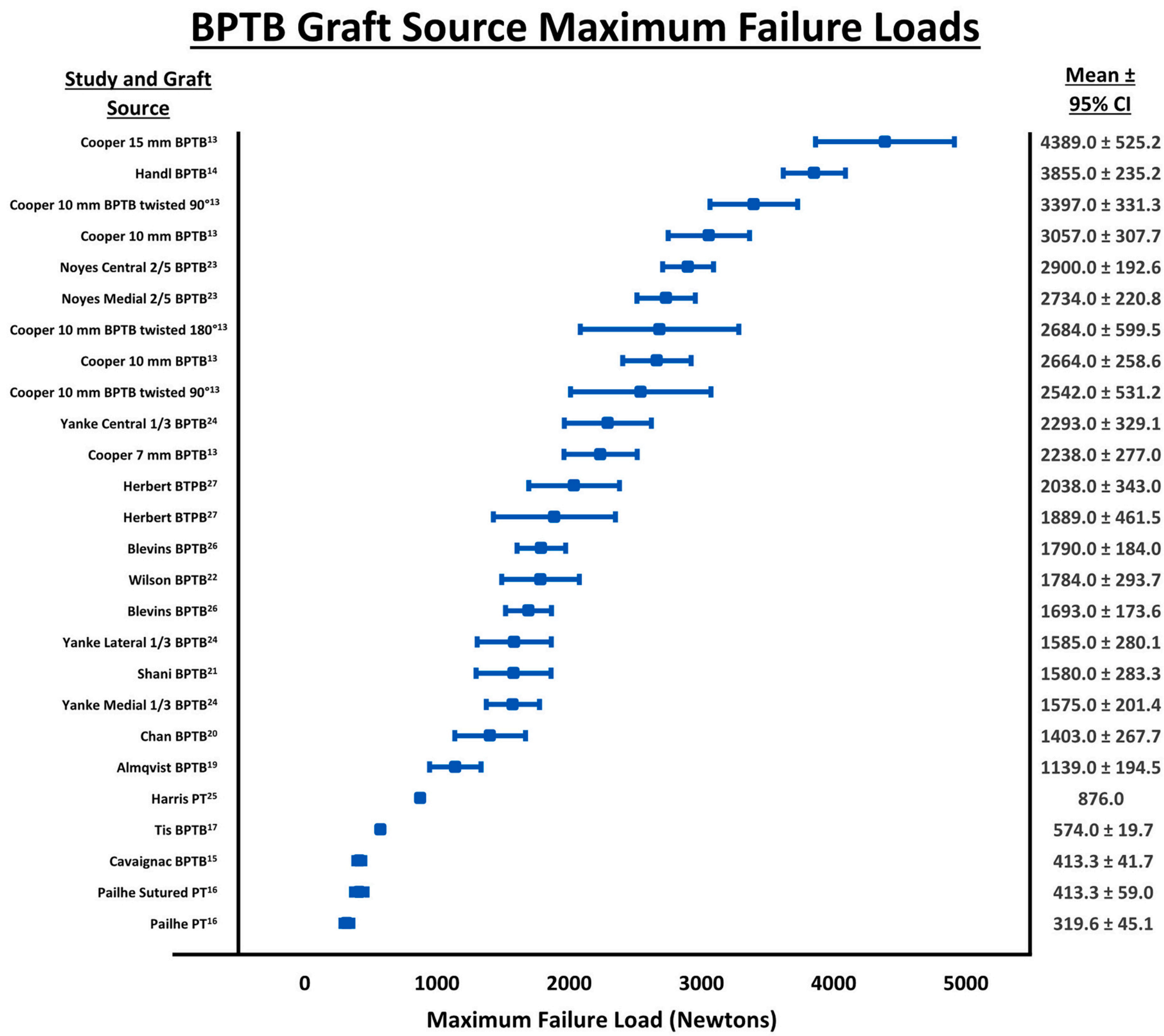


Fig. 2. Results of systematic review.

percent (%) were recorded by one investigator using an Excel spreadsheet. Data was reported using mean values, standard deviation, and 95% confidence intervals, looking for any difference in overall graft property ranges. Weighted means and a meta-analysis were not performed due to the heterogeneity of the included studies. Young's Modulus (modulus of elasticity) is defined as stress (force divided by area) divided by strain (change in length divided by initial length). It is the intrinsic material property upon which stiffness (a geometric property) is directly proportional to. A bias assessment was performed within individual studies (using RoBANS tool) and across studies (publication bias) by two authors (detailed for each study in the results section) (Kim et al., 2013a). However, each study was included in our study regardless of bias and given equal importance due to the limited number of studies that met our stringent inclusion criteria.

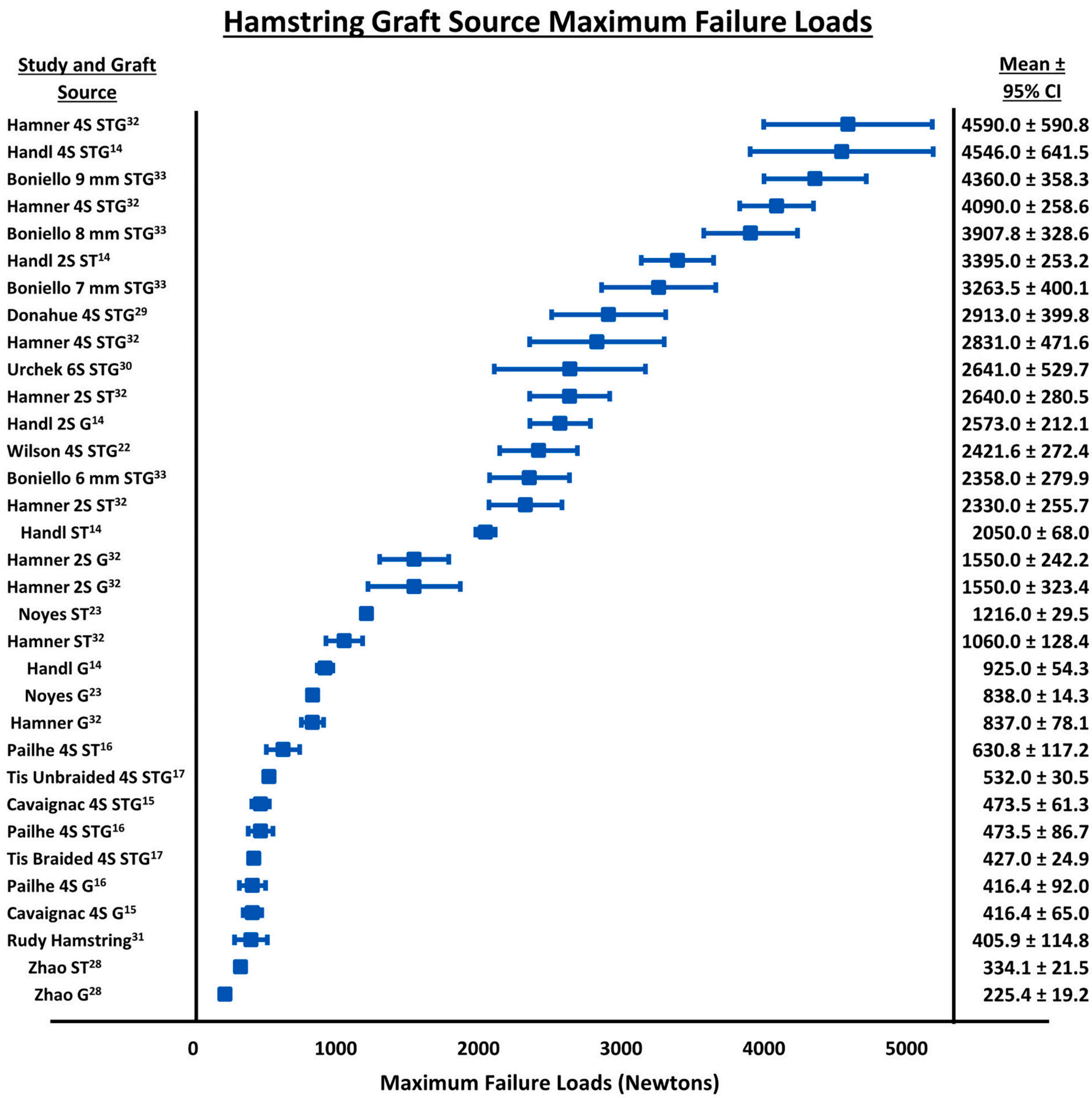
3. Results

3.1. Bone-patellar tendon-bone graft

Fifteen studies tested the biomechanical properties of 401bone-patellar tendon-bone (BPTB) grafts (Almqvist et al., 2007; Biuk et al., 2015; Blevins et al., 1994; Cavaignac et al., 2016; Chan et al., 2010; Harris et al., 1997; Herbert et al., 2016; Noyes et al., 1984; Pailhé et al., 2015; Shani et al., 2016; Tis et al., 2002; Wilson et al., 1999; Yanke et al., 2013). Overall, in the included studies, failure load ranged from 319.56 to 4389 N, stiffness from 158 to 685.2 $N^{/mm}$, Young's Modulus from 184 to 337.8 MPa, maximum stress from 21.6 to 101.3 MPa, and failure strain from 0.162 to 25% (Figs. 3–7).

Most studies utilized a central-third bone-patellar tendon-bone graft. Cooper et al.'s (Cooper et al., 1993) 15 mm graft had the highest reported failure loads (4389 N and graft stiffness (555.5 N/mm) in this group. Cavaignaic, Pailhe, and Tis reported the lowest graft failure loads and stiffness in this group (Cavaignac et al., 2016; Pailhé et al., 2015; Tis et al., 2002). Cooper also tested graft properties when placed in different configurations, reporting that twisting their BPTB graft to 90 degrees and 180 degrees yielded similar biomechanical properties to their non-twisted grafts.

