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SYSTEMATIC REVIEW

What is the Evidence for and Validity of Return-to-Sport Testing after Anterior Cruciate Ligament Reconstruction Surgery? A Systematic Review and Meta-Analysis

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Abstract

Background Anterior cruciate ligament (ACL) return-to-sport (RTS) test batteries are popular and are employed to test athletes' sport performance and help ensure a safe return to sport.

Objective To perform a systematic review and meta-analysis to determine: (1) the proportion of patients who passed RTS test batteries after ACL reconstruction, (2) whether passing RTS test batteries increased rates of return to play, and (3) whether passing RTS test batteries reduced subsequent rates of knee and ACL injury.

Methods Five databases (PubMed, MEDLINE, Embase, CINAHL, and SPORTDiscus) were searched to identify relevant studies and data were extracted regarding the number of patients who passed the RTS test battery, as well as subsequent RTS rates and re-injury data when available. Results were combined using proportional and risk-ratio meta-analyses.

Results Eighteen studies met eligibility criteria. Proportional meta-analysis showed that only 23% of patients passed RTS test batteries. One study showed that passing an RTS test battery led to greater RTS rates. Two studies showed passing RTS test batteries did not significantly reduce the risk of a further knee injury (risk ratio (RR) = 0.28 (95% CI 0.04–0.94), $p = 0.09$) and five studies showed that passing RTS test batteries did not reduce the risk for all subsequent ACL injuries (RR = 0.80 (95% CI 0.27–2.3), $p = 0.7$). However, passing an RTS test battery did significantly reduce the risk for subsequent graft rupture (RR = 0.40 (95% CI 0.23–0.69), $p < 0.001$], although it increased the risk for a subsequent contralateral ACL injury (RR = 3.35 (95% CI 1.52–7.37), $p = 0.003$].

Conclusion These analyses shows that there are equivocal findings in terms of the validity of current RTS test batteries in relation to reduction of the risk of graft rupture and contralateral ACL injuries. These findings have implications for RTS advice given to patients based on the results of RTS test batteries, and further work is needed to validate the criteria currently used and determine the true value.

Key Points

Current return-to-sport criteria do not appear to decrease the risk of subsequent anterior cruciate ligament (ACL) injury in athletes.

Though passing return-to-sport criteria reduced the risk of subsequent graft rupture by 60%, it increased the risk of a contralateral ACL rupture by 235%.

1 Introduction

Most athletes who undergo anterior cruciate ligament (ACL) reconstruction surgery plan to return to their pre-injury level of sport [1]. However, only approximately one-half at 1 year

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and two-thirds at 2 years achieve this goal and those who return have a high risk for further ACL injury [2, 3]. The rates of second ACL injury are highest in younger athletes [4–8], in whom rates of up to 35% have been reported [9].

There has consequently been marked interest and a rapid growth in studies that propose return-to-sport (RTS) criteria to reduce the risk of a second ACL injury. Typically, these are a set of criteria or "test battery" that is used to clear the athlete for return to sport at the final stage of rehabilitation [10]. Whilst the specific content of reported RTS test batteries has varied, overall, they are designed to incorporate a number of domains of risk factors. A systematic review and multidisciplinary consensus indicated that an RTS test battery should at least include a series of strength tests, hop tests and measures of quality of movement [11]. Thus, studies have attempted to cover a broad range of risk factors that has resulted in the inclusion of up to 15–20 different RTS tests [12, 13], which few patients pass [14, 15] and the validity of many of the included tests is unknown [16].

The true value of any RTS test battery is its ability to assess whether patients have returned to their prior level of sport at a high-performance level whilst also reducing the risk for a second ACL injury. There is no current systematic review or meta-analysis that has determined what proportion of patients pass RTS test batteries or whether passing an RTS test battery indeed reduces the risk for subsequent knee or second ACL injury. Thus, this review sought to answer three questions: (1) What proportion of patients pass RTS test batteries after ACL reconstruction? (2) Is passing RTS test batteries associated with increased rates of return to play? and 3) Is passing RTS test batteries associated with reduced rates of subsequent knee injury (all knee injuries and ACL injury)?

2 Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [17] were used in preparing, conducting and reporting this systematic review.

2.1 Search Strategy

The electronic databases PubMed, MEDLINE, Embase, CINAHL, and SPORTDiscus were searched from the earliest possible dates through to 7 May 2018. Search terms were entered under two concepts; terms within each concept were combined with the OR Boolean operator, and the two concepts were combined with the AND Boolean operator. Where possible, terms were mapped to medical subject headings (MeSH) and searched using keywords; wildcards were also used. Examples of terms included in Concept 1 included 'anterior cruciate ligament reconstruction', and 'ACL reconstruction'. Examples of terms included in Concept 2 included 'return to sport', 'return to sport criteria', 'return to play', 'return to play criteria', 'functional testing' and 'return to athletic*'.

