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Similar clinical outcome between patellar tendon and hamstring tendon autograft after anterior cruciate ligament reconstruction with accelerated, brace-free rehabilitation: a systematic review

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ABSTRACT

Importance Controversy exists with respect to the best graft choice for anterior cruciate ligament reconstruction (ACLR) with accelerated, brace-free rehabilitation.

Objective To investigate differences in clinical outcome between patellar tendon (PT) and hamstring tendon (HS) autografts for ACLR with accelerated, brace-free rehabilitation.

Evidence review Systematic review, all settings. Search from 1 January 1974 till 31 January 2017 in Medline (Pubmed), EMBASE (OVID), Cochrane Library and CINAHL according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines. All study designs that reported clinical outcome in adults after arthroscopic, primary ACLR with accelerated, brace-free rehabilitation, HS or PT autografts were included. A risk of bias assessment of the eligible articles was determined. Data collection included surgical techniques, graft type, patient demographics, details of rehabilitation, patient-reported outcome, clinical outcome measures and radiological evaluation. A 'best-evidence synthesis' was performed for the formulated research questions. Eighteen studies were included.

Findings After autograft ACLR with accelerated, brace-free rehabilitation: (1) PT and HS autografts provide satisfactory short and long-term results in terms of range of motion, subjective stability and functional scores; (2) PT autograft is associated with more pain on kneeling and increased risk of knee osteoarthritis; (3) there is 'conflicting' evidence between PT and HS autografts for objective knee stability, knee laxity in females, return to sports and muscle strength; (4) there is no difference between males and females in return to sports irrespective of the chosen graft type; (5) HS autograft is correlated with tunnel widening; (6) early progressive eccentric exercises from 3 weeks postsurgery can safely be added irrespective of graft type; (7) early start of open kinetic exercises (4 weeks) causes increased laxity of HS autograft; (8) focus on quality of movement is important as part of ACL rehabilitation protocols and return to sports criteria.

Conclusions and relevance PT and HS autografts may both be selected for ACLR with accelerated, brace-free rehabilitation. Specific considerations for each graft type must be made during rehabilitation. PT reconstructions are more likely to result in statically stable knees, but are also associated with more complications and osteoarthritis. There is insufficient evidence to draw conclusions on differences between PT and HS autograft for long-term outcome.

What is already known

- After anterior cruciate ligament (ACL) surgery, graft healing in patellar tendon (PT) and hamstring autograft (HS) is characterised by a remodelling process. Brace-free rehabilitation protocols that incorporate immediate motion of the knee and full weight bearing appear to be safe and effective.
- Overlapping systematic reviews of ACL reconstruction (ACLR) comparing PT and HS autografts complicate the choice between the two graft types. Critical appraisal of each study's methodology should be done before it can guide clinical decision making or policy change.

What are the new findings

After ACLR with autograft tendons and accelerated, brace-free rehabilitation:

- PT and HT autografts provide satisfactory short and long-term results in terms of range of motion, subjective stability and functional scores. However, there is 'conflicting' evidence between the graft types for objective knee stability, knee laxity in females, return to sports and muscle strength. PT ACLRs are more likely to result in statically stable knees, but are also associated with more complications and osteoarthritis.
- Gender does affect return to sports irrespective of graft type.
- Early progressive eccentric exercises from 3 weeks postsurgery can safely be added irrespective of graft type. However, early start of open kinetic exercises (4 weeks) causes increased laxity of HT ACL autograft. Focus on quality of movement is important as part of ACLR protocols and return to sports criteria.

Level of evidence III.

INTRODUCTION

The choice of graft for anterior cruciate ligament reconstruction (ACLR) is a matter of debate, with patellar tendon (PT) and hamstring tendon (HS) autografts being the most popular graft options. Poolman *et al*[1] concluded that overlapping systematic reviews of ACLR, comparing PT and HS autografts, complicated the choice between the two graft types. Critical appraisal of each study's methodology should be done to guide clinical decision making or policy change. Currently, a minority of randomised controlled trial (RCT) studies on this topic are of high quality.[2]

Successful ACLR requires understanding of several factors: anatomical graft placement, mechanical properties of graft tissue, mechanical behaviour and fixation strength of fixation materials as well as the biological processes that occur during graft remodelling and incorporation.[3–5] They influence the mechanical properties of the knee joint after ACLR and determine the rehabilitation and time course until normal function of the knee joint can be expected.[3–5] After surgery, graft healing in PT and HS autografts is characterised by a remodelling process.[4–5] Rehabilitation protocols that incorporate immediate motion of the knee appear to be safe and effective.[6–8] There is no clinical advantage of a postoperative knee brace after PT ACLR.[2] Early mobilisation with full weight bearing is possible without graft damage.[6] The primary research aim is to investigate whether graft choice affects clinical outcome after ACLR with accelerated, brace-free rehabilitation. The secondary aim is to identify possible factors that influence graft-specific ACLR with accelerated, brace-free rehabilitation.

MATERIALS AND METHODS

A systematic literature search was performed according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines using a PRISMA checklist.[9]

Eligibility criteria

Inclusion criteria were all study designs reporting outcome after ACLR with brace-free, accelerated rehabilitation. Only studies on human adults with isolated ACL ruptures were eligible for inclusion in the systematic review. HS and PT autografts for ACLR were included. Therapeutic studies comparing accelerated rehabilitation with non-accelerated rehabilitation, no reconstruction, wait-and-see, brace or no comparison at all were included. Outcome was defined as subjective (questionnaires), objective (strength, hop indices), knee stability (passive and active), functional performance, level of activity, return to sports and osteoarthritis (box 1).