In comparison, two studies evaluated BPTB grafts harvested from different parts of the donor patellar tendon. In their classic study, Noyes et al. (1984)) explored BPTB grafts harvested from the central 40% and the medial 40% of the donor patellar tendon, finding similar failure load (2900.0 N versus 2734.0 N) and stiffness (685.0 N/mm versus 650.0 N/mm) between the two grafts. Both were biomechanically superior to native ACL grafts. However, Yanke et al. reported higher mean failure load (2293.0 N), stiffness (365.0 N/mm), maximum stress (45.0 MPa), and failure strain (19.0%) in their grafts harvested from the central 1/3 compared to the medial and lateral 1/3 of the donor tendon, but the difference between values did not always represent a significant



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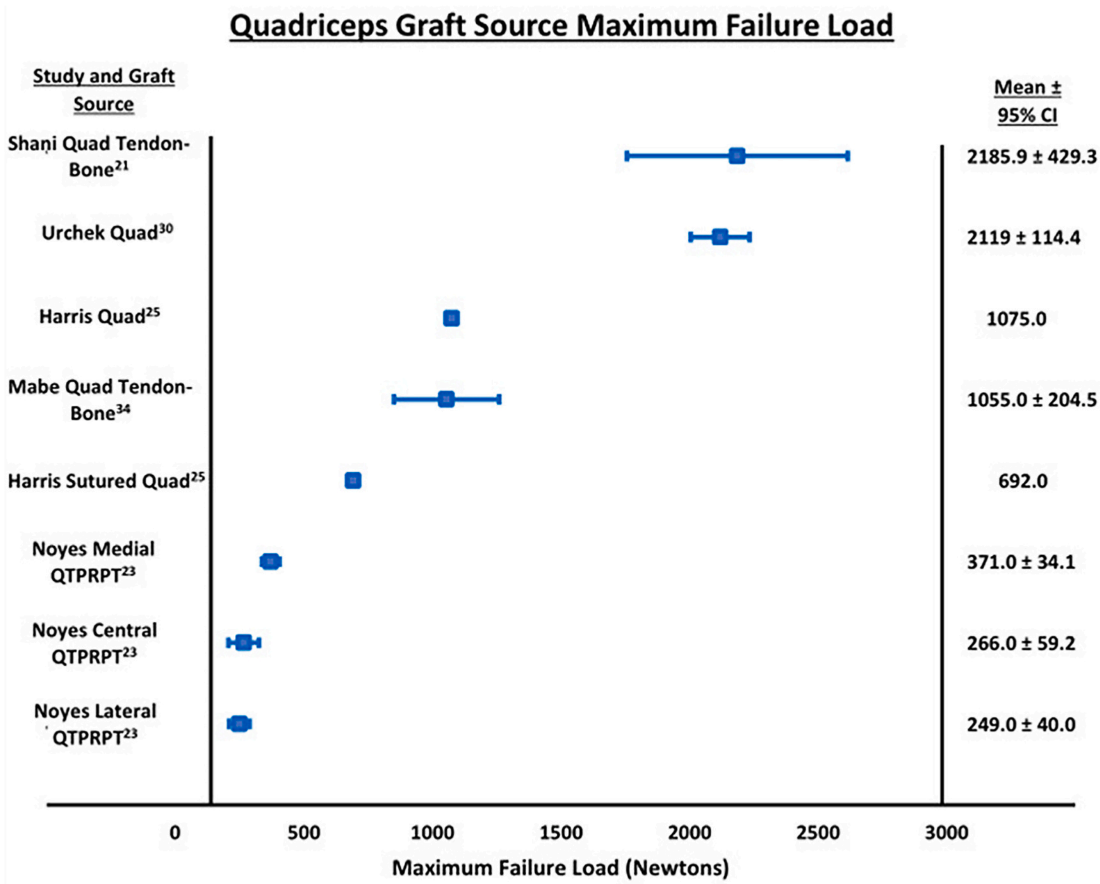
difference (Yanke et al., 2013). In addition, only one study tested a patellar tendon graft without edge bone blocks, reporting a relatively low failure load (876.0 N) (Harris et al., 1997).

Additional studies explore the effect of miscellaneous extrinsic factors on graft biomechanics. Pailhe et al. studied the effecting of suturing grafts on biomechanical properties, reporting higher failure loads (413.0 N versus 319.0 N) but similar stiffness (159.0 N/mm versus 165.0 N/mm) of sutured versus non-sutured BPTB grafts. Furthermore, Blevins et al. (1994)) explored the effects of donor age and strain rate on the biomechanical properties of their BPTB grafts. After testing at both 10% and 100% elongation per second, they found that tensile strength and elastic modulus were not affected by strain rate, while their specimens tested at 100% strain rate had a weak but significant negative correlation between modulus and age. Finally, conventional and decellularized BPTB grafts were found to have similar failure loads (1889.0 N and 2038.0 N) and failure strain (7% and 8%) in Herbert's study (Herbert et al., 2016).

3.2. Hamstring

Thirteen studies tested the biomechanical properties of 581 total hamstring grafts (Biuk et al., 2015; Boniello et al., 2015; Cavaignac et al., 2016; Donahue et al., 2002; Hamner et al., 1999; Handl et al., 2007; Noyes et al., 1984; Pailhé et al., 2015; Rudy and Phatama, 2017; Tis et al., 2002; Urchek and Karas, 2019; Wilson et al., 1999; Zhao and Huangfu, 2012). This group has a high degree of variability in graft type tested (one to eight strands using gracilis and semitendinosus tendons). Overall, in the included studies failure load ranged from 225.4 to 4590.0 N, stiffness from 4.1 to 1148.0 $N^{/mm}$, Young's Modulus from 144.8 to 904.0 MPa, maximum stress from 65.6 to 156.0 MPa, and failure strain from 0.3 to 33.0% (Figs. 3–7).

It is important to first highlight the differences between grafts of different strands. When single strand hamstring grafts were tested, semitendinosus grafts (334.0 N–2050.0 N) had higher maximum loads to failure than gracilis grafts (225.0 N–925.0 N) (Hamner et al., 1999; Handl et al., 2007; Noyes et al., 1984; Zhao and Huangfu, 2012). Biuk et al. (2015)) only tested failure strain for their single strand grafts and at a submaximal load to failure of 30 N, reporting values



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[semitendinosus (0.9%) and gracilis (1.5%)] much lower than other reported final strains in this group (13.3%–33.0%) but higher than their 4-strand hamstring graft (0.3%). Only 2 studies reported on 2-strand grafts, with semitendinosus grafts having higher failure loads [2330.0 N–3395.0 N) vs. (1550.0 N–2573.0 N)] and stiffness values [(469.0 N/mm–534.0 N/mm) vs. (336.0 N/mm vs. 432.0 N/mm)] compared to gracilis grafts (Hamner et al., 1999; Handl et al., 2007). These values were also higher than the biomechanical properties of single strand grafts in their respective studies, although these were not statistically compared. Hamner et al. did find that their four strand grafts had higher maximum load to failure (4090.0 N) and stiffness (776.0 N/mm) but not stress (77.7) compared to their 2-strand grafts. Multiple other studies tested the properties of 4-strand grafts, the most common hamstring graft tested, reporting failure loads from 416.4 N to 4590.0 N and stiffness from 192.9 N/mm to 861.0 N/mm (Cavaignac et al., 2016; Donahue et al., 2002; Hamner et al., 1999; Handl et al., 2007; Pailhé et al., 2015; Wilson et al., 1999). Urchek was the only study that studied 6-strand STG grafts, reporting loads to failure (2641.0 N) and stiffness (1148.0 N/mm) similar to other hamstring grafts and higher than the native ACL (Urchek and Karas, 2019). In addition, Rudy et al. (Rudy and Phatama, 2017) tested an unspecified hamstring graft, reporting the lowest failure load for hamstring grafts in this study (405.9 N).

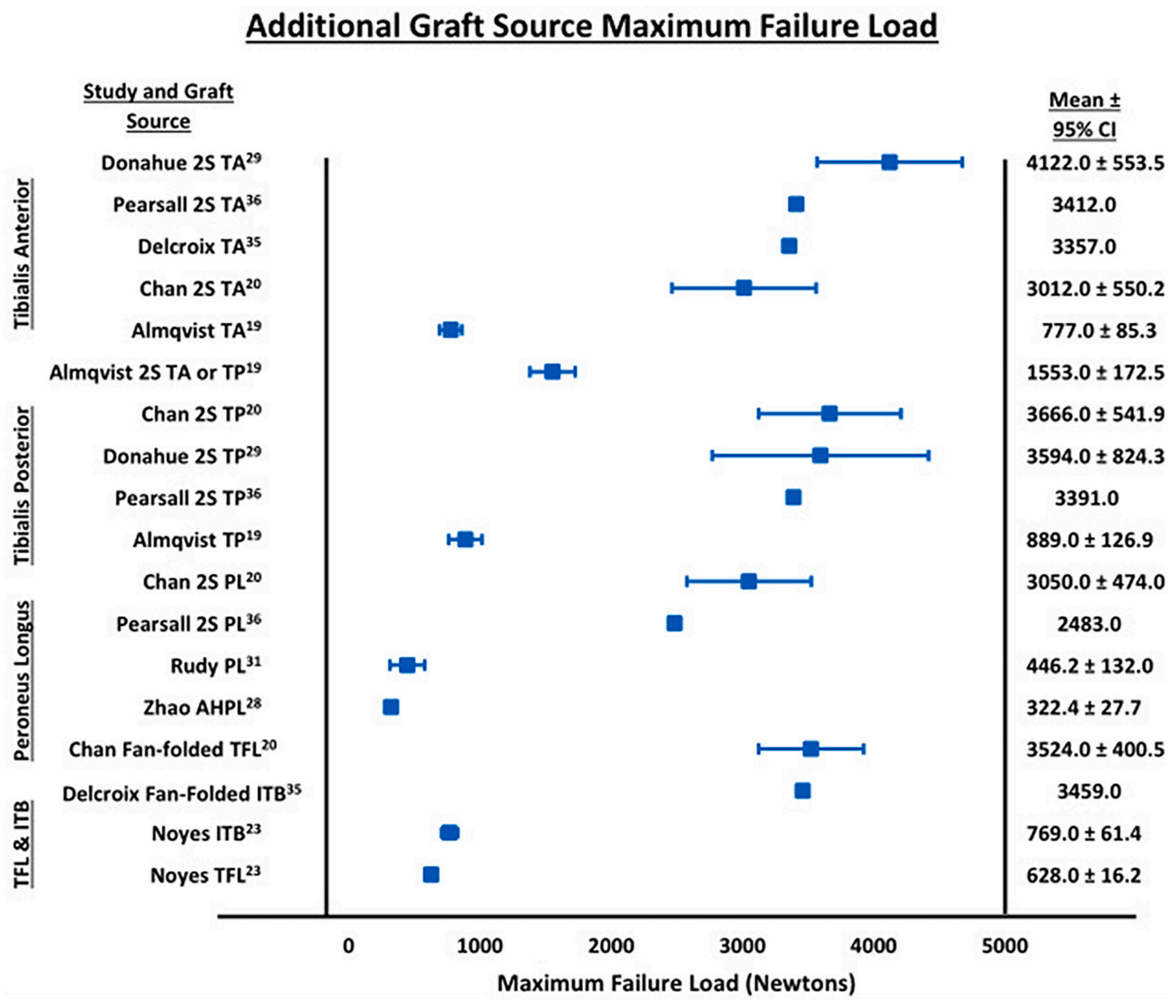
Two other studies looked at hamstring configuration and diameter. When hamstring graft configuration was explored, braided 4-strand STG (semitendinosus and gracilis combined) grafts (maximum failure load 427.0 N and stiffness 76.1 N/mm) were biomechanically inferior to unbraided 4-strand STG grafts (maximum failure load 532.0 N and stiffness 139.0 N/mm) (Tis et al., 2002). Furthermore, only one study tested STG grafts of different sizes (Boniello et al., 2015), finding that tensile strength increased with size from 6 to 9 mm grafts.

Finally, two studies explored testing conditions on their reported graft biomechanical properties. Handl et al. (2007)) tested single, double, and 4-strand tendon grafts using a custom designed drop weight system, finding increases in maximum load to failure and stiffness and a decreased maximum stress with increasing graft strand number (without any statistical comparison between graft sizes). Hamner et al. (1999)) found similar trends when testing single, double, and 4-strand hamstring grafts (as mentioned above), including higher values when their graft was tensioned by weight versus manually.

3.3. *Quadriceps*

Five studies explored the biomechanical properties of 59 quadriceps tendons in isolation (Harris et al., 1997; Mabe and Hunter, 2014; Noyes et al., 1984; Shani et al., 2016; Urchek and Karas, 2019). Overall, in the included studies, failure loads ranged from 249.0 to 2185.9 N, stiffness from 17.0 to 809.0 N/mm, Young's Modulus from 153.0 to 255.3 MPa, maximum stress from 9.7 to 23.9 MPa, and failure strain from 2.0 to 10.7% (Figs. 3–7). Shani et al. (2185.9 N) (Shani et al., 2016) and Urchek et al. (2119 N) (Urchek and Karas, 2019) reported the highest biomechanical properties in the quadriceps group,.

