Graft Selection for Anterior Cruciate Ligament Reconstruction: A Level I Systematic Review Comparing Failure Rates and Functional Outcomes

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KEYWORDS

- Anterior cruciate ligament
- Bone-patellar tendon-bone composites
- Combined semitendinosus and gracilis hamstring tendons
- Revision

Tear of the anterior cruciate ligament (ACL) is the most common ligamentous injury of the knee. Reconstructing this ligament is often required to restore functional stability of the knee.[1,2] Despite the popularity of the procedure, the preferred graft remains controversial. Ideally, the graft should have similar characteristics as the native ACL. Regardless of graft type, the biologic and mechanical properties of the graft material should provide a favorable setting for early biologic incorporation, be amenable to secure fixation, and limit potential morbidity related to donor site.

Many graft options are available for ACL reconstruction, including different autograft and allograft tissues. Autografts include bone-patellar tendon-bone composites (PT), combined semitendinosus and gracilis hamstring tendons (HT), and quadriceps tendon. Allograft options include the same types of tendons harvested from donors, in addition to Achilles and tibialis tendons. Tissue-engineered anterior cruciate grafts are not yet available for clinical use, but may become a feasible alternative in the future.

For the past few decades, PT autograft has been the gold standard for ACL reconstruction. Reasons for this include the strength of the tissue, relative ease of harvest, and bone-to-bone healing with secure fixation. More recently, HT autografts have joined PT in surgeons' popularity.[3] The recent trend toward increased use of HT resulted from concerns with use of PT relating to a potential negative effect on the knee extensor mechanism and donor site morbidity, including anterior knee pain and risk for patella fracture.[4] Nevertheless, despite their increasing popularity, HT grafts also have potential limitations, including slower soft-tissue graft-tunnel healing compared with bone-to-bone healing with PT grafts, potential for tunnel

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Table 1
Details of studies

Study	Year of Publication	Mean Age (Years) (Range)		Sample Size (N) (% Follow-up)	Mean Follow-up (Months)	Number of HT Strands	Method of Fixation			
							PT		HT	
		PT	HT				Tibia	Femur	Tibia	Femur
Aglietti et al[10]	1994	NA		60 (95)	28	4	IfSc	ScW	ScW	ScW
Aglietti et al[11]	2004	25 (16–39)	25 (15–39)	120 (100)	24	4	IfSc	S	ScW	Sc
Anderson et al[12]	2001	23.6 (14–44)	21 (14–40)	68 (97)	35	2	St	IfSc	Su	St
Beynnon et al[13]	2002	29.2 (18–46)		44 (79)	36	2	IfSc	IfSc	St	St
Biau et al[14,c]	2007	NA		1263 (NA)	NA	2, 3, 4 or 5	Variable	Variable	Variable	Variable
Ejerhed et al[15]	2003	26 (14–49)	29 (15–59)	66 (93)	24	3 or 4	IfSc	IfSc	IfSc	IfSc
Eriksson et al[16]	2001	25.7		154 (94)	33	4	IfSc	IfSc	Sc	Eb
Feller & Webster[17]	2003	26.3	25.8	57 (88)	36	4	IfSc	Eb	Post	Eb
Grontvedt et al[18,b]	1996	26 (16–48)		92 (92)	24	0	IfSc	IfSc + St	IfSc + St	IfSc + St
Harilainen et al[19]	2006	31		79 (80)	60	4	IfSc	IfSc	ScW	P
Ibrahim et al[20]	2005	22.3 (17–34)		85 (77)	81	4	IfSc	Eb	ScW, P + St	P
Jansson et al[21]	2003	NA		89 (90)	24	4	IfSc	IfSc	ScW	P
Laxdal et al[22]	2005	28 (16–52)	25 (12–41)	118 (88)	26	3 or 4	IfSc	IfSc	IfSc	IfSc
Liden et al[23]	2007	28 (14–49)	29 (15–59)	68 (96)	86	3 or 4	IfSc	IfSc	IfSc	IfSc
Maletis et al[24]	2007	27.2 (15–42)	27.7 (14–48)	96 (97)	24	4	IfSc	IfSc	2 IfSc	IfSc