Electronic search

A systematic electronic search was performed using specific search terms in the following databases: Medline (Pubmed), EMBASE (OVID), the Cochrane Library and CINAHL. All study designs were eligible for inclusion for study selection. The time range was defined 1 January 1974 till 31 January 2017.

Study selection

All studies were screened by title and abstract by two teams of reviewers (RJ&NM and RJ&JM). When two reviewers did not reach consensus, a third reviewer (NM or JM) made the final decision. After this first inclusion, the full-text articles were assessed. These were excluded if they did not meet the inclusion criteria. Furthermore, all references of both excluded and included articles were analysed for eligible articles.

Data collection process

The data from each study were independently extracted by two reviewers (RJ and NM). Disagreement regarding data extraction was resolved by consensus.

Box 1 Inclusion and exclusion criteria

Inclusion criteria

- Studies (meta-analysis, randomised, non-randomised, systematic reviews, case series, prospective or retrospective design) evaluating outcome in adult patients undergoing isolated anterior cruciate ligament (ACL) reconstruction
- Studies must have included an accelerated rehabilitation protocol. Accelerated rehabilitation is characterised by immediate postoperative weight bearing, without restriction in motion and brace-free rehabilitation. Return to sports is allowed after 4–6 months
- Any arthroscopic surgical method of primary intra-articular ACL reconstruction
- Hamstring and bone-patellar tendon-bone autograft
- Human in vivo studies with reported outcome
- English language
- Abstract and full text available

Exclusion criteria

- Concomitant surgery limiting an accelerated rehabilitation protocol (meniscal repair or transplant, osteotomy, microfracture, autologous cartilage implantation or matrix autologous chondrocyte implantation
- Revision surgery
- Allografts, quadriceps tendon or synthetic grafts
- Multiligament reconstructions
- Posterolateral, medial or posterior cruciate ligament instability
- Non-defined rehabilitation protocol
- Children and adolescents
- Animal or cadaveric (in vitro) studies
- Non-arthroscopic ACL reconstruction
- Non-English language
- Abstract or full text not available

Data items

The data included surgical techniques, graft type, patient demographics, details of rehabilitation, patient-reported outcome, clinical outcome measures and radiological evaluation.

Synthesis of results

Due to substantial heterogeneity with regard to surgical techniques, populations, outcome and study design, it was not possible to pool the data for statistical analysis. Therefore, a 'best-evidence synthesis'[10 11] was performed, by means of the system developed by van Tulder *et al*.[12] The following ranking of levels of evidence was formulated:

1. Strong evidence is provided by two or more studies with good quality (low risk of bias) and by generally consistent findings in all studies (≥75% of the studies reported consistent findings).
2. Moderate evidence is provided by one good quality (low risk of bias) study and two or more questionable quality (higher risk of bias) studies and by generally consistent findings in all studies (≥75%).
3. Limited evidence is provided by one or more questionable quality (higher risk of bias) studies or one good quality (low risk of bias) study and by generally consistent findings (≥75%).
4. Conflicting evidence is provided by conflicting findings (<75% of the studies reported consistent findings).[12]

Table 1 Cochrane criteria and risk of bias assessment of RCTs and CCTs

1. Is a method of randomisation applied?
2. Is randomisation blinded?
3. Are the patients blinded?
4. Is the therapist blinded?
5. Is the outcome assessor blinded?
6. Are the groups comparable?
7. Is there an acceptable lost-to-follow-up?
8. Is there an intention-to-treat?
9. Are treatments comparable?

Study	Study design	1	2	3	4	5	6	7	8	9	Accurate description rehab	Ratio men:women	Total score
Beard *et al*[13]	RCT	+	+	–	?	?	+	–	+	+	+	?	Good
Clatworthy *et al*[22]	CCT	–	–	?	–	?	+	+	?	+	–	+	Questionable
Corry *et al*[23]	CCT	–	–	?	–	?	+	+	?	+	+	+	Questionable
Ejerhed *et al*[14]	RCT	+	+	?	–	?	+	+	?	+	+	–	Good
Feller and Webster[15]	RCT	+	+	?	–	?	+	+	–	+	+	–	Good
Gerber *et al*[16]	RCT	+	–	?	–	+	?	+	+	+	+	?	Good
Gerber *et al*[21]	RCT	+	–	?	–	+	?	+	+	+	+	?	Good
Heijne and Werner [17]	RCT	+	+	?	–	–	+	–	?	+	+	+	Good
Heijne and Werner[18]	RCT	+	+	?	–	+	?	?	+	+	+	+	Good
Laoruengthana *et al*[19]	RCT	+	+	?	–	?	+	+	?	+	+	–	Good
Mohammadi *et al*[20]	RCT	+	+	–	?	?	+	+	+	+	–	+	Good
Pinczewski *et al*[24]	CCT	–	–	?	–	?	+	+	–	+	+	+	Questionable
Pinczewski *et al*[28]	CCT	–	–	?	–	?	+	+	–	+	+	+	Questionable
Rudroff *et al*[25]	CCT	–	–	–	?	?	+	+	+	+	+	–	Questionable
Svensson *et al*[26]	CCT	–	–	?	–	–	+	+	?	+	+	–	Questionable
Witvrouw *et al*[27]	CCT	–	–	?	–	?	+	+	+	+	+	+	Good

CCT, clinical controlled trial; RCT, randomised controlled trial; rehab, rehabilitation.