Noyes et al. (1984)) tested a quadriceps tendon-patella retinaculum-patellar tendon graft construct. They divided their graft into thirds (medial, central, and lateral 1/3 grafts), reporting that all three of their grafts had the lowest biomechanical strength (249.0–371.0 N) and stiffness (17.0–24.0 N/mm) values of all the quadriceps tendon grafts included in this review. Additionally, a comparison of sutured and unsutured quadriceps tendon grafts found higher failure loads in unsutured grafts (692.0 N versus 1075.0 N) (Harris et al., 1997). Two studies tested a quadriceps tendon-bone graft, reporting maximum failure loads of 1055.0 N and 2185.9 N that were similar to the other biomechanical properties reported for the other quadriceps tendon grafts in this review



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(Mabe and Hunter, 2014; Shani et al., 2016).

3.4. Tibialis anterior, tibialis posterior, peroneus longus, and achilles tendon grafts

Nine studies tested lower leg graft sources (50 tibial anterior, 50 tibialis posterior, 93 peroneus longus, and 9 Achilles grafts) for ACL reconstruction [19–20, 28–29,31,34–37. Of studies that tested tibial anterior grafts, overall failure load ranged from 777.0–4122.0 N, stiffness from 61.0 to 460.0 N/mm, Young's Modulus from 0.5 to 847.0 MPa, maximum stress from 50.0 to 89.8 MPa, and failure strain from 12.7 to 39.1%. Out of studies that tested tibialis posterior grafts, overall failure load ranged from 889.0 to 3666.0 N, stiffness from 73.0 to 392.0 N/mm, Young's Modulus from 0.2 to 905.- MPa, maximum stress at 89.1 MPa (1 study), and failure strain from 13.2 to 41.0% (Figs. 3–7). Almqvist et al. (2007)) tested single strand and double strand tibialis anterior (TA) and tibialis posterior (TP) tendon grafts, noting expected greater maximum loads to failure (1553.0 N) and stiffness (236.0 N/mm) in the double strand group compared to their single strand grafts. Donahue et al. (2002)) tested 2-strand TA and TP tendon grafts, noting higher maximum load to failure (4122.0 and 3594.0 N) and stiffness (460.0 N/mm and 379.0 N/mm) than the 2-strand grafts Almqvist et al. (2007)) reported. However, these were similar to the values reported when Chan et al. (2010)) and Pearsall et al. (Pearsall IV et al., 2003) tested their 2-strand TA and TP tendon grafts.

Five studies tested peroneus longus (PL) tendon grafts. Overall, failure load ranged from 322.4 to 3050.0 N, stiffness from 7.8 to 347.0 N/mm, Young's Modulus from 0.2 to 157.7 MPa, and failure strain at 47.5% (1 study) with no studies tested maximum stress (Figs. 3–7). The two that studied 2 strand PL grafts (Claes et al., 2011; Shani et al., 2016) reported failure loads (3050.0 N and 2483.0 N) and stiffnesses (347.0 N/mm and 244.0 N/mm) that were the highest in this group. In comparison, single strand PL grafts were found to have lower failure loads (446.2 N) compared to other PL grafts in Rudy et al.'s study (Rudy and Phatama, 2017). The one study that specifically tested the anterior half of the peroneus longus tendon reported failure loads (322.4 N) and stiffness (7.8 N/mm) lower than other grafts in this group (Zhao and Huangfu, 2012). Furthermore, age was found to decrease stiffness in PL tendon grafts (Wong et al., 2019). Finally, the only study that tested Achilles tendon grafts found similar biomechanical properties between Achilles grafts and quadriceps tendon-bone graft (Mabe and Hunter, 2014). The maximum load to failure (915.0 N) and the elastic modulus (201.0 MPa) of the Achilles graft was lower than other grafts in this group but stiffness (217.0 N/mm) was similar to other grafts.

3.5. Tensor fascia lata and iliotibial band grafts

Three studies executed biomechanical testing of 46 total tensor fascia lata (TFL) and iliotibial band (ITB) grafts (Chan et al., 2010; Delcroix et al., 2013; Noyes et al., 1984). Overall, failure load ranged from 628.0–2459.0 N, stiffness from 39.0 to 445.0 N/mm and maximum stress from 19.1 to 78.7 MPa (Figs. 3–7).

Chan et al. (2010)) tested different fan-folded TFL grafts of various diameters, excluding diameters of 7 mm in final calculations due to the

Table 1

Systematic review article summary. Age of donors reported as range or mean ± standard deviation depending on how it was reported in original article. All grafts were thawed to room temperature and kept at this temperature the day of testing other than Zhao et al. which tested at 25°C. BPTB = Bone Patellar-Tendon Bone Graft; ITB = Iliotibial Band Graft; PT = Patellar Tendon; PL = Peroneus Longus Tendon Graft; Quad = Quadriceps Tendon Graft; TA = Tibialis Anterior Tendon Graft; TFL = Tensor Fascia Lata Grafts; TP = Tibialis Posterior Tendon Graft; NR = Not Reported. Biuk et al. tested their grafts at a submaximal load to failure of 30 N.

First author	Grafts tested	# of grafts	Age of donors (years)	Cadaver Storage	Graft Storage/prep	Testing system
Almqvist (Almqvist et al., 2007)	BPTB TA/TP	16 24/24	16–82 16–82	Grafts harvested within 24 h post-mortem	Fresh-frozen (−20°C) and thawed before testing (4°C)	LR50K Lloyd Computerized MTS
Biuk (Biuk et al., 2015)	BPTB Hamstring	40 120	50–70 50–70	NR	Preserved with 1% formaldehyde for 6–10 months	Custom Designed Vice-Grip Testing Machine
Blevins (Blevins et al., 1994)	BPTB	82	17–54	NR	Fresh-frozen (−20°C)	Instrom 1331
Boniello (Boniello et al., 2015)	Hamstring	44	14–66	NR	Disinfected using Allowash and frozen (−80°C)	Instrom MTS
Cavaignac (Cavaignac et al., 2016)	BPTB Hamstring	32 64	77–90 77–90	Fresh-frozen (−20°C) and thawed to 2°C before graft harvest	Immediate testing	Instrom 3300
Chan (Chan et al., 2010)	BPTB PL TA/TP TFL	8 16 8/8 18	25–61 25–61 25–61 21–56	Fresh-frozen (−20°C)	Fresh-frozen (−20°C)	858 Bionix MTS
Cooper (Cooper et al., 1993)	BPTB	37	28 ± 7	Grafts harvested within 12 h post-mortem	Fresh-frozen (−20°C)	MTS Machine
Delcroix (Delcroix et al., 2013)	ITB TA	NR NR	16–61 16–61	NR	Sterile plastic packaging and frozen (−80°C)	858 Bionix MTS
Donahue (Delcroix et al., 2013)	TA/TP Hamstring	10/10 10	20–45 46–67	NR	Fresh-frozen (−80°C or − 20°C)	858 Bionix MTS
Hamner (Hamner et al., 1999)	Hamstring	73	37–102	NR	Wrapped in saline-soaked towel, aluminum foil, and plastic bag. Frozen (−20°C) and thawed before testing (4°C)	Instrom 1331
Handl (Handl et al., 2007)	BPTB Hamstring	21 21	51–84 51–84	Fresh-frozen (−20°C)	Wrapped in saline-soaked towel, aluminum foil, and plastic bag. Frozen (−18°C) and thawed before testing (4°C)	Drop-weight Velocity Custom System
Harris (Harris et al., 1997)	PT Quad	6 21	51–76 51–108	15 preserved and 6 Fresh-frozen (−20°C)	NR	Instron 1321
Herbert (Herbert et al., 2016)	BTPB	16	45–69	NR	Decellularization	Instron 3365
Mabe (Mabe & Hunter, 2014)	Achilles Quad	9 9	37–74 37–74	Fresh-frozen (−20°C)	Sterilized via gamma irradiation (9.2–11.0 kGy), frozen at −65°C, and thawed before testing to 37°C	Instron ElectroPuls E3000
Noyes (Noyes et al., 1984)	BPTB Hamstring TFL ITB Quad	14 28 18 10 20	26 ± 6 26 ± 6 26 ± 6 26 ± 6 26 ± 6	NR	Wrapped in saline-soaked towel, aluminum foil, and plastic bag and then frozen (−30°C)	LeBow load-cell 6467–103 or 3132
Pailhe (Pailhé et al., 2015)	PT Hamstring	32 48	17–70 17–70	Stored at 4°C	Stored at −4°C in a freezing solution containing saline and 10% dimethylsulfoxide	Instrom 3300
Pearsall (Pearsall IV et al., 2003)	PL TA/TP	16 16/16	66–89 66–89	Fresh-frozen (−20°C)	Fresh-frozen (−20°C)	Custom Hydraulic Testing Machine
Rudy (Rudy & Phatama, 2017)	Hamstring PL	12 12	NR NR	Fresh-frozen (−20°C)	NR	Hydraulic Servo Pulser
Schmidt (Schmidt et al., 2019)	Pediatric	5	7–11	Fresh-frozen (−20°C)	Tested immediately	ElectroForce 3330
Shani (Shani et al., 2016)	BPTB Quad	11 12	19–55 24–52	Fresh-frozen (−20°C)	NR	MTS servohydraulic test machine
Tis (Tis et al., 2002)	BPTB Hamstring	21 16	79 ± 1.6 79 ± 1.6	Fresh-frozen (−20°C)	Wrapped in sterile gauze, soaked in saline solution, and fresh-frozen (−20°C)	858 Bionix MTS
Urchek (Urchek & Karas, 2019)	Quad Hamstring	6 6	49–74 49–74	Fresh-frozen (−20°C)	Tested immediately	Instron E1000
Wilson (Wilson et al., 1999)	BPTB Hamstring	15 15	17–53 17–53	Fresh-frozen (−20°C)	Wrapped in saline-soaked gauze and plastic bag and fresh-frozen (−20°C)	858 Bionix MTS
Wong (Wong et al., 2019)	PL	38	22–74	NR	Fresh-frozen (−20°C)	Instron 5566
Yanke (Yanke et al., 2013)	BPTB	30	24–64	NR	AlloSource sterilization and irradiation (1.0–1.2 Mrad)	Insight 5 MTS
Zhao (Zhao & Huangfu, 2012)	PL Hamstring	20 40	56–84 56–84	Fresh-frozen (−20°C)	Fresh-frozen (−20°C)	Instron 5500

unlikelihood of its use in a clinical setting, and reported similar maximum failure loads (3524.0 N) as Delcroix et al. (2013)) did (3459.0 N) in their testing of 9 to 10 mm fan-folded ITB grafts. Chan studied TFL grafts ranging from 8 to 10 mm, finding that grafts of increased size had higher reported average strength and stiffness (not statistically compared). The ITB grafts (studied by Delcroix) had tensile strength values 4 times higher than the native ACL (886.0 N), and they were also found to have creep properties significantly larger than ACLs but similar to TA grafts. ITB grafts had similar stress-relaxation behavior compared to ACLs and TA grafts, noting higher forces at 10% strain than ACLs but similar plateau values to ACLs and TA grafts. Finally, Noyes et al. (1984)) reported much lower values for maximum failure load and stiffness of their TFL (628.0 N) and ITB (769.0 N) grafts but significantly stronger and stiffer compared to ACLs.