Marder et al[25]	1991	21.6 (16–35)	23.8 (17–41)	72 (90)	29	4	PW	PW	PW	PW
Matsumoto et al[26]	2006	23.7	24.4	72 (90)	87	5	IfSc	IfSc	IfSc	IfSc
Moyen et al[27,b]	1992	24	24	64 (64)	36	0	St	St	St	St
Muren et al[28,b]	2003	25 (20–33)	25 (19–44)	40 (100)	84	0	Su	Post + Su	Su	ScW
O'Neill[29]	1996	27 (14–56)		125 (98)	42	2	IfSc or St	IfSc	St	St
O'Neill[30]	2001	NA		225 (95)	102	2	IfSc or St	IfSc	St	St
Sajovic et al[31]	2006	27 (16–46)	24 (14–42)	54 (84)	60	4	IfSc	IfSc	IfSc	IfSc
Shaieb et al[32]	2002	32 (14–48)	30 (14–53)	70 (85)	33	4	IfSc	IfSc	IfSc	IfSc
Sun et al[33,a]	2009	29.7 (16–59)	30.1 (20–63)	65 (96)	31	0	IfSc	IfSc	IfSc	IfSc
Sun et al[34,a]	2009	31.7 (20–54)	32.8 (19–65)	156 (93)	67	0	IfSc	IfSc	IfSc	IfSc
Taylor et al[35]	2009	21.7 (18–37)	22.1 (17–44)	53 (83)	36	4	IfSc + ScW	IfSc + Eb	IfSc + ScW	IfSc + Eb
Webster et al[36]	2001	26	27	61 (94)	24	4	IfSc	Eb	Post + Su	Eb
Zafagnini et al[37]	2006	30.5 (22–47)	29 (15–49)	75 (100)	60	2 or 4	IfSc	IfSc	IfSc ± St	Eb ± St

Abbreviations: Eb, endobutton; IfSc, interference screw; NA, not available; P, plate; PW, post + washer; Sc, screw; St, staples; Su, sutures; ScW, screw and washer.

[a] PT autograft compared with PT allograft.

[b] Comparison made with PT with KLAD.

[c] Meta-analysis.

Table 2
Quality assessment of study methodology

Study	Randomization Method	Selection Bias	Performance Bias	Detection Bias	Attrition Bias
Aglietti et al[10]	Alternating sequence	+	–	+	–
Aglietti et al[11]	Alternating sequence	+	–	–	–
Anderson et al[12]	Computer-generated	–	–	+	–
Beynnon et al[13]	Random numbers table	–	–	+	+
Biau et al[14,c]	Variable	+	–	–	–
Ejerhed et al[15]	Sealed envelopes	+	–	–	–
Eriksson et al[16]	NA	+	–	–	–
Feller&Webster[17]	Computer-generated	–	–	–	–
Grontvedt et al[18,b]	Sealed envelopes	+	–	+	–
Harilainen et al[19]	Even/odd birth year	+	–	+	+
Ibrahim et al[20]	Even/odd birth year	+	–	+	+
Jansson et al[21]	Even/odd birth year	+	–	+	+
Laxdal et al[22]	Sealed envelopes	+	–	–	+
Liden et al[23]	Sealed envelopes	+	–	–	+
Maletis et al[24]	Computer-generated	+	–	–	–
Marder et al[25]	Alternating sequence	+	–	+	–
Matsumoto et al[26]	Even/odd birth year	+	–	+	–
Moyen et al[27,b]	Drawing of lots	–	–	+	+
Muren et al[28,b]	Random sealed envelopes	–	–	+	–
O'Neill[29]	Birth month allocation	+	–	+	–
O'Neill[30]	Birth month allocation	+	–	+	–
Sajovic et al[31]	Even/odd registration number	–	–	+	–
Shaieb et al[32]	Even/odd birth year	+	–	–	–
Sun et al[33,a]	Computer-generated	–	–	+	–
Sun et al[34,a]	Computer-generated	–	–	+	–
Taylor et al[35]	Random sealed envelopes	–	–	–	–
Webster et al[36]	Computer-generated	–	–	+	–
Zafagnini et al[37]	Alternating sequence	+	–	+	–

Abbreviations: +, bias present in the study; NA, not available.
[a] PT autograft compared with PT allograft.
[b] Comparison made with PT with KLAD.
[c] Meta-analysis of RCTs.