Assessment of risk of bias

Two reviewers (RJ and NM) assessed the risk of bias of studies with the Cochrane Library checklists (www.cochrane.nl). When the reviewers did not reach consensus, a third reviewer (JM) made the final decision. Reviewers were not blinded for author, journal or publication.

The assessment of risk of bias for RCT used nine criteria (table 1). These items could be rated 'yes' (+), 'no' (−) or 'do not know' (?). The same list was used for assessing clinical controlled trials (CCT), but these scored a 'no' for items 1 and 2.

The assessment of risk of bias for cohort studies described eight items (table 2). All items could be rated positive (+), negative (−) or 'do not know' (?). The same list was used for cross-sectional studies (CS), but these scored a '−' for item two because the study design could cause a selection bias.

Based on the research question, two additional items were evaluated: (1) accurate description of the rehabilitation protocol and (2) ratio of men and women. A total score was calculated by adding up all positive items. A final judgement of 'good', 'questionable' or 'poor' was given to every study. 'Good' was assigned to articles scoring positive for more than 50% of all items (low risk of bias); 'questionable' if the positive score was between 30% and 50% (questionable risk of bias) and 'poor' to articles with a positive score <30% (high risk of bias). The articles with total score of 'good' and 'questionable' were included.

RESULTS

Study selection

Eighteen studies were selected for risk of bias assessment: nine RCT,[13–21] seven CCT[22–28] and two CS[28 29] (figure 1).

Assessment of risk of bias

The results of the risk of bias assessment of the 18 studies are presented in tables 1 and 2.

Table 2 Risk of bias assessment of CS

1. Are study groups clearly defined?
2. Is there any selection bias?
3. Is the exposure clearly defined?
4. Is the outcome clearly defined?
5. Is the outcome assessment blinded?
6. Is the follow-up accurate?
7. Is there an acceptable loss-to-follow-up?
8. Are confounders described and/or eliminated?

Study	Study design	1	2	3	4	5	6	7	8	Accurate description rehab.	Ratio men:women	Total score
Engelen *et al*[30]	CS	+	–	+	+	?	+	?	–	–	+	Questionable
Smith *et al*[29]	CS	+	–	+	+	?	+	–	?	+	+	Good

CS, cross-sectional study; rehab; rehab, rehabilitation.