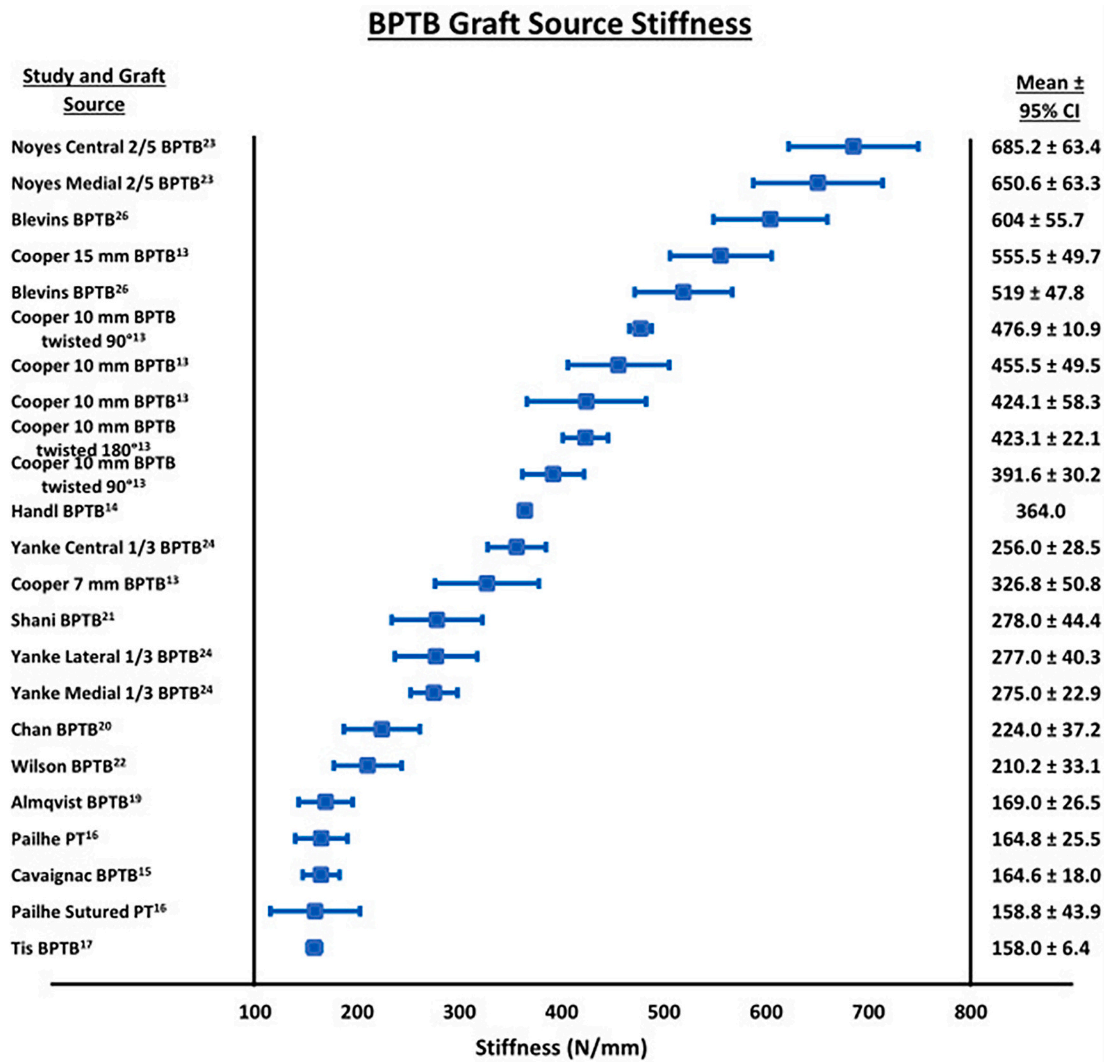


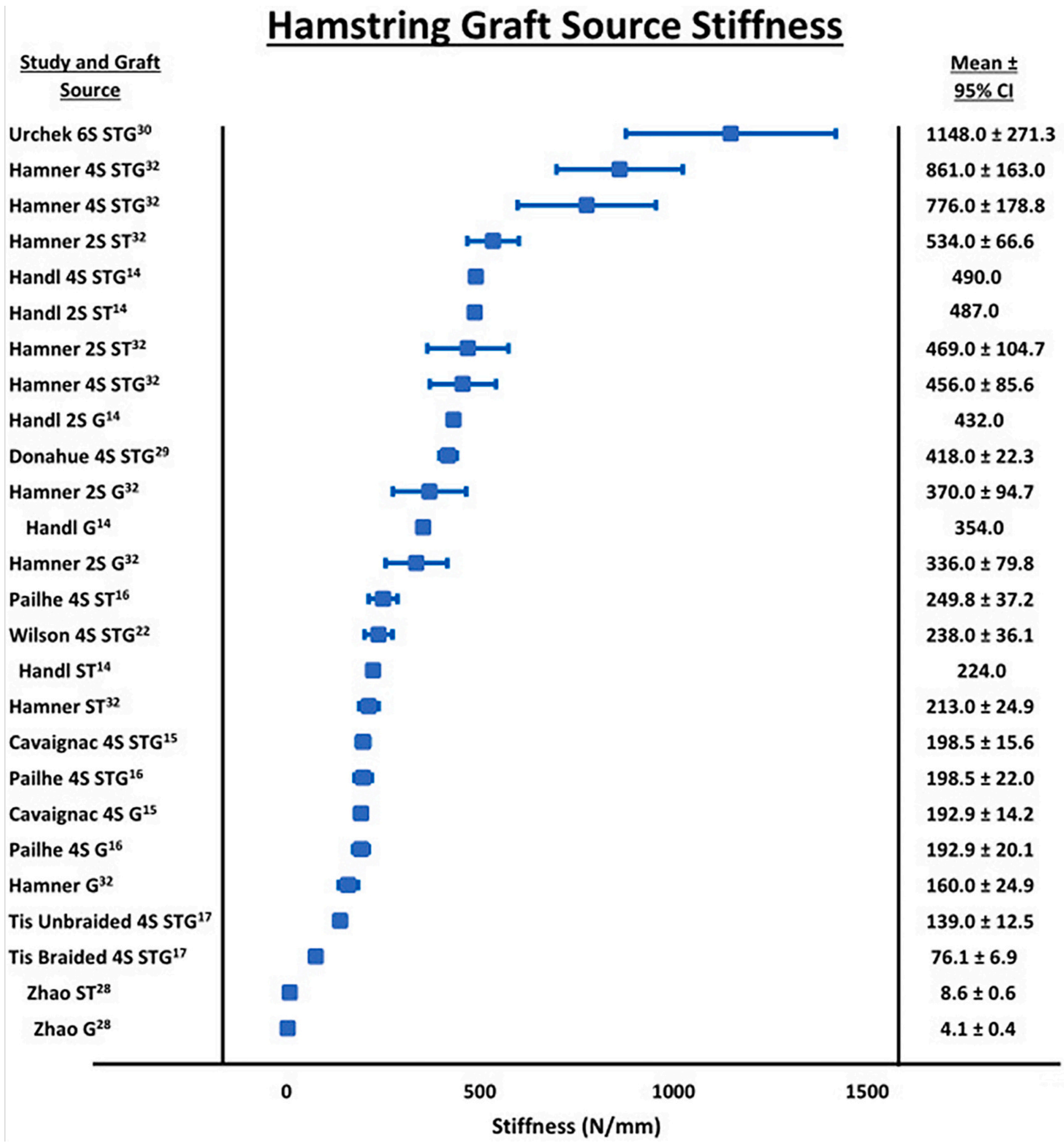
Fig. 3. (a) BPTB graft source maximum failure loads. Mean ± 95% CI Presented for each study as well as type of graft tested. Failure Loads measured in Newtons. BPTB=Bone-Patellar Tendon Bone; PT = Patellar Tendon.
(b) Hamstring graft source maximum failure loads. Mean ± 95% CI Presented for each study as well as type of graft tested. Failure Loads measured in Newtons. G = Gracilis; ST = Semitendinosus; STG = Combined Semitendinosus and Gracilis; S=Strands.
(d) Additional graft source maximum failure loads. Mean ± 95% CI Presented for each study as well as type of graft tested. Failure Loads measured in Newtons. TA = Tibialis Anterior; TP = Tibialis Posterior; PL = Peroneus Longus; AHPL = Anterior Half of Peroneus Longus; TFL = Tensor Fascia Lata; ITB=Iliotibial Band; S=Strands.

3.6. Skeletally immature grafts

The pediatric population presents a unique set of circumstances and considerations. The presence of open physes, and time until predicted skeletal maturity, affects the decision to use soft tissue grafts versus bone plug grafts. Schmidt et al. (2019)) is the only study that explored the biomechanical properties of grafts in exclusively skeletally immature graft donors. Five pediatric cadaveric specimens were used to test BPTB grafts, semitendinosus hamstring tendon grafts, quadriceps tendon grafts, and ITB grafts. They reported that their BPTB grafts had ultimate stress (5.2 MPa), ultimate strain (35.3%), and Young's Modulus (27.0 MPa) values that were most similar to native ACLs, while semitendinosus and ITB grafts had the highest Young's modulus (197.2 MPa and 161.7 MPa), ultimate stress (29.0 MPa and 29.0 MPa), and strain energy density (3.1 MPa and 3.8 MPa).

3.7. Bias assessment

Given the strict inclusion and exclusion criteria set out at the beginning of this study, the two authors had 100% agreement in the articles included in this study. Each study was assessed for bias using the RoBANS Tool (Kim et al., 2013b). Two studies had grafts damaged during harvest (Almqvist et al., 2007; Noyes et al., 1984), one study did not detail what type of hamstring graft they tested (Rudy and Phatama, 2017), and one study used different graft sources to construct their grafts of different diameters (Boniello et al., 2015), all of which could have biased overall results. In addition, ten other studies had graft donors much older than the young cadavers used in many of these studies (Table 1). Given the nature of biomechanical testing, each specimen could only be tested once, precluding performance bias from any of the articles included in this review. Furthermore, Yanke et al. is the only study that blinded its authors from graft types during testing, while all other articles technically suffer from detection bias (Yanke et al., 2013). In addition, only three studies reported all five measured outcomes in