widening and graft laxity, and functional hamstring weakness resulting from graft harvesting.[5,6]

There are several randomized controlled trials (RCTs) in the literature comparing the two most popular graft choices, PT and HT, either used as autografts or allografts. Many of the systematic reviews and meta-analyses in the literature that investigate graft choice for ACL reconstruction are biased by their inclusion of inadequately randomized trials that are not true level I studies.[7–9] Also, functional outcomes, rather than graft failure, tend to be the focus of these reviews. The authors believe, however, that graft failure represents a critically important outcome measure in ACL reconstruction, which has not been given enough attention in previous systematic reviews and meta-analyses. The purpose of this systematic review is to assess whether one of the popular grafts (PT and HT) is preferable for reconstructing the ACL. For this objective the authors selected only true level I studies that compared these graft choices in functional clinical outcomes, failure rates, and other objective parameters following reconstruction of the ACL.

METHODS

A systematic literature review was performed using the following data sources: MEDLINE with OVID and PubMed (basic search, related articles, clinical queries search), EMBASE, and the Cochrane Central Register of Controlled Trials for relevant articles in the English language. Bibliographies of the identified articles on this topic were also reviewed. In addition, a manual search of recent pertinent hard copy journals from the previous 6 months was undertaken to identify journal articles that may not yet have been included in electronic databases.

Initial inclusion criteria included prospective RCTs, meta-analyses of RCTs, studies comparing PT and HT, either autografts or allografts, for ACL reconstruction, minimum of 2-year follow-up after the reconstruction for RCTs but not for meta-analyses of RCTs, no restrictions on date of publication or publication status. Following this initial search the inclusion criteria were further refined to include, in addition to the above criteria, only properly randomized trials comparing 2-strand HT or 4-strand HT with PT autografts. The criteria for proper randomization were strict to avoid any potential selection bias. Proper randomization techniques included random numbers table, computer-generated randomization, and randomly ordered sealed envelopes. Trials using even and odd birth years/months, patient registration numbers, or another alternating sequence of allocation were excluded because of inadequate randomization and the associated potential bias.

All studies identified in the initial search were screened for duplications by entering them into a computer-based reference management system. All eligible articles were then screened first by title and abstract, followed by an in-depth review of the methodology and outcomes. The results of this search are shown in **Tables 1** and **2**, which include studies with proper randomization techniques and those that were quasi-randomized. Following this, the authors limited the review further to studies with appropriate randomization only, as described earlier. A standardized data extraction form was modified and used to retrieve data from each article on study design, population, interventions, and outcomes.[38] Outcomes of particular interest included return to preinjury level of activity, graft failure rate, donor site morbidity, laxity measurements, knee range of motion, isokinetic muscle strength, and standardized knee outcomes scores. The authors defined graft failure rate as either revision ACL reconstruction or a 2-plus positive pivot shift test. KT-1000 measurements were not included as a criterion for failure because of variability in testing and because the pivot shift test is associated with function, whereas the KT-1000 is not.[39]

The quality of the studies, including internal and external validity, was appraised using the items contained in the CONSORT Statement: Revised Recommendations for Improving the Quality of Reports of Parallel-Group Randomized Trials.[38] Furthermore, each study was assessed for the 4 main biases affecting method quality: selection bias, performance bias, detection bias, and attrition bias.

RESULTS

General Description of Studies

Twenty-eight studies published between 1991 and 2009 (27 prospective RCTs and 1 meta-analysis of RCTs) met the initial inclusion criteria (see **Table 1**). The data for each study were collected using a worksheet developed by the authors. The basic details of the studies are shown in **Table 1**, including sample sizes, length of follow-up, and methods of fixation of the grafts. Of the 28 studies, 23 prospectively compared PT autografts with 2-, 3-, 4-, or 5-strand semitendinosus and gracilis (HT) composite autografts (including 1 meta-analysis of studies comparing PT autografts with HT autografts of varying sizes).[10–17,19–26,29–32,35–37] Three studies compared PT autografts with PT autografts augmented by the Kennedy ligament augmentation device (KLAD),[18,27,28] and two studies compared PT autografts with PT fresh-frozen allografts, which were γ-irradiated in 1 study[33] and nonirradiated in the other.[34]

Study Design Appraisal

The presence of the 4 main biases affecting study quality, and the treatment allocation methods used in each of the studies, are shown in **Table 2**. Each of the studies in the initial stage of this review allocated patients during the same period in a prospective random fashion, either by computer-generated random models or via quasi-randomized allocation methods (ie, birth date, alternating sequence, sealed envelopes that were not randomly ordered).