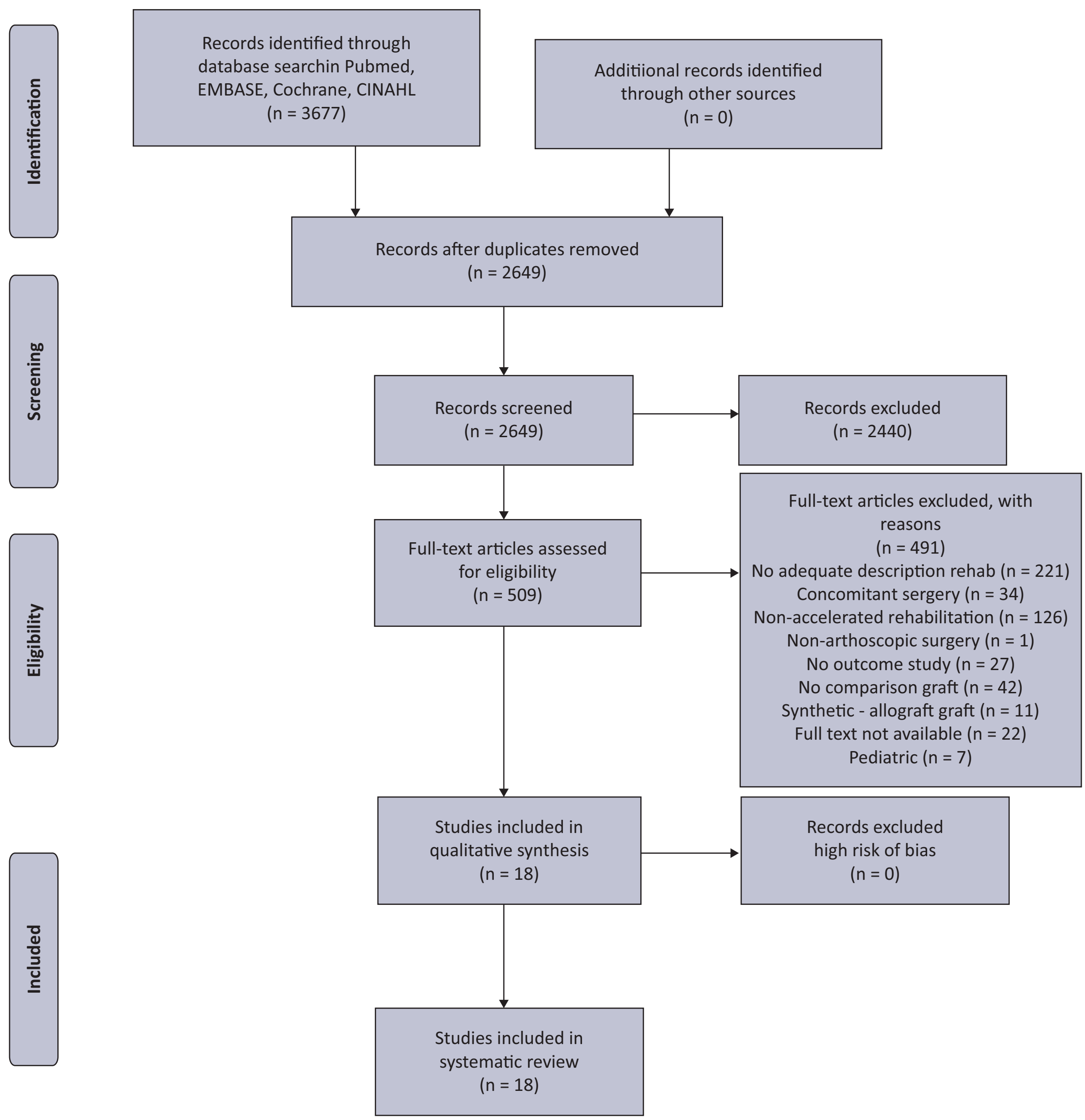

Figure 1 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) flow diagram.

Details of rehabilitation

The specific details of accelerated rehabilitation per study are presented in table 3.

Answers to research questions

Does graft choice affect the outcome after ACLR with accelerated, brace-free rehabilitation?

Thirteen studies compared outcome between PT and HS autograft ACLR (table 4).[1,2,15–17,20–22,24–27,29,30] All studies demonstrated a significant improvement postoperatively compared with preoperative measurements for both graft types of ACLR.

After autograft ACLR with accelerated, brace-free rehabilitation: (1) both PT and HS autografts provide satisfactory short and long-term results in terms of range of motion, subjective stability and functional scores ('strong' level of evidence); (2) PT autograft is associated with more pain on kneeling ('strong' level of evidence) and increased risk of early signs of osteoarthritis ('limited' level of evidence); (3) HS autograft is correlated with femoral and tibial tunnel widening compared with PT autograft ('limited' level of evidence). Tunnel widening does not correlate with clinical outcome ('limited' level of evidence); (4) There is 'conflicting' evidence between PT and HS autografts for objective knee stability, return to sports and muscle strength; (5) focus on quality of movement is important for ACLR protocols and return to sports criteria for both graft types ('limited' level of evidence).

Identification of possible factors that influence graft-specific ACLR with accelerated, brace-free rehabilitation?

Gender

Four studies analysed differences for gender on graft-specific clinical outcome after ACLR with accelerated, brace-free rehabilitation (table 5).[1,3,28–29] There is 'conflicting' evidence for instrumented knee laxity measurements in female patients between PT and HS autografts. There is no difference between males and females in functional performance and return to sports irrespective of the chosen graft type ('moderate' level of evidence).

Differences in rehabilitation protocols

Three studies analysed differences in accelerated, brace-free rehabilitation after ACLR with PT and HS autografts.[16–17,21] Early

Table 3 Details accelerated rehabilitation

Study	Preop rehab	Brace	Full weight bearing allowed	FROM allowed	CKC exercises	OKC exercises	Concentric exercises	Eccentric exercises	Running	Return to light sports	Unrestricted RTS	Criteria RTS
Beard *et al*[13]	?	No	Immediate (Program Shelbourne)	Immediate	Program Shelbourne	Program Shelbourne	Program Shelbourne	Program Shelbourne	?	?	?	?
Clatworthy *et al*[22]	?	No	'Accelerated rehabilitation protocol	?	?	?	?	?	?	?	?	?
Corry *et al*[23]	Yes	No	Immediate	Immediate	Immediate?	?	?	?	6 weeks	6 weeks	9 months	?
Ejerhed *et al*[14]	?	No	Immediate	Immediate	Immediate	6 weeks	?	?	3 months	?	6 months	Full functional stability
Engelen *et al*[30]	?	No	Immediate	Immediate	?	?	?	?	?	?	?	?
Feller and Webster[15]	?	No	Immediate (Program Shelbourne)	Immediate	Program Shelbourne	6 months	Program Shelbourne	Program Shelbourne	10 weeks	6 months	9 months	?
Gerber *et al*[16 19]	?	No	PT immediate, HS 2-3 weeks?	Immediate	Immediate	5 weeks vs 7 weeks?	3 weeks	3 vs 15 weeks	?	?	?	90% strength and performance ability compared with uninvolved leg
Heijne and Werner [17 18]	?	No	Immediate	Immediate	Immediate	4 vs 12 weeks	?	?	4–6 months	?	6 months	Functional capacity
Laoruengthana *et al*[18]	?	No	Immediate (Program Howell)	Immediate	4 weeks	4 weeks	?	?	?	?	9 months	No effusion, FROM
Mohammadi *et al* [20]	?	No	'Accelerated rehabilitation protocol'	?	?	?	?	?	?	?	6–9 months	Ability to do sports-related movements safely
Pinczewski *et al*[24 28]	?	No	Immediate	Immediate	6 weeks?	?	?	?	6 weeks	?	6 months	Knee stability
Rudroff[25]	?	No	Immediate (Program Shelbourne)	Immediate	Program Shelbourne	Program Shelbourne	Program Shelbourne	Program Shelbourne	?	?	3 months?	
Smith *et al*[29]	Yes	No	Immediate (Program Shelbourne)	Immediate	Program Shelbourne	Program Shelbourne	Program Shelbourne	Program Shelbourne	?	?	?	?
Svensson *et al*[26]	?	No	Immediate	Immediate	Immediate	6 weeks	?	?	3 months	?	6 months	Full functional stability
Witvrouw *et al*[27]	?	No	Immediate	Immediate	Immediate	?	?	?	6 weeks	?	9 months	?