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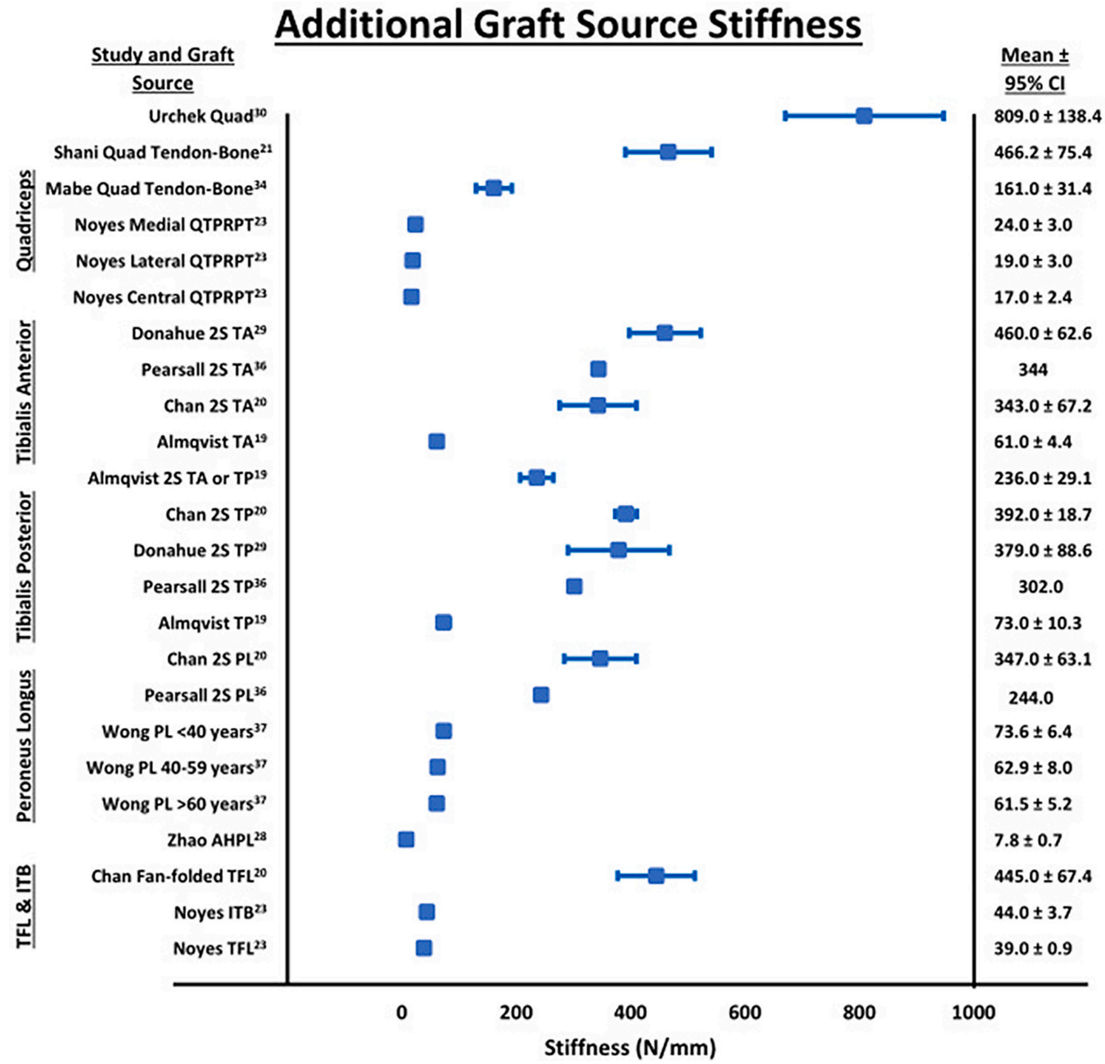
their studies, while the other 23 studies suffered from reporting bias (Chan et al., 2010; Donahue et al., 2002; Mabe and Hunter, 2014). None of the studies suffered from selection bias due to other confounding variables (other than age) or attrition bias (Fig. 1). Finally, when looking at the review overall, there is a possibility of publication bias, as only studies that reported biomechanical properties of their chosen tested graft source that are superior to the native ACL and commonly equivalence or superiority to another graft source have been published.

4. Discussion

This systematic review summarizes studies that explore the intrinsic biomechanical properties of various ACL reconstruction graft sources. While an ideal graft source has a high maximum failure load, the graft should look to emulate the stiffness of the native ACL. High graft stiffness would not allow graft deformation but might restrict knee motion, pointing to the need to match native ACL stiffness rather than trying to maximize it. Maximum stress and strain contribute to the Young's Modulus, a biomechanical property of the native ACL that an ideal graft should also try to mirror. Most existing studies report on failure loads and stiffness, and these are the two properties that this review accordingly focuses on.

Interestingly, individual studies found similarity or superiority of one graft over another when tested together, but which grafts were found superior varied by study. However, the five graft types overall had failure load, stiffness, Young's Modulus, maximum stress, and maximum strain ranges that overlapped, pointing to the overall similarity between graft biomechanics. Furthermore, a meta-analysis that would include statistical comparison between graft types was not possible due to the heterogeneity of the included studies. These results should signal to orthopaedic surgeons that the use of one graft source over another will not maximize the biomechanical strength of the reconstruction. Instead, they should consider all patient factors and pay attention to proper surgical technique (tunnels and graft fixation) when aiming to maximize success.

Overall, most studies reported equal or increased biomechanical failure load of their tested graft compared to the native ACL. This consensus finding that any of the tested graft sources can be used to biomechanically recreate the native ACL is the most important point that orthopaedic surgeons should take heed of. Woo et al.'s study



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reported the failure load of the native femur-ACL-tibia complex as 2160.0 N. When comparing against the reported value of 496.0 N needed to act as a dependable ACL replacement, most grafts tested had higher failure loads than this, while all graft types had ranges reaching much higher than this. Most of the grafts with lower tested values than this still tested higher than the native ACLs they tested in their own studies, pointing to the importance of analyzing the various testing conditions and graft harvesting between studies. It is important to highlight Biuk et al.'s study, as they are the only ones that tested their grafts at a submaximal load to failure of 30 N (Biuk et al., 2015). Furthermore, all 5 graft types had most of their stiffness range higher than the reported 242.0 N/mm of the native ACL. As before, the authors expect the true stiffness value of the native ACL tested in isolation to have a lower stiffness. The Young's Modulus of the native ACL is more variable in the literature, with one study reporting a range of 5.0 to 76.0 MPa (Paschos et al., 2010). The BPTB, hamstring, and quadriceps tendon grafts had reported ranges all higher than this, while the tibialis anterior, tibial posterior, and peroneal longus graft groups had most of their grafts higher than this (there were no TFL or ITB grafts with tested Young's Modulus). Maximum stress and strain values of the native ACL are not well reported in the literature but are important properties to understand of any native ligament or graft. It should also be noted that Yanke et al. misreported their strain values by a factor of 100. Instead of 0.178%, 0.190%, and 0.162%, the true strain values seem to be 17.8%, 19.0%, and 16.2% for their central, medial, and lateral 1/3 BPTB grafts, respectively (Yanke et al., 2013).

There is a paucity of biomechanical articles published that test skeletally immature grafts. Because of this, it is difficult to establish biomechanical superiority of one graft type versus another. All soft tissue grafts can then be considered in a variety of physeal-sparing approaches if needed, including the Micheli-Kocher combined intra-articular and extra-articular approach, the modified Anderson all-epiphyseal approach, the Ganley-Lawrence all-epiphyseal approach, the trans-physeal approach, and other hybrid approaches. Bony grafts can be considered in techniques where the graft does not cross an open physis or if growth arrest is not a concern. Finally, similarly to adult reconstruction, previous surgery, limb deformity, activity level, and attention to surgical technique must be considered.

Very few articles correlated differences in graft diameter or cross-sectional area to biomechanical properties. The few that did found increased strength and stiffness with increased size (Boniello et al., 2015; Cooper et al., 1993). What is also not addressed in this review is the difference between autografts and allografts. While a biomechanical comparison of the two graft types is hard to complete (all grafts from cadavers can be considered allografts), many studies explore differences in clinical outcomes between the two. In 2014, the AAOS released clinical practice guidelines recommending the use of autografts or non-irradiated allograft sources (AAOS. Management of Anterior Cruciate Ligament Injuries Evidence-Based Clinical Practice Guidelines, 2014). However, even though early literature does report clinical non-

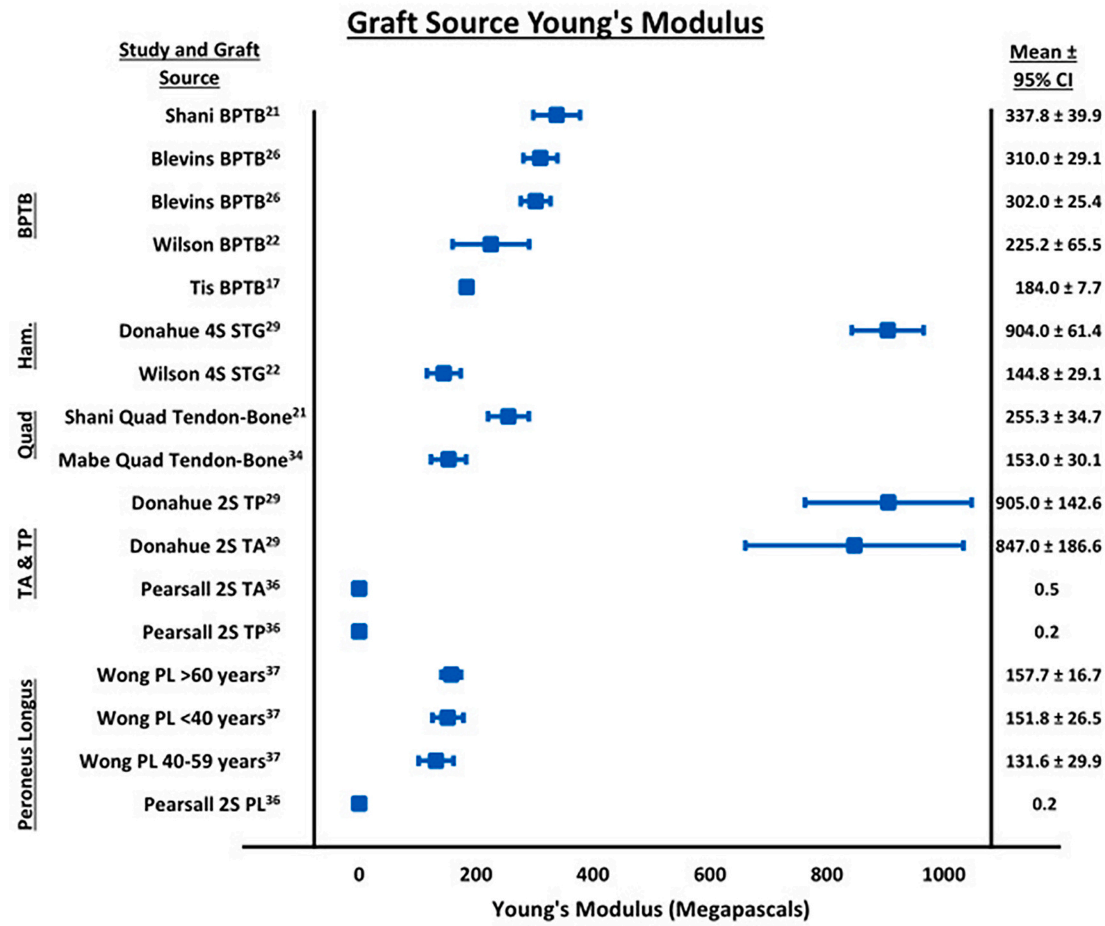


Fig. 4. (a) BPTB graft source stiffness. Mean ± 95% CI Presented for each study as well as type of graft tested. Stiffness measured in Newtons/mm (N/mm). BPTB=Bone-Patellar Tendon Bone; PT = Patellar Tendon.
(b) Hamstring graft source stiffness. Mean ± 95% CI Presented for each study as well as type of graft tested. Stiffness measured in Newtons/mm (N/mm). G = Gracilis; ST = Semitendinosus; STG = Combined Semitendinosus and Gracilis; S=Strands.
(c) Additional graft source stiffness. Mean ± 95% CI Presented for each study as well as type of graft tested. Stiffness measured in Newtons/mm (N/mm). Quad = Quadriceps; Quad-Tendon Bone = Quadriceps plus Patellar Tendon Bone Plug; QTPRPT = Quadriceps Patellar Retinaculum Patellar Tendon; TA = Tibialis Anterior; TP = Tibialis Posterior; PL = Peroneus Longus; AHPL = Anterior Half of Peroneus Longus; TFL = Tensor Fascia Lata; ITB=Iliotibial Band; S=Strands.

inferiority between the two (Wei et al., 2015), larger, more recent studies discuss the higher rate of failure experienced after use of allografts, especially in younger patients (Harner et al., 1996; Kaeding et al., 2011; Kaeding et al., 2015).