Detection bias can be minimized by blinding patients and investigators at follow-up evaluations. No patient in any study was blinded to the type of graft they received, but several independent follow-up evaluations were performed by blinded investigators, and the outcomes of the treatment groups in each study were assessed in identical fashion, thereby minimizing detection bias (see **Table 2**).

Attrition bias pertains to loss of patients from treatment groups after allocation, by either late exclusion or lost to follow-up. As shown in **Table 2**, several studies excluded patients after treatment allocation, but 1 study[27] had more than 30% lost to follow-up, which has been reported as the threshold for acceptable follow-up, with less than 20% being preferable.[40] Another study had 23% lost to follow-up.[20] Attrition bias was also prevalent in another study,[21] and in its subsequent study with longer follow-up,[19] in which data from 4 graft failures (all in the HT group) were excluded in the final analysis. This finding may represent a systematic exclusion of data that could potentially overestimate the favorable results in the HT group. Graft failures were similarly excluded from final data analysis in another study.[23] As graft failure rate is a critical outcome following ACL reconstruction, methodology that excludes failures from the final analysis limits the value of the conclusions reached in these studies.

To improve the validity of our conclusions, our analysis of functional clinical outcomes, failure rates, and other objective parameters was limited to RCTs that had proper randomization (ie, computer-based, random numbers table, random sealed envelopes), and 80% follow-up at a minimum of 2 years follow-up. Also, as discussed earlier, trials comparing PT with HT were required to use HT composites of 2- or 4-strand quadrupled grafts only. Studies not meeting these strict criteria were excluded from all subsequent analyses, leaving 6 of 28 studies. Of these, 4 studies compared PT autografts with 4-strand HT autografts,[17,24,35,36] and two studies compared PT autografts with 2-strand HT autografts.[12,13] These 6 studies served as the basis for our analyses and subsequent conclusions. One study had a follow-up rate of 79% and we elected to include it.

OUTCOMES

Graft Failure Rate

In the 6 studies that met the inclusion criteria, the authors evaluated graft failure rates and included all patients with a final follow-up pivot shift test of 2+ or greater or patients who required revision ACL surgery (**Table 3**). The results of the graft failure analysis are shown in **Table 3**. In the two

Table 3
ACL graft failure (defined as 2+ positive pivot shift or ACL revision reconstruction)

Study	Sample Size (N) Total	PT	HT	Graft Failure (Number of Patients) (%) PT	HT
Anderson et al[12,b]	68	35	33	7 (20)	8 (24.2)
Beynnon et al[13,b]	44	22	22	0	6 (27.3)
Feller & Webster[17]	57	26	31	1 (3.8)	5 (16.1)
Maletis et al[24]	96	46	50	0	2 (4.0)
Taylor et al[35]	53	24	29	3 (12.5)	5 (17.2)
Webster et al[36]	61	28	33	NR	NR
Totals	379	181	198	11 (7.2)[a]	26 (15.8)[a]

Abbreviation: NR, not reported.
[a] Patients from Webster et al[36] were not included in total ACL graft failure calculations because this was not reported in their study. Inclusion criteria: properly randomized controlled trials comparing PT autograft with 2-strand or 4-strand HT autograft, and minimum 2 years' follow-up with 80% complete follow-up (1 study had 79% follow-up).
[b] Comparison between PT and 2-strand HT.

studies that compared PT with 2-strand HT autografts,[12,13] 7 graft failures were seen in 57 PT reconstructions (12.3%), whereas 14 graft failures occurred in 55 HT reconstructions (25.5%). In the 4 studies that used 4-strand HT as the comparison graft, 4 PT graft failures were seen in 96 reconstructions (4.2%), and 12 failures occurred in 110 4-strand HT reconstructions (10.9%). The graft failure rate was significantly higher in the Beynnon study that compared PT with 2-strand HT (P = .024). Overall the graft failure rate for the 6 studies was 11 failures out of 153 reconstructions in the PT groups (7.2%) and 26 failures out of 165 reconstructions in the HT groups (15.8%) (P = .02).