CKC, closed kinetic chain; FROM, full range of motion; OKC, open kinetic chain; RTS, return to sports.

Table 4 Details outcome studies comparing graft type after ACLR and accelerated, brace-free rehabilitation

Study	HS	PT	N (PT-HS)	Follow-up	Assessment methods	Results
Beard *et al*[13]	Four-strand ST-G	Central-third	45 total	1 year	Lysholm, Tegner, IKDC, KT-1000, isokinetic muscle strength	No differences
Clatworthy *et al*[22]	Four-strand ST-G	Central- third	38–35	1 year	IKDC, KT-1000, isokinetic muscle strength, X-rays, MRI	HS: mean increase femoral tunnel area was 100.4% compared with decrease of 25% in PT group HS: mean increase tibial tunnel was 73.9% versus decrease of 2.1% in PT group No differences clinical findings, knee scores, KT-1000 testing or isokinetic muscle strength
Corry *et al*[23]	Four-strand ST-G	Central- third	82–85	2 years	Lysholm, IKDC, KT-1000, thigh atrophy, kneeling pain	No differences: ligament stability, ROM, general symptoms, thigh atrophy at 2 years PT: more thigh atrophy at 1 year PT: more kneeling pain
Ejerhed *et al*[14]	Triple or quadruple ST	Central- third	32–34	2 years	Lysholm, Tegner, IKDC, KT-1000, single-leg hop test, knee walking test	No differences: Lysholm, Tegner, KT-1000, hop test PT: worse knee walking test
Engelen *et al*[30]	Four-strand ST-G	Central- third	47–50	2–9 years	Questionnaires, isokinetic peak torque and endurance tests, a hop test battery and drop jump including video analysis	No differences: gender, quantity of movement PT and HS: higher occurrence dynamic knee valgus compared with controls
Feller and Webster[15]	Four-strand ST-G	Central- third	31–34	3 years	Kneeling pain, Cincinnati knee score, IKDC, KT-1000, return to pre-injury level, isokinetic muscle strength	No differences: Cincinnati knee score, IKDC, rate return pre-injury activity PT: more kneeling pain PT: greater extension deficits HS: increased knee laxity
Heijne and Werner[18]	Four-strand ST-G	Central-third	34–34	2 years	KT-1000, pivot-shift, thigh muscle torque, one-leg hop test, postural sway, anterior knee pain, Tegner	No differences: one-leg hop test, postural sway, ROM PT: more anterior knee pain PT: earlier return to sports and higher level HS: increased knee laxity and pivot shift HS: less quadriceps-hamstring strength ratio
Laoruengthana *et al*[19]	Six-strand ST	Central-third	15–13	19 months	KT-2000, IKDC, Lysholm	PT: more anterior knee pain PT: increased knee laxity HS: higher return to sports
Mohammadi *et al*[20]	Four-strand ST-G	Central-third	21–21	8 months	Isokinetic strength, single, triple and crossover hop tests, jump landing	HS: better quadriceps strength, triple hop test, crossover hop, jump landing
Pinczewski *et al*[24]	Four-strand ST-G	Central-third	89–75	5 years	IKDC, Lysholm, KT-1000, thigh atrophy, kneeling pain, weight-bearing radiographs	No differences: knee stability, complications PT: more osteoarthritis
Pinczewski *et al*[28]	Four-strand ST-G	Central-third	53–58	10 years	IKDC, Lysholm, KT-1000, thigh atrophy, kneeling pain, weight-bearing radiographs	No differences: graft rupture, clinical outcome PT: more harvest site symptoms and osteoarthritis
Rudroff[25]	Four-strand ST-G	Central-third	15–15	2 years	Thigh circumference, maximal isometric strength, two- and one-leg hop tests, squat and gait analysis (EMG data)	PT: decreased functional performance, decreased less flexion knee during jumps, lower activation of quadriceps and hamstring muscles, increased gait asymmetry
Witvrouw *et al*[27]	Four-strand ST-G	Central-third	17–32	1 year	Thigh atrophy, ROM, swelling, KT-1000, isokinetic muscle strength, Lysholm, Tegner, Kujala score	No differences: quadriceps strength, functional scores, ROM, swelling HS: increased knee laxity HS: decreased isokinetic peak strength

EMG, electromyographic; G, gracilis tendon; HS, hamstring autograft; PT, patellar tendon autograft; ROM, range of motion; ST, semitendinosus tendon.

progressive eccentric exercises 3 weeks postsurgery can safely be added irrespective of graft ('limited' level of evidence). Early start of open kinetic quadriceps exercises (4 weeks postsurgery vs 12 weeks postsurgery) causes increased knee laxity with HS autografts ('limited' level of evidence).