The authors also believe that results from testing grafts that are fixed in knees is dependent on a variety of complex in vitro factors, including tunnel position, femoral and tibial fixation, and knee position. Including other components in the analysis of graft source biomechanical properties introduces variability that makes drawing meaningful conclusions difficult. In contrast, the intrinsic biomechanical properties of a graft are dependent solely on its composition and structure.

Each study also tested all included grafts with the same equipment and same testing conditions. Unfortunately, testing conditions between studies had high variability, making the comparison of graft properties difficult. What makes this variability hard to quantify is a lack of understanding of the differences between testing devices and the effect of storage time, and storage temperature on graft deterioration and properties. While not explicitly studied for ACL grafts, graft storage time had no effect on osteochondral allograft graft survivorship in one study (Schmidt et al., 2017), while another showed improved survivorship when implanted within 25 days (Merkely et al., 2020). In addition, studies in other specialties have explored the effect storage temperature and medium have on graft properties (Arabiun, 2020), and the same must be done for ACL graft sources to truly understand the effect the variability in testing conditions encountered in this review has on biomechanical testing (Smith et al., 1996).

Given that this review includes studies involving biomechanical testing, the authors believe that these articles do not suffer from the same bias as other clinical studies. The authors see minimal benefit to randomization of samples or blinding of personnel (detection bias), as graft properties are determined by external equipment rather than human observations. One of the two biases that must be considered is the lack of standardized reporting of all five reviewed outcomes for each graft (reporting bias), which can be a result of lack of testing or even a lack of testing results that supports the overall superiority of one graft over another (depending on the specific study). The other is selection

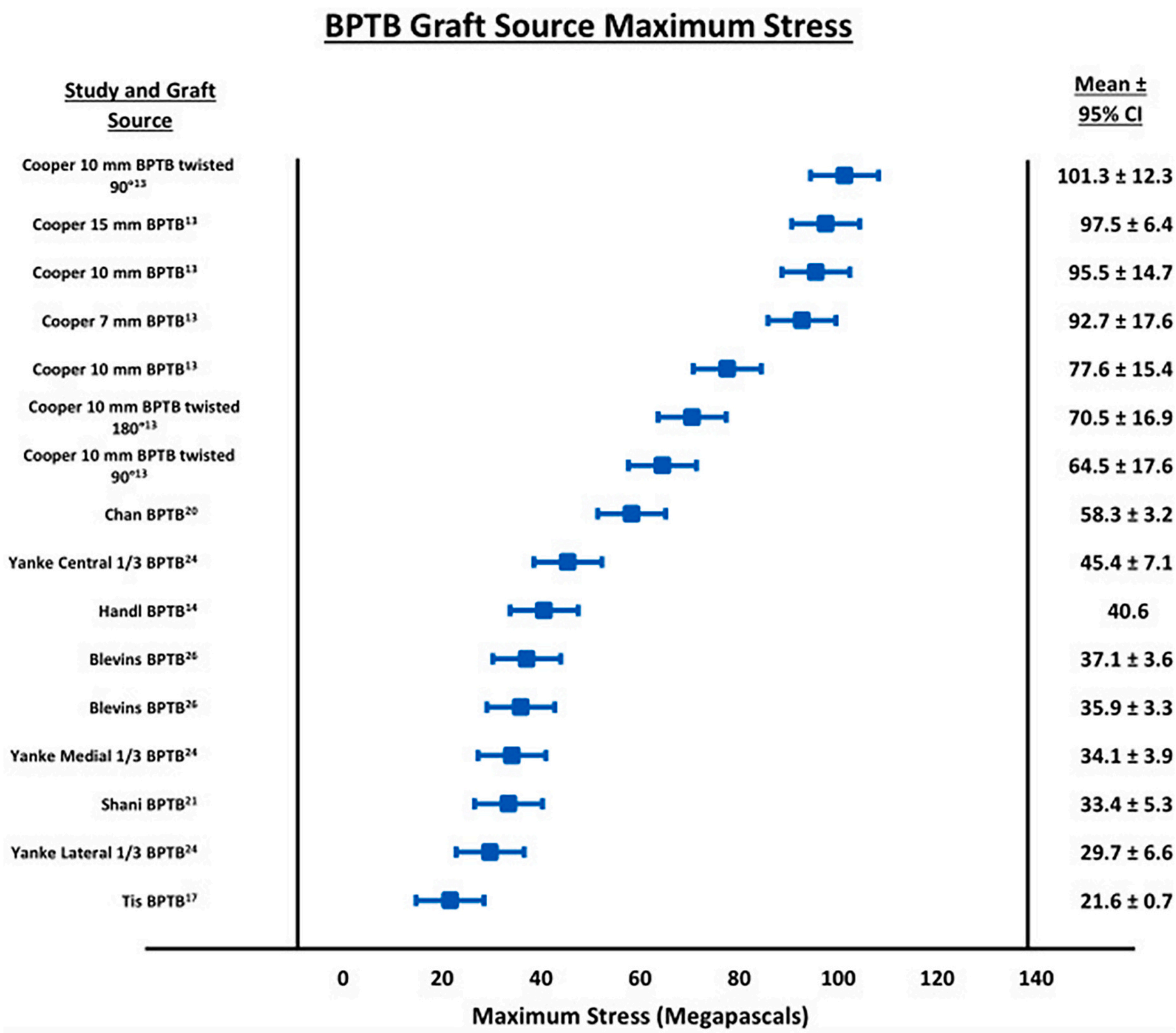
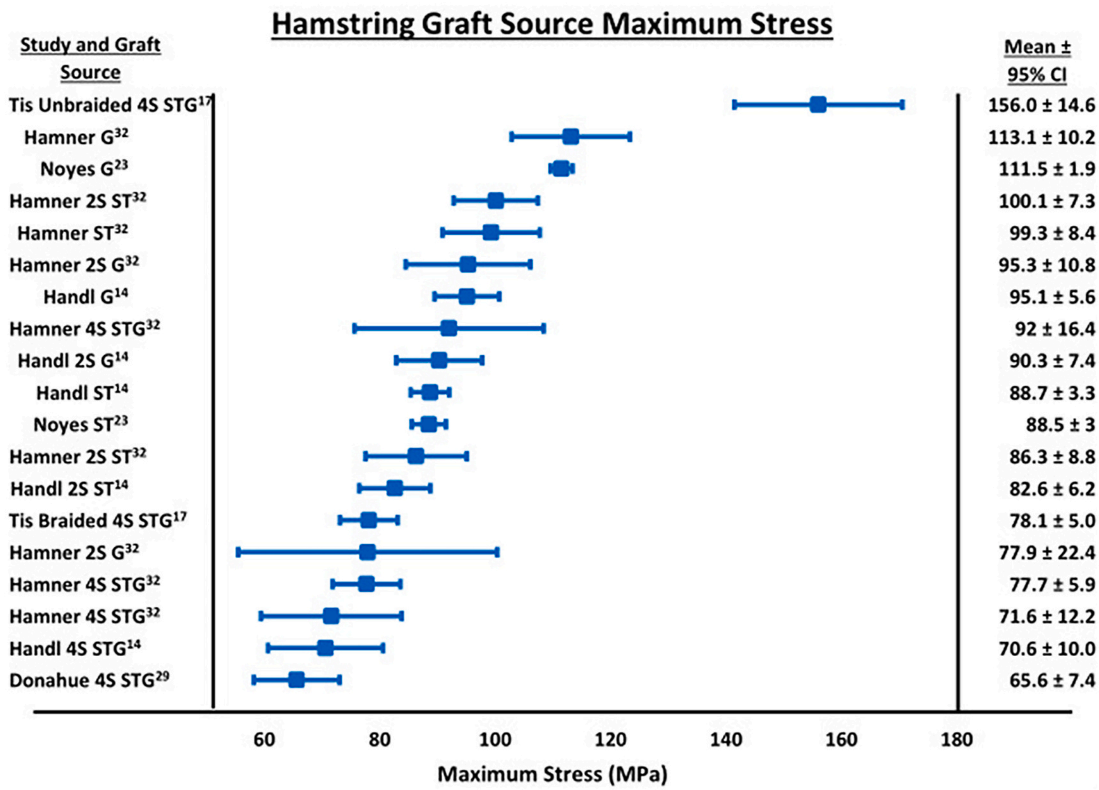


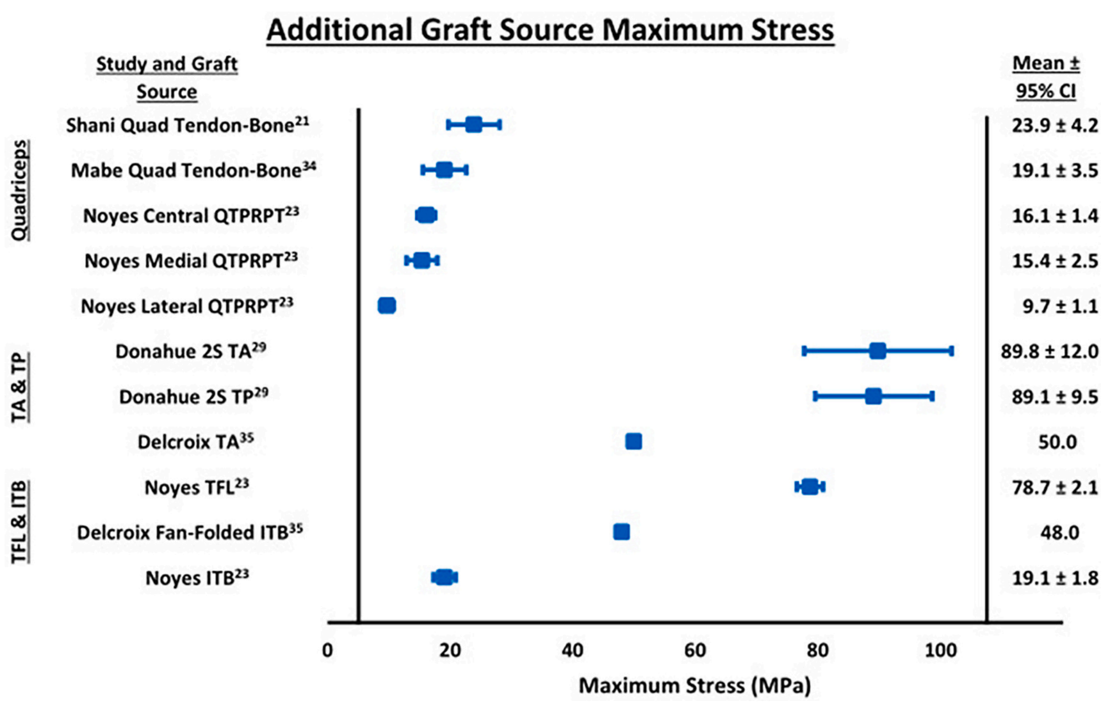
Fig. 5. Graft source Young's modulus. Mean ± 95% CI Presented for each study as well as type of graft tested. Modulus measured in Megapascals (Mpa). BPTB=Bone Patellar-Tendon Bone; Ham = Hamstring; STG = Semitendinosus and Gracilis; S=Strand; Quad-Tendon Bone = Quadriceps plus Patellar Tendon Bone Plug; TA = Tibialis Anterior; TP = Tibialis Posterior; PL = Peroneus Longus.

bias, as ten studies had donors much older than the other studies in this review. Therefore, the well-published effect of increasing age on graft biomechanics, a finding reported in many of the studies included in this review as well as external studies, must be considered when interpreting these results (Lansdown et al., 2017; Wong et al., 2019; Woo et al., 1991). In addition, each study is a Level IV case series of consecutive grafts. Even though no study in this series meets criteria for higher than Level IV evidence, it is difficult to design a biomechanical study that does. Finally, the authors believe that there is high internal and external validity to the results in this review. Even though the variability between studies makes comparisons between graft types difficult, the biomechanical superiority of all included graft sources to the native ACL should be trusted, making all sources a possibility for use in ACL reconstruction given the right patient characteristics.