Knee Range of Motion

All 6 studies, in some fashion, reported on range of motion deficits at final follow-up **(Table 4)**. Neither of the two studies comparing PT with 2-strand HT found a significant difference in knee range of motion.[12,13] Two of the 4 studies that compared PT with 4-strand HT found significantly higher extension deficits in the PT groups (see **Table 4**).[17,36] Neither of the remaining two studies reported significant differences in knee range of motion.

Patellofemoral Pain

In this review, 5 of the 6 included studies reported on donor site morbidity, specifically patellofemoral pain **(Table 5)**. Of the 2 studies comparing PT with 2-strand HT, one study reported on patellofemoral crepitus and found no significant difference,[12] and the other looked at the incidence of anterior knee pain and again found no significant difference.[13] Three studies comparing PT with 4-strand HT used patient reports of pain with kneeling, or difficulty or inability to walk on their knees, as a surrogate for patellofemoral pain. Of those 3 studies, 1 found a significantly higher incidence of pain with kneeling and knee-walking in the PT group (P<.01).[17] That same study also presented subjective patient reports of anterior knee pain, and found significantly more subjective anterior knee pain in the PT group (P<.05). Of the 4 studies that found no significant differences statistically in knee pain outcomes, 3 of them reported higher absolute pain scores in the PT groups, and one study reported higher absolute pain ratings in the HT group (see **Table 5**).

Activity Level and Functional Assessments

As shown in **Table 6**, studies used various measures of patient activity for preinjury and follow-up assessments (**Tables 6** and **7**). Neither study that used 2-strand HT as the comparison group found significant differences in final follow-up activity levels compared with PT (see **Table 6**). Of the 4 studies comparing PT with 4-strand HT, 2 studies found significant differences in activity level at final follow-up, one of which found a significantly higher percentage of patients in the PT groups returning to their preinjury level of activity compared with the HT groups.[24] However, in that particular study the preinjury Tegner activity level was found to be significantly lower in the PT group (P = .03), which theoretically could have made it easier for PT patients to return to their preinjury activity level because it was lower to start with. **Table 7** contains the data on standardized functional outcome assessments for each of the studies.

Anterior Knee Laxity

All the studies in this review included instrumented-laxity testing as an objective outcome measure (**Table 8**). As seen in **Table 8**, both studies comparing PT with 2-strand HT grafts reported significantly more laxity in the 2-strand HT grafts at final follow-up.[12,13] One of 4 studies comparing PT with 4-strand HT found higher laxity in the HT group (P<.05).[17] All studies, except one,[35] reporting side-to-side differences of a 3-mm threshold reported higher absolute values of anterior laxity in the HT groups compared with the PT groups.

Isokinetic Muscle Strength

Five of the 6 studies reported on isokinetic muscle strength testing of the quadriceps and hamstrings muscles at final follow-up (**Table 9**). As shown in **Table 9**, the only significant difference in muscle strength found between PT and 2-strand HT grafts was a greater peak hamstring muscle torque deficit at 240 degrees/s in the 2-strand HT group (P = .04).[13] Also, two of the 3 studies comparing PT with 4-strand HT showed significantly more hamstring weakness in the HT autograft groups.[17,24] Only 1 study found significantly weaker quadriceps in the PT autograft group (P = .04).[24]

DISCUSSION

Over the past two decades, the most commonly asked question in ACL surgery has been “what is the best graft option?” From this systematic review, since 1991 27 prospective RCTs and 1 meta-analysis of RCTs meeting the authors’ initial inclusion criteria have been conducted looking for the answer to this question. These studies for the most part compared PT autografts with HT autografts; however, 3 of them compared PT autografts with PT autografts plus KLAD,[18,27,28] and 2 studies used PT allografts[33,34] (1 γ-irradiated,