DISCUSSION

In order to better understand the current perspective on accelerated rehabilitation, one needs to review the history of ACL rehabilitation. During the 1980s, former basic animal research suggested that intra-articular PT autograft undergoes remodelling, including a phase in which the graft was partially necrotic and therefore needed protection.[3 5 8 31 32] This protection against excessive stress on the reconstructed graft required wearing a knee brace, limited weight bearing, restricted range of motion and avoidance of early full terminal extension.[3 8] Despite good ligamentous stability, common rehabilitation problems occurred including knee stiffness, lack of full extension, anterior knee pain, muscle weakness and knee crepitus.[3 8 33] Shelbourne *et al*[34] noticed that non-compliant patients, achieving full range of motion, normal gait and resuming normal activities of daily living (ADL) earlier than prescribed, achieved faster return of strength and a quicker return to activities without graft failure. They adapted their rehabilitation programme to obtain full range of motion preoperatively with immediate weight bearing, full leg extension and knee flexion past 90° after

Table 5 Details clinical outcome studies on gender after graft-specific ACLR and accelerated, brace-free rehabilitation

Study	HS ratio men:women	PT ratio men:women	Follow-up	Assessment methods	Results
Corry *et al*[23]	52%–48%	53%–47%	2 years	Lysholm, IKDC, KT-1000, thigh atrophy, kneeling pain	*Women:* HS increased laxity compared to women PT *Women:* HS increased laxity compared with men HS and men PT *Women:* more pivot shift grade 1 than grade 0, irrespective of the graft source *Men:* no difference side-to-side difference HS and PT
Engelen *et al*[30]	54%–46%	51%–49%	2–9 years	Questionnaires, isokinetic peak torque and endurance tests, a hop test battery and drop jump including video analysis	No differences for gender
Smith *et al*[29]	48%–52%	48%–52%	1 year	Cincinnati knee score	No differences between men and women in terms of return to competition at 12 months, whether the overall return or return to the pre-injury levels were assessed
Svensson *et al*[26]	Only women	Only women	2 years	Lysholm, KT-1000, one leg hop test, knee walking test	*Women:* no differences PT-HS for functional parameters and knee stability *Women PT:* more anterior knee pain compared with preoperatively

HS, hamstring autograft; PT, patellar tendon autograft.

ACLR.[33] These evolutionary changes became the basis of current accelerated, brace-free rehabilitation models with a progressive scheme that allows patients to advance as they achieve quantifiable goals.[3 33–39] The programme starts at the time of injury and includes aggressive swelling reduction, hyperextension exercises, gait training and mental preparation preoperatively. [33] Prehabilitation leads to improved knee function and should aim for quadriceps muscle strength deficit of the injured limb to be <20% of the uninjured limb at time of surgery.[3]

Regardless of the graft source, rehabilitation after ACLR must first strive to achieve full symmetrical knee range of motion before aggressive strengthening is started.[33 40] After quadriceps-strengthening goals are reached, patients can shift to sport-specific exercises.[33] Beynnon *et al* demonstrated that there were no significant differences in subjective and clinical outcome after accelerated versus non-accelerated rehabilitation.[6] In contrast to the studies in the present review, their protocol included a knee brace postsurgery for both programmes. The authors however noted that it still needs to be defined how quickly the frequency and magnitude of quadriceps activity can be increased without the risk of increased anterior knee laxity.[6] This review has demonstrated conflicting evidence for quadriceps muscle torque and knee joint laxity if open kinetic chain exercises started 4–6 weeks after PT autograft ACLR.[6] It also showed a 'moderate' level of evidence that knee joint laxity increases with start of early (4 weeks) open kinetic chain exercises after HS autograft ACLR.[16–17 41] Timing and safety of strengthening in accelerated compared with standard rehabilitation has been studied in a systematic review on rehabilitation after ACLR by Kruse *et al*.[38] Based on the available literature on both PT and HS autografts, they concluded that brace-free, accelerated rehabilitation has not shown any deleterious effects. It was likely to be safe for patients to begin immediate postoperative weight-bearing knee range of motion 0°−90° of flexion and perform closed chain strengthening exercises. Eccentric quadriceps muscle strengthening and isokinetic hamstring muscle strengthening were safely incorporated 3 weeks after surgery.[38] Although Kruse *et al*[38] included the studies by Gerber *et al*[16 21] also presented in the current review, they did not include the important RCT study by Heijne *et al*[17] that contradicts some of the findings by Kruse *et al*.[38] Heijne *et al* found that early start of open kinetic quadriceps strengthening (4 weeks) after HS autograft ACLR resulted in significantly increased anterior knee laxity in comparison with both late start (12 weeks postsurgery) and with early and late start after PT autograft.[17] Furthermore, early introduction of open kinetic exercises for quadriceps strength did not influence quadriceps muscle torques in either group. The authors found that the choice of the graft affected the strength of the specific muscle more than the type of exercises performed and they could not determine the appropriate time for starting open kinetic quadriceps chain exercises for patients after hamstring ACLR. This influence of graft choice on isokinetic muscle strength after ACLR is in agreement with the systematic review by Xergia *et al*.[42] They demonstrated that patients with PT autograft showed a greater deficit in extensor muscle strength and lower deficit in flexor muscle strength compared with the patients with HS autograft.[42] The deficits were associated with the location of the donor site and still unresolved at 2-year follow-up.[42] Irrespective of the chosen autograft type for ACL, there is growing support for the principles of early weight bearing and the incorporation of closed and open kinetic quadriceps chain exercises at the appropriate time frames.[40] However, the safe time frame for start of eccentric and open kinetic chain exercises after HS autograft ACLR warrants further research.[2]