4.1. Limitations

Most articles in our review tested grafts after harvesting and freezing them until testing, rather than in succession as would be done during reconstruction using autografts. Furthermore, these results should be interpreted understanding that the effect of graft size, age of donor, and different testing systems was not explored in most studies. Failure testing also most commonly involved axial loading rather than the torsional loading that many ACLs fail in in vivo. The authors also decided not to perform a meta-analysis given the variability in testing conditions and graft types between studies, as well as the lack of uniformity in reporting biomechanical variables. It should also be noted that studies inconsistently detail the temperature the testing environment was kept in as well as how successful they were at reducing graft slippage at the clamps of their testing machine, both of which can potentially change test results. While the overall number of grafts tested in this review is large, many individual studies report their mean graft biomechanical values based on a small sample size. Each study was given similar weight while reporting results in this review regardless of individual sample size since only descriptive reporting was completed rather than statistical analysis. Finally, as with all in vitro studies, there may be a difference in the reported time zero properties here and true in vivo properties as well as their effect on clinical outcomes.





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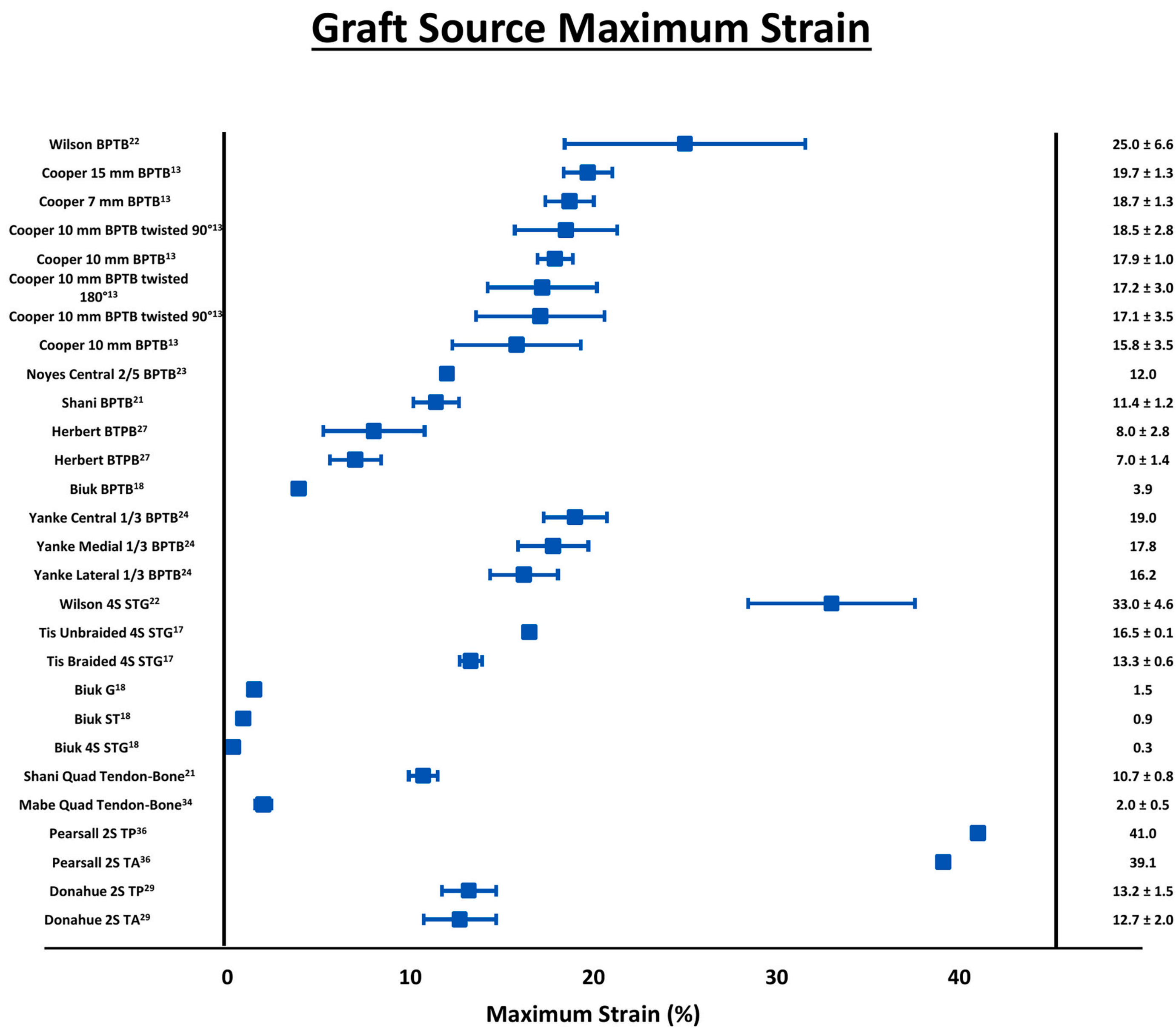

Fig. 6. (a) BPTB graft source maximum stress. Mean ± 95% CI Presented for each study as well as type of graft tested. Stress reported in Megapascals (Mpa) and calculated as force divided by area. BPTB=Bone-Patellar Tendon Bone.
(b) Hamstring graft source maximum stress. Mean ± 95% CI Presented for each study as well as type of graft tested. Stress reported in Megapascals (Mpa) and calculated as force divided by area. G = Gracilis; ST = Semitendinosus; STG = Combined Semitendinosus and Gracilis; S=Strands.
(c) Additional graft source maximum stress. Mean ± 95% CI Presented for each study as well as type of graft tested. Stress reported in Megapascals (Mpa) and calculated as force divided by area. Quad = Quadriceps; Quad-Tendon Bone = Quadriceps plus Patellar Tendon Bone Plug; QTPRPT = Quadriceps Patellar Retinaculum Patellar Tendon; TA = Tibialis Anterior; TP = Tibialis Posterior; TFL = Tensor Fascia Lata; ITB=Iliotibial Band; S=Strands.

5. Conclusion

The goal of ACL reconstruction surgery is to provide stability to the knee while restoring native knee kinematics. BPTB, hamstring, quadriceps, tibialis anterior, tibialis posterior, peroneus longus, Achilles, tensor fascia lata, and iliotibial band grafts all possess in vitro biomechanical properties that are similar. However, most of these grafts are biomechanically superior to the native ACL. In addition, special consideration needs to be given to graft types utilized in pediatric patients. Further research is needed to both establish superiority of one graft source over another and to determine how any in vitro biomechanical differences correlate to changes in clinical outcomes.

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First Author	Selection Bias (Patient)	Selection Bias (Confounding)	Performance Bias	Detection Bias	Attrition Bias	Reporting Bias
Almqvist[19]	+	−	−	+	−	+
Biuk[18]	+	−	−	+	−	+
Blevins[26]	−	−	−	+	−	+
Boniello[33]	+	−	−	+	−	+
Cavaignac[15]	+	−	−	+	−	+
Chan[20]	−	−	−	+	−	+
Cooper[13]	−	−	−	+	−	+
Delcroix[35]	−	−	−	+	−	+
Donahue[29]	−	−	−	+	−	−
Hamner[32]	+	−	−	+	−	+
Handl[14]	+	−	−	+	−	+
Harris[25]	+	−	−	+	−	+
Herbert[27]	+	−	−	+	−	+
Mabe[34]	−	−	−	+	−	−
Noyes[23]	−	−	−	+	−	+
Pailhe[16]	−	−	−	+	−	+
Pearsall[36]	+	−	−	+	−	+
Rudy[31]	+	−	−	+	−	+
Schmidt[38]	−	−	−	+	−	+
Shani[21]	−	−	−	+	−	−
Tis[17]	+	−	−	+	−	+
Urchek[30]	+	−	−	+	−	+
Wilson[22]	−	−	−	+	−	+
Wong[37]	−	−	−	+	−	+
Yanke[24]	−	−	−	−	−	+
Zhao[28]	+	−	−	+	−	+

Fig. 7. Graft source maximum strain. Mean ± 95% CI Presented for each study as well as type of graft tested. Strain Reported as % and calculated as change in length divided by original length. BPTB=Bone Patellar-Tendon Bone; STG = Semitendinosus and Gracilis; S=Strand; Quad-Tendon Bone = Quadriceps plus Patellar Tendon Bone Plug; TA = Tibialis Anterior; TP = Tibialis Posterior. Biuk et al. tested their grafts at a submaximal failure load of 30 N.

IRB

Not applicable.

Declaration of Competing Interest

KS is a Board/Committee Member of AAOS, POSNA, PRISM, and ROCK and obtains research support from Ossur and Vericel. TG is a Board/Committee Member of AAOS, AAP Orthopaedic Section, IPOS, PRISM, POSNA, and ROCK, on the editorial/governing board of AJSM, and obtains research support from Allosource and Vericel.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clinbiomech.2022.105636.

References

AAOS. Management of Anterior Cruciate Ligament Injuries Evidence-Based Clinical Practice Guidelines, 2014. Sept 5. https://www.aaos.org/quality/quality-programs/lower-extremity-programs/anterior-cruciate-ligament-injuries/.

Almqvist, K.F., Jan, H.A., Vercruysse, C., Verbeeck, R., Verdonk, R., 2007. The tibialis tendon as a valuable anterior cruciate ligament allograft substitute: biomechanical properties. Knee Surg. Sports Traumatol. Arthrosc. 15 (11), 1326–1330. Nov 1.

Anderson, M.J., Browning III, W.M., Urband, C.E., Kluczynski, M.A., Bisson, L.J., 2016. A systematic summary of systematic reviews on the topic of the anterior cruciate ligament. Orthop. J. Sports Med. 4 (3). Mar 15. 2325967116634074.

Arabiun, H., 2020. Effects of different storage media, temperature, and time on osteoblast preservation in autogenous bone grafts: a histomorphometrical analysis. J. Dent. 21 (3), 225. Sep.

Biuk, E., Zelić, Z., Rapan, S., Ćurić, G., Biuk, D., Radić, R., 2015. Analysis of biomechanical properties of patellar ligament graft and quadruple hamstring tendon graft. Injury 1 (46), S14–S17. Nov.

Blevins, F.T., Hecker, A.T., Bigler, G.T., Boland, A.L., Hayes, W.C., 1994. The effects of donor age and strain rate on the biomechanical properties of bone-patellar tendon-bone allografts. Am. J. Sports Med. 22 (3), 328–333. May.

Boniello, M.R., Schwingler, P.M., Bonner, J.M., Robinson, S.P., Cotter, A., Bonner, K.F., 2015. Impact of hamstring graft diameter on tendon strength: a biomechanical study. Arthroscopy 31 (6), 1084–1090. Jun 1.

Brand, J., Weiler, A., Caborn, D.N., Brown, C.H., Johnson, D.L., 2000. Graft fixation in cruciate ligament reconstruction. Am. J. Sports Med. 28 (5), 761–774. Sep.