Table 4
Knee range of motion deficits at final follow-up

	Extension Deficits (Number of Patients) (%)				Flexion Deficits (Number of Patients) (%)				
	PT		HT		PT		HT		
Study	**3–5°**	**≥5°**	**3–5°**	**≥5°**	**3–5°**	**≥5°**	**3–5°**	**≥5°**	**Comments**
Anderson et al[12,a]	3 (9)	0	1 (2)	7 (10)	0	1 (3)	0	10 (15)	NS
Beynnon et al[13,a]	–	–	–	–	–	–	–	–	Deficits reported as means (NS)
Feller & Webster[17]	–	–	–	–	–	–	–	–	Extension deficit means: PT 2.7, HT 1.2 (*P*<.05)
Maletis et al[24]	–	–	–	–	–	–	–	–	Deficits reported as means (NS)
Taylor et al[35]	–	–	–	–	–	–	–	–	Deficits reported as means (NS)
Webster et al[36]	6 (26)	4 (17)	4 (13)	1 (3)	–	–	–	–	*P*<.05

Abbreviations: –, unclear from presentation of data within the study, not reported, or categorized differently by study; NS, no significant difference.
[a] Comparison between PT and 2-strand HT.

Table 5
Patellofemoral pain at latest follow-up

	Patellofemoral Crepitus (Number of Patients) (%)			Pain with Kneeling or Knee-Walking (Number of Patients) (%)			Anterior Knee Pain (Number of Patients) (%)		
Study	**PT**	**HT**	***P***	**PT**	**HT**	***P***	**PT**	**HT**	***P***
Anderson et al[12,a]	9 (26)	14 (21)	NS						
Beynnon et al[13,a]							7 (32)	5 (23)	NS
Feller & Webster[17]				17 (67)	8 (26)	<0.01	11 (43)	10 (33)	<0.05
Maletis et al[24]				9 (20)	3 (6)	NS			
Taylor et al[35]				2 (9.5)	5 (20.8)	NS			
Webster et al[36]	NR	NR		NR	NR		NR	NR	

Abbreviations: NR, not reported; NS, no significant difference; *P*, *P* value.
[a] Comparison between PT and 2-strand HT.

Table 6
Preinjury and latest follow-up activity levels after ACL reconstruction

Study	Preinjury Activity Level: Scale	PT	HT	P	Latest Follow-up Activity Level: Scale	PT	HT	P
Anderson et al[12,a,b]	NR	NR	NR		IKDC level I	83%	81%	NS
Beynnon et al[13,a,b]	NR	NR	NR		Tegner/IKDC level I	4/59%	4/45%	NS
Feller & Webster[17]	Cincinnati activity score	91.6 (8)[b]	87.3 (13)[b]	NS	Cincinnati level I	27%	36%	NS
Maletis et al[24]	Tegner	6.8	7.2	0.03	Return to preinjury Tegner	51%	26%	0.01
Taylor et al[35]	NR	NR	NR		Tegner	6.8	5.3	0.04
Webster et al[36]	NR	NR	NR		IKDC level I or II	61.3%	60.9%	NS

Abbreviations: IKDC, International Knee Documentation Committee; NR, preinjury activity level not reported; NS, no significant difference; *P*, *P* value.
[a] Comparison between PT and 2-strand HT.
[b] Number in parentheses denotes standard deviation.

Table 7
Functional assessments at latest follow-up

Study	IKDC Score (% Normal/Nearly Normal): PT	HT	P	Lysholm Score (Mean): PT	HT	P	Cincinnati Score (Mean) (SD): PT	HT	P
Anderson et al[12,a]	97	73	0.02						
Beynnon et al[13,a]	NA	NA		NA	NA		NA	NA	
Feller & Webster[17]	71	93	NS				92.7 (9.0)	93.7 (8.2)	NS
Maletis et al[24]				97	98	NS			
Taylor et al[35]	86	78	NS	90.4	90.3	NS			
Webster et al[36]	61	61	NS						

Abbreviations: IKDC, International Knee Documentation Committee; NA, not applicable to study; NS, no significant difference; *P*, *P* value.
[a] Comparison between PT and 2-strand HT.