Leading ACL experts generally let their patients return to play after an average of 6 months, with return to full competition after an average of 8 months.[43] However, a recent study showed that most patients, in terms of neuromuscular abilities and compared with healthy controls, were most likely not ready for a safe return to sports, even 8 months postoperatively.[44] The most limiting factor was a poor Limb Symmetry Index (LSI) value of <90% if the dominant leg was involved and <80% if the non-dominant leg was involved.[44] Gokeler *et al* found that the majority of patients at 6 months after ACLR require additional rehabilitation to pass return to sports criteria.[45] Nagelli *et al*[46] presented evidence that athletes achieve baseline joint health and function approximately 2 years after ACLR. The authors postulated that delay in returning to sports for nearly 2 years will significantly reduce the incidence of second ACL injuries.[46] Further studies identifying sport-specific differences in ACLR outcomes in athletes could further enhance accelerated rehabilitation protocols for athletes after ACLR.[45 47]

The choice of graft type also influenced radiological results after ACLR. This review has presented a 'limited' level of evidence that HS autograft is correlated with tunnel widening compared with PT autograft after ACLR with accelerated, brace-free rehabilitation.[22] Other authors have also shown the relationship between aggressive rehabilitation and tunnel widening.[48–50] The aetiology of tunnel widening seems multifactorial.[22 48 50] Limitation of weight bearing and the use of platelet-rich plasma at time of reconstruction did not prevent tunnel widening.[50 51] Although tunnel widening may pose problems for ACL revision surgery, there is no significant correlation between tunnel widening and clinical outcome including laxity and International Knee Documentation Committee (IKDC) score.[2 22 48–51] This is in agreement with the conclusions of the present review.

Graft choice has also been correlated to knee osteoarthritis in the long term after ACLR. This review has shown 'limited' level of evidence that PT autograft is associated with increased risk of developing early signs of osteoarthritis.[24 28] Two reviews have focused on osteoarthritis after ACLR and found similar findings to the present review.[52 53] However, considering the multifactorial aetiology of osteoarthritis, this result should be cautiously interpreted. More high-quality RCT studies with strictly specified inclusion criteria are needed.[53]

Controversy exists in the correlation between risk of knee osteoarthritis and female gender. Some authors described an increased risk of developing osteoarthritis in females.[53 54] More recent studies suggested equal risk of osteoarthritis in both men and women[54–56] as well as an increased risk in males following ACL injury.[57] However, women demonstrated more knee laxity compared with men with greater biomechanical asymmetries.[58 59] Female sex predisposes to ACL injury, but it remains unclear whether female sex predisposes to poor outcome after ACLR.[60] The present review has shown that there is conflicting evidence for instrumented measurements in female patients between PT and HS autograft ACLR with accelerated, brace-free rehabilitation.[23 26] Paterno *et al*[61] published a systematic review on gender comparison of knee laxity after ACLR with PT and HS autografts. Female patients had greater antero-posterior knee laxity after HS autograft ACLR compared with males with a similar procedure, and with both females and males following a PT autograft ACLR. There was no correlation between knee laxity and patient-reported outcome or functional disability.[61] In a meta-analysis on differences in outcome after ACLR, Ryan *et al* concluded that there were no differences in graft failure risk for both type of autografts, contralateral ACL rupture or knee laxity on physical examination between men and women.[60] The present review showed 'moderate' level of evidence that there is no difference between males and females in functional performance and return to sports irrespective of the chosen graft type.[26 29–30] To date, no study has been published confirming significantly higher failure rates related to gender after HS autograft ACLR.[62]