Cavaignac, E., Pailhé, R., Reina, N., Murgier, J., Laffosse, J.M., Chiron, P., Swider, P., 2016. Can the gracilis replace the anterior cruciate ligament in the knee? A biomechanical study. Int. Orthop. 40 (8), 1647–1653. Aug 1.

Chalmers, P.N., Mall, N.A., Moric, M., Sherman, S.L., Paletta, G.P., Cole, B.J., Bach Jr., B. R., 2014. Does ACL reconstruction alter natural history? A systematic literature review of long-term outcomes. J. Bone Joint Surg. 96 (4), 292–300. Feb 19.

Chan, D.B., Temple, H.T., Latta, L.L., Mahure, S., Dennis, J., Kaplan, L.D., 2010. A biomechanical comparison of fan-folded, single-looped fascia lata with other graft tissues as a suitable substitute for anterior cruciate ligament reconstruction. Arthroscopy 26 (12), 1641–1647. Dec 1.

Claes, S., Verdonk, P., Forsyth, R., Bellemans, J., 2011. The "ligamentization" process in anterior cruciate ligament reconstruction: what happens to the human graft? A systematic review of the literature. Am. J. Sports Med. 39 (11), 2476–2483. Nov.

Cooper, D.E., Deng, X.H., Burstein, A.L., Warren, R.F., 1993. The strength of the central third patellar. Tendon graft: a biomechanical study. Am. J. Sports Med. 21 (6), 818–824. Nov.

Delcroix, G.J., Kaimrajh, D.N., Baria, D., Cooper, S., Reiner, T., Latta, L., D'Ippolito, G., Schiller, P.C., Temple, H.T., 2013. Histologic, biomechanical, and biological evaluation of fan-folded iliotibial band allografts for anterior cruciate ligament reconstruction. Arthroscopy 29 (4), 756–765. Apr 1.

Donahue, T.L., Howell, S.M., Hull, M.L., Gregersen, C., 2002. A biomechanical evaluation of anterior and posterior tibialis tendons as suitable single-loop anterior cruciate ligament grafts. Arthroscopy 18 (6), 589–597. Jul 1.

Hamner, D.L., Brown, C.H., Steiner, M.E., Hecker, A.T., Hayes, W.C., 1999. Hamstring tendon grafts for reconstruction of the anterior cruciate ligament: biomechanical evaluation of the use of multiple strands and tensioning techniques. J. Bone Joint Surg. 81 (4). Apr 1. 549–547.

Handl, M., Držík, M., Cerulli, G., Povýšil, C., Chlpík, J., Varga, F., Amler, E., Trč, T., 2007. Reconstruction of the anterior cruciate ligament: dynamic strain evaluation of the graft. Knee Surg. Sports Traumatol. Arthrosc. 15 (3), 233–241. Mar 1.

Harner, C.D., Olson, E., Irrgang, J.J., Silverstein, S., Fu, F.H., Silbey, M., 1996. Allograft versus autograft anterior cruciate ligament reconstruction: 3-to 5-year outcome. Clin. Orthop. Relat. Res. 324, 134–144. Mar 1.

Harris, N.L., Smith, D.A., Lamoreaux, L., Purnell, M., 1997. Central quadriceps tendon for anterior cruciate ligament reconstruction: part I: morphometric and biomechanical evaluation. Am. J. Sports Med. 25 (1), 23–28. Jan.

Herbert, A., Brown, C., Rooney, P., Kearney, J., Ingham, E., Fisher, J., 2016. Bi-linear mechanical property determination of acellular human patellar tendon grafts for use in anterior cruciate ligament replacement. J. Biomech. 49 (9), 1607–1612. Jun 14.

Kaeding, C.C., Aros, B., Pedroza, A., Pifel, E., Amendola, A., Andrish, J.T., Dunn, W.R., Marx, R.G., McCarty, E.C., Parker, R.D., Wright, R.W., 2011. Allograft versus autograft anterior cruciate ligament reconstruction: predictors of failure from a MOON prospective longitudinal cohort. Sports Health 3 (1), 73–81. Jan.

Kaeding, C.C., Pedroza, A.D., Reinke, E.K., Huston, L.J., Moon Consortium, Spindler, K. P., 2015. Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: prospective analysis of 2488 primary ACL reconstructions from the MOON cohort. Am. J. Sports Med. 43 (7), 1583–1590. Jul.

Kim, S.Y., Park, J.E., Lee, Y.J., Seo, H.J., Sheen, S.S., Hahn, S., Jang, B.H., Son, H.J., 2013a. Testing a tool for assessing the risk of bias for nonrandomized studies showed moderate reliability and promising validity. J. Clin. Epidemiol. 66 (4), 408–414. Apr 1.

Kim, S.Y., Park, J.E., Lee, Y.J., Seo, H.J., Sheen, S.S., Hahn, S., Jang, B.H., Son, H.J., 2013b. Testing a tool for assessing the risk of bias for nonrandomized studies showed moderate reliability and promising validity. J. Clin. Epidemiol. 66 (4), 408–414. Apr 1.

Lansdown, D.A., Riff, A.J., Meadows, M., Yanke, A.B., Bach, B.R., 2017. What factors influence the biomechanical properties of allograft tissue for ACL reconstruction? A systematic review. Clin. Orthop. Relat. Res. 475 (10), 2412–2426. Oct.

Lobb, R., Tumilty, S., Claydon, L.S., 2012. A review of systematic reviews on anterior cruciate ligament reconstruction rehabilitation. Phys. Ther. Sport 13 (4), 270–278. Nov 1.

Mabe, I., Hunter, S., 2014. Quadriceps tendon allografts as an alternative to Achilles tendon allografts: a biomechanical comparison. Cell Tissue Bank. 15 (4), 523–529. Dec 1.

Marieswaran, M., Jain, I., Garg, B., Sharma, V., Kalyanasundaram, D., 2018. A review on biomechanics of anterior cruciate ligament and materials for reconstruction. Appl. Bio. Biomech. 2018. May 13.

Merkely, G., Ackermann, J., Farina, E.M., VanArsdale, C., Lattermann, C., Gomoll, A.H., 2020. Shorter storage time is strongly associated with improved graft survivorship at 5 years after osteochondral allograft transplantation. Am. J. Sports Med. 48 (13), 3170–3176. Nov.

Noyes, F.R., Butler, D.L., Grood, E.S., Zernicke, R.F., Hefzy, M.S., 1984. Biomechanical analysis of human ligament grafts used in knee-ligament. J. Bone Joint Surg. Am. 66, 344–352.

Pailhé, R., Cavaignac, E., Murgier, J., Laffosse, J.M., Swider, P., 2015. Biomechanical study of ACL reconstruction grafts. J. Orthop. Res. 33 (8), 1188–1196. Aug.

Pappas, E., Zampeli, F., Xergia, S.A., Georgoulis, A.D., 2013. Lessons learned from the last 20 years of ACL-related in vivo-biomechanics research of the knee joint. Knee Surg. Sports Traumatol. Arthrosc. 21 (4), 755–766. Apr 1.

Paschos, N.K., Gartzonikas, D., Barkoula, N.M., Moraiti, C., Paipetis, A., Matikas, T.E., Georgoulis, A.D., 2010. Cadaveric study of anterior cruciate ligament failure patterns under uniaxial tension along the ligament. Arthroscopy 26 (7), 957–967. Jul 1.

Pearsall IV, A.W., Hollis, J.M., Russell Jr., G.V., Scheer, Z., 2003. A biomechanical comparison of three lower extremity tendons for ligamentous reconstruction about the knee. Arthroscopy 19 (10), 1091–1096. Dec 1.

Posthumus, M., Collins, M., September, A.V., Schwellnus, M.P., 2011. The intrinsic risk factors for ACL ruptures: an evidence-based review. Phys. Sportsmed. 39 (1), 62–73. Feb 1.

Rudy, Mustamsir E., Phatama, K.Y., 2017. Tensile strength comparison between peroneus longus and hamstring tendons: a biomechanical study. Int. J. Surg. 9, 41–44. Jan 1.

Schmidt, K.J., Tírico, L.E., McCauley, J.C., Bugbee, W.D., 2017. Fresh osteochondral allograft transplantation: is graft storage time associated with clinical outcomes and graft survivorship? Am. J. Sports Med. 45 (10), 2260–2266. Aug.

Schmidt, E.C., Chin, M., Aoyama, J.T., Ganley, T.J., Shea, K.G., Hast, M.W., 2019. Mechanical and microstructural properties of pediatric anterior cruciate ligaments and autograft tendons used for reconstruction. Orthop. J. Sports Med. 7 (1). Jan 23. 2325967118821667.

Shani, R.H., Umpierez, E., Nasert, M., Hiza, E.A., Xerogeanes, J., 2016. Biomechanical comparison of quadriceps and patellar tendon grafts in anterior cruciate ligament reconstruction. Arthroscopy 32 (1), 71–75. Jan 1.

Smith, C.W., Young, I.S., Kearney, J.N., 1996. Mechanical properties of tendons: changes with sterilization and preservation. ASME J. Biomech. Eng. 118 (1), 56–61. February.

Tis, J.E., Klemme, W.R., Kirk, K.L., Murphy, K.P., Cunningham, B., 2002. Braided hamstring tendons for reconstruction of the anterior cruciate ligament: a biomechanical analysis. Am. J. Sports Med. 30 (5), 684–688. Sep.

Urchek, R., Karas, S., 2019. Biomechanical comparison of quadriceps and 6-strand hamstring tendon grafts in anterior cruciate ligament reconstruction. Orthop. J. Sports Med. 7 (10). Oct 16. 2325967119879113.

Wei, J., Yang, H.B., Qin, J.B., Yang, T.B., 2015. A meta-analysis of anterior cruciate ligament reconstruction with autograft compared with nonirradiated allograft. Knee 22 (5), 372–379. Oct 1.

Wilson, T.W., Zafuta, M.P., Zobitz, M., 1999. A biomechanical analysis of matched bone-patellar tendon-bone and double-looped semitendinosus and gracilis tendon grafts. Am. J. Sports Med. 27 (2), 202–207. Mar.

Wong, A.K., Calvo, R., Schaffler, B.C., Nixon, R.A., Carrero, L.C., Neufeld, E.V., Grande, D.A., Calvo, R., 2019. Biomechanical and geometric characterization of peroneus longus allografts with respect to age. Clin. Biomech. 67, 90–95. Jul 1.

Woo, S.L., Hollis, J.M., Adams, D.J., Lyon, R.M., Takai, S., 1991. Tensile properties of the human femur-anterior cruciate ligament-tibia complex: the effects of specimen age and orientation. Am. J. Sports Med. 19 (3), 217–225. May.

Woo, S.L., Fox, R.J., Sakane, M., Livesay, G.A., Rudy, T.W., Fu, F.H., 1998. Biomechanics of the ACL: measurements of in situ force in the ACL and knee kinematics. Knee 5 (4), 267–288. Oct 1.

Woo, S.L., Debski, R.E., Withrow, J.D., Janaushek, M.A., 1999. Biomechanics of knee ligaments. Am. J. Sports Med. 27, 533–543.

Yanke, A.B., Bell, R., Lee, A.S., Shewman, E., Wang, V.M., Bach Jr., B.R., 2013. Central-third bone–patellar tendon–bone allografts demonstrate superior biomechanical failure characteristics compared with hemi–patellar tendon grafts. Am. J. Sports Med. 41 (11), 2521–2526. Nov.

Zhao, J., Huangfu, X., 2012. The biomechanical and clinical application of using the anterior half of the peroneus longus tendon as an autograft source. Am. J. Sports Med. 40 (3), 662–671. Mar.