Table 8
Objective knee stability testing at final follow-up

Study	Instrument	Force	≥3 mm Side-to-Side Difference PT (%)	HT (%)	*P*	Mean Laxity (mm) (SD) PT	HT	*P*
Anderson et al[12,a]	KT-1000 arthrometer	Manual maximum	29	48	NS	2.1 (2.0)	3.1 (2.3)	<0.05
Beynnon et al[13,a]	KT-1000 arthrometer	133 N	23	55	0.004	1.1	4.4	0.001
Feller & Webster[17]	KT-1000 arthrometer	134 N	5	15	NS	0.5 (1.5)	1.6 (1.3)	<0.05
Maletis et al[24]	KT-1000 arthrometer	Manual maximum				2.3	2.8	NS
Taylor et al[35]	KT-2000 arthrometer	134 N	50	36.4	NS			
Webster et al[36]	KT-1000 arthrometer	30 pounds	7.1	9.1	NS	1.1	1.7	NS

Abbreviations: N, newtons; NS, no significant difference; *P*, *P* value.
[a] Comparison between PT and 2-strand HT.

one nonirradiated fresh-frozen) as the comparison group. The criteria by which all of these studies have attempted to judge the superiority of one graft to another include the rate of graft failure, knee range of motion, donor site morbidity, quadriceps/hamstring muscle strength, anterior knee laxity, return to preinjury activity level, and standardized functional knee outcome scores.

In the authors' opinion, the two most important issues for patients who have undergone ACL reconstruction are knee stability (in the relative short-term) and the development of osteoarthritis (in the long-term). The latter requires decades of follow-up and it is not yet possible to determine from the literature whether one graft source has a higher risk than another for the development of degenerative changes. On a more basic level, ACL reconstruction is performed to provide a stable knee for the patient. If this is not achieved, then the operation has not accomplished the main

Table 9
Isokinetic strength of the quadriceps and hamstrings (reported as % of contralateral uninvolved knee)

Study	Instrument	Speed (Degrees/s)	Knee Extension (Quadriceps) (%) PT	HT	*P*	Knee Flexion (Hamstrings) (%) PT	HT	*P*
Anderson et al[12,a]	Cybex II	60	86	96	NS	96	96	NS
		180	91	99	NS	100	96	NS
Beynnon et al[13,a]	Cybex	60	94.7	88.1	NS	99.4	95.5	NS
		180	95.9	92.1	NS	95.8	90.9	NS
		240	96.6	93.5	NS	100.3	89.3	0.04
Feller & Webster[17]	Cybex II	60	77.3	88.9	NS	98.3	92.3	<0.05
		240	85.2	91	NS	99.4	105.5	NS
Maletis et al[24]	Dynanometer (Biodex)	60	85	92	0.04	99	91	NS
		180	93	96	NS	102	90	0.0001
		300	94	96	NS	96	93	NS
Taylor et al[35]	Dynanometer (Biodex)	60	87.9	96.9	NS	83.2	97.5	NS
		300	91.6	94.3	NS	95.9	100.3	NS
Webster et al[36]	NR	NR	NR	NR		NR	NR	

Abbreviations: NR, not reported; NS, no significant difference; *P*, *P* value.
[a] Comparison between PT and 2-strand HT.

goal. Stability can be challenging to define and is affected by many factors, not the least of which is patient activity level. To clarify this definition, we selected two end points that we felt clearly indicated that stability was not achieved: documentation of a positive pivot shift test and revision ACL reconstruction. Although it is possible that a patient may have an unstable knee without a detectable pivot shift on examination, the authors believed that if either of these two outcomes was documented, then the procedure could clearly be considered a failure.

Most of the randomized clinical trials comparing graft sources have significant potential biases that could affect the conclusions. In an attempt to eliminate this potential problem, the authors further refined the analysis, limiting it only to trials that compared PT with either 2-strand or 4-strand HT autografts, trials that used appropriate methods of randomization, and that had a minimum of 2 years' follow-up with 80% follow-up. These criteria eliminated 22 of 28 studies, leaving 6 trials. Using these 6 studies with these criteria for failure, PT autografts had 11 failures of 153 cases (7.2%) and HT autografts had 26 failures of 165 cases (15.8%). This difference in failure rate using only the best evidence available is important clinical information that has not been previously reported. Although fixation and other techniques used in the studies vary, this difference in graft failure rate is statistically significant and clinically meaningful.

Other outcomes are discussed in detail in the results section. Overall, there is a trend toward increased donor site morbidity in PT autografts compared with HT autografts. The authors believe that this potential increase in morbidity is better tolerated by younger, more active patients who also have a higher risk of graft failure.[41] Therefore the authors favor PT autografts for younger patients who tend to have fewer problems caused by donor site morbidity and who also have a higher risk of re-tearing their graft.