This review has a 'strong' level of evidence that both PT and HS autografts provide satisfactory short and long-term results in terms of range of motion, subjective stability and functional scores after ACLR with accelerated, brace-free rehabilitation. PT autograft is associated with more pain on kneeling. There was conflicting evidence between PT and HS autografts for knee stability, return to sports and muscle strength.[13–15 18–20 23–25 27 28] In the last 5 years, several systematic reviews and a Cochrane review have examined the influence of graft choice on clinical outcome after ACLR.[53 63-68] Li *et al*[63] concluded that ACLR with PT or HS autografts achieved similar postoperative effects in terms of restoring knee joint function, graft failure and incidence of re-operations related to the meniscus. HS autografts were inferior to PT grafts for restoring knee stability, but were associated with fewer postoperative complications.[63] Romanini *et al*[67] reviewed 30 studies and demonstrated that PT grafts appeared superior to HS grafts in terms of stability, return to pre-injury level activity and flexion strength. HS autograft was associated with less anterior knee pain and less risk of extension loss compared with PT autograft.[67] Xie *et al*[66] showed that PT autograft might be superior in resuming rotation stability of the knee joint and allow patients to return to higher levels of activity in comparison to HS autograft after ACLR. However, postoperative complications (including anterior knee pain, pain on kneeling and loss of extension) were lower in the HS patients. The authors claim that there was insufficient evidence to identify which of the two autografts was significantly better for ACLR. Furthermore, they hypothesised that the HS autograft was less able to recreate the ACL footprint compared with the PT autograft.[66] The smaller size of HS grafts in their study could have been related to the Chinese population. A previous study has demonstrated that HS size was smaller in Chinese compared with Caucasian patients and could be predicted by body height, weight and gender.[69] Another meta-analysis of prospective trials did not detect any significant differences in clinical results, as evidenced by the objective IKDC score, return to pre-injury activity level, KT-1000, Lachman test, pivot shift test, extension loss, flexion loss and graft failure.[53] However, PT autografts resulted in increased anterior knee pain and kneeling pain compared with HS autografts.[53] Reinhardt *et al*[64] examined graft selection for ACLR in 28 studies comparing failure rates and functional outcome. When only high-quality RCTs were evaluated, the risk of graft failure was significantly higher with HS reconstruction compared with PT autograft.[64] In a recent systematic review of level I/II RCTs on anatomic ACLR via independent tunnel drilling, Ciccotti *et al*[68] compared PT versus HS autografts. In some studies, PT reconstructed knees experienced a greater incidence of anterior knee pain and radiographic evidence of degenerative change, and in others, HS autograft reconstructed knees had increased laxity and less flexion strength.[68] However, clinical outcome and failure rates showed no differences for anatomic reconstruction using either autograft. Evaluating return to competitive sport following ACLR, Ardern *et al*[70] concluded that receiving a HS autograft favoured returning to competitive sport, whereas receiving a PT autograft favoured returning to the pre-injury level sport. The authors found conflicting evidence regarding the risk of ACL graft rupture according to graft type.[70] The difference in return to sports rate between graft types should be interpreted with caution as the majority of studies were non-randomised and there was a possible selection bias for HS autografts.[70] One Cochrane review examined 19 trials for outcome data of 1597 patients.[65] The pooled data showed no statistically significant differences between PT and HS autograft choices for functional assessment, return to activity, Tegner and Lysholm scores, subjective outcome measures, graft re-rupture or IKDC scores. All tests for static stability (manual and instrumented) showed that PT ACLR resulted in better stability than HS autograft patients. PT resulted in statistically significant loss of extension and a trend towards loss of knee extension strength. HS reconstructions demonstrated a trend towards loss of flexion and a statistically significant loss of knee flexion strength. The clinical importance of the range of motion loss was unclear. There were inadequate long-term results to assess the development of osteoarthritis.[65] These results adhere with the findings of the present review.

In summary, there is insufficient evidence to date to draw conclusions on differences between PT and HS autograft ACLR with accelerated, brace-free rehabilitation for long-term outcome. While PT reconstructions were more likely to result in less knee laxity, they were also associated with more anterior knee problems and osteoarthritis.[65]

Knowledge about the duration of the remodelling process of ACL grafts may further improve rehabilitation protocols.[5] The biological findings have shown that human autograft remodelling takes at least 1 year after ACLR.[5] The current biological evidence on graft healing after HS autograft ACLR with accelerated, brace-free rehabilitation did not support return to sports at 4–6 months.[4 5] Human biopsy studies of PT autografts after ACLR found that the graft was viable at 3 weeks after reconstruction and necrosis never involved more than 30% of the graft's biopsies.[4 5 71] Falconiero *et al* found that PT graft remodelling was complete at 12 months, whereas Zaffagnini *et al* concluded that the PT autograft underwent a transformation period up to 2 years without reaching the mean diameter and bimodality of the native ACL.[4 72] While there is evidence that intra-articular remodelling of PT and HS autograft continues for up to 2 years after ACLR, recent data indicated that there is no significant improvement in function between 1 and 2 years.[73] Recovery of activity level, function and subjective satisfaction all appear to plateau within the first 6 months of surgery.[73] Evidence of such a plateau offers opportunities for further research to define the optimal balance of graft loading and graft healing in the various rehabilitation phases after ACLR as well as the development of valid, criterion-based assessments to determine readiness for sport-specific training and eventual safe return to sports.[3]

This systematic review has several limitations. In the search for the available knowledge on clinical outcome after accelerated, brace-free rehabilitation after ACLR, studies of various level of evidence were included. It must be noticed that the type of rehabilitation was not a primary intervention in all of the included studies. Some conclusions of the 'best-evidence synthesis' may therefore not be primarily related to accelerated rehabilitation. Another weakness of this review is the inclusion of studies with small population size and the lack of reported details for the rehabilitation protocols. This may limit the level of evidence in the chosen 'best-evidence synthesis' by van Tulder *et al*.[12] Although strict and adapted for various study types, the risk of bias assessment of the Cochrane Library and the classifications of 'low', 'questionable' and 'high' risk of bias for the studies may limit the strength of evidence. One might argue that a 'low' risk of bias RCT study is of higher level of evidence than a 'low' risk of bias prospective cohort study.

Another weakness of this study is that only articles in English were included. Additional relevant articles published in languages other than English could contribute to the level of evidence presented in this review.

In conclusion, PT and HS autografts may both be selected for ACLR with accelerated, brace-free rehabilitation. Specific considerations for each type of graft must be made during rehabilitation. PT reconstructions are more likely to result in more statically stable knees, but are also associated with more complications and osteoarthritis. There is insufficient evidence to draw conclusions on differences between PT and HS autograft for long-term outcome.

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