Aside from clinical outcomes, there are biologic and biomechanical aspects of the various grafts that are useful to explore. For ideal reconstruction and postoperative rehabilitation planning, ACL graft selection should take into consideration the following factors: graft tissue mechanical properties compared with native ACL properties, the time frame for solid biologic graft incorporation, the mechanical stability of the initial fixation technique and device used, and the effect of the sterilization method on the quality of the tissue when using allograft.

Biomechanical testing in cadaveric knees of the native human femur-ACL-tibia complex in anatomic orientation to maximize stiffness and load to failure has shown that younger specimens (22–35 years) demonstrate the highest values of linear stiffness (242 N/mm) and ultimate load to failure (2160 N), whereas older specimens (60–97 years) demonstrate the lowest values of linear stiffness (180 N/mm) and ultimate load to failure (658 N).[42] Comparing mechanical characteristics of different ACL grafts is challenging because of study methodology differences in graft size, age, orientation of specimen, and methods of testing and fixation devices. Nevertheless, tensile properties and load to failure of several graft tissues provide some helpful information for graft selection.

Bone-patellar composites, investigated in vitro, have demonstrated mechanical properties comparable to the native ACL. Nonetheless, some investigators have suggested a possible correlation between mechanical characteristics of the graft and donor age.[43,44] Load to failure of 10-mm patellar tendon-bone composites was around 2900 N when donor tissue was from a young group (average age 28 years), and was comparable to thicker grafts (14 mm) obtained from an older population.[43,44] On the other hand, other investigators did not find a correlation between mechanical characteristics of patellar tendon grafts and age between 18 and 55 years.[45]

For human hamstring quadruple grafts, the composite was stiffer (776 N/mm) and had higher loads to failure (4090 N) compared with previously described 10-mm patellar tendon grafts, supporting its use from a mechanical standpoint as an ACL graft tissue.[46] From a surgical technical standpoint all 4 strands of the graft must be under equal tension for the composite to have its optimum biomechanical properties. Other soft-tissue grafts such as doubled tibialis anterior, doubled tibialis posterior, and doubled peroneus longus have also been measured mechanically, and have demonstrated load to failure of around 3000 N and stiffness of around 300 N/mm.[47]

Although less popular for ACL reconstruction, quadriceps tendon has also been tested mechanically and was found to have comparable mechanical properties to patellar tendon tissue (1.36 times load to failure compared with similar width patellar tendon graft, which was not statistically significant), and thus is appropriate also for ACL reconstruction.[48]

With regard to allograft tissue, the sterilization process may affect the mechanical characteristics of the tissue and therefore should also be thought of when selecting a graft. This process is necessary to decrease viral disease transmission and bacterial infection rate, but it may also adversely affect the quality of the tissue. Several techniques have been used for this purpose. Although ethylene oxide sterilization does not alter directly the mechanical properties of the graft, it has been shown to cause clinical failure because of persistent synovitis, and therefore is less favorable.[49,50] Another sterilization technique involves applying γ-irradiation. High-dose irradiation (3 Mrad or more) is unacceptable as it severely affects mechanical properties of the tissue. Irradiation (2–2.5 Mrad) has also been shown in several studies to cause unacceptable inferior clinical outcomes and high failure rates.[51,52]

The use of allograft tissue has increased significantly in the past decade because of increased availability and the elimination of donor site morbidity. However, Carey and colleagues[53] have recently demonstrated that there are limited data from randomized trials. Most case series include a smaller number of young patients (ie, less than 30 years of age) and there have been early reports of unacceptably high failure rates in young patients.[54,55] Furthermore, procurement, storage, sterilization, and processing vary widely within the industry and the authors encourage all surgeons to be familiar with the methods and standards of the tissue bank they use. The authors currently use allograft tissue for certain revision and multiligament cases, and primary ACL reconstruction in patients who are typically more than 40 years of age, not active in highly aggressive cutting and pivoting sports, and who wish to minimize donor site morbidity related to graft harvest.

SUMMARY

When only high-quality randomized clinical trials are evaluated, the risk of graft failure is significantly higher with hamstring tendon reconstruction compared with patellar tendon autograft. This difference has been discussed but not demonstrated previously because of bias in study design and inadequate power. The authors believe this finding is particularly important when selecting a graft for higher-risk patients who are sufficiently skeletally mature for patellar tendon autograft ACL reconstruction.

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