To supplement the electronic database search, the online contents pages and 'articles in press' lists of leading sports medicine journals were hand searched, and studies on the reference lists of the included studies were screened. Publication details from all identified studies in the literature search were exported to bibliographic software and duplicates removed.

2.2 Selection Criteria

Studies were included if they were: (1) published in the English language, (2) included participants who had undergone ACL reconstruction (primary or revision) surgery, (3) utilized a return-to-sport (RTS) test battery, and (4) reported the number of participants who passed the test battery or were cleared for return based on test battery results. There was no minimum number of tests that was required to be included in a test battery and the test could be from any domain; however, multiple domains needed to be represented. For example, studies that only measured strength (even if there were multiple strength tests used) or only measured function (i.e. only used hop tests) were excluded. Studies that only included the number of participants who passed single components of a test battery and not the full test battery were also excluded if the authors could not provide data for the full test battery. Similarly, studies that only included a cohort of patients who were selected because they had either failed or passed criteria were excluded. For studies that reported cut-off values for passing the RTS test battery they used there were no restrictions placed on what the actual cut-off value had to be. Conference proceedings, case studies, clinical commentaries and review studies were excluded.

The titles and abstracts were first screened for eligibility and those that did not meet the inclusion criteria, or had at least one exclusion criterion, were excluded. The full text versions of the remaining studies were retrieved, and the selection criteria were applied by two reviewers with any discrepancies discussed until consensus was reached.

2.3 Quality Assessment (Risk of Bias)

Included studies were assessed for methodological quality based on both the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies and the Quality Assessment Tool for Case-Series Studies from the National

Institutes of Health [18]. This was appropriate as the primary aims were to determine the proportion of patients passing RTS test batteries and whether passing an RTS test battery was related to return to sport or further knee injury. Therefore, there was no intervention or exposure. Items 1–5 from the Observational Cohort and Cross-Sectional Studies tool were combined with Items 5–9 from the Case-Series checklist to produce a 10-item list (Electronic Supplementary Material Table S1). The purpose of the assessment was to identify characteristics of study quality and design for all included studies and to provide a qualitative description of the study characteristics. Item 6 (Was the intervention described?) was assessed in reference to the RTS test battery. For studies that only reported percentage of participants who passed RTS criteria items 7 (Were outcome measures clearly defined?) and 8 (Was length of follow-up adequate?) were not applicable. Studies were assessed independently by two reviewers.

2.4 Data Extraction and Synthesis

Data from each of the studies were extracted using a standard form. For all studies, the number of patients who passed the RTS test battery was recorded. Pass rates were calculated from the number of patients who passed, out of the total number of patients, and were expressed as a percentage. Pooled pass rates were calculated using random-effects proportion meta-analyses (StatsDirect medical statistics software, Version 2.8, Cambridge, UK). This analysis was performed according to: (1) the proportion of patients who passed RTS criteria *before* return to sport and (2) the proportion of patients who passed RTS criteria *after* return to strenuous sports. Studies in which patients could not be classified as having returned to sport or not when the RTS testing was conducted were not included in the meta-analyses. Several studies with potential patient overlap were identified (i.e. same institution, same RTS test battery). For these studies, contact was made with the authors, and for studies in which 50% or more patient group overlap was identified, only the study with the largest number of patients was used for the meta-analysis.

Where available, the number of patients who passed RTS criteria and subsequently returned to sport was recorded along with the number of patients who had failed criteria but later returned to sport. Similarly, the number of patients who passed RTS criteria and sustained a subsequent knee and/or ACL injury was recorded along with the number of patients who failed RTS criteria and sustained a subsequent knee and/or ACL injury. These data were analysed with risk-ratio (RR) meta-analyses (RevMan V5.3; Copenhagen: The Nordic Cochrane Center, The Cochrane Collaboration, 2014). Separate analyses were conducted for all subsequent knee injuries and for ACL injuries. An RR value of less than 1 indicated reduced risk of subsequent injury if the patient passed RTS criteria.

3 Results

The electronic database search identified 3771 studies; eight were identified from the manual search of reference lists and relevant journals. After 2002 duplicates were removed, 1777 articles remained as the total yield. From reviewing titles and abstracts, 1664 studies were excluded, and the full text of the remaining 113 were downloaded for detailed assessment. Of these 95 were excluded (refer to Fig. 1 and Electronic Supplementary Material Table S2), 18 studies were included for qualitative analysis and 17 studies were included in one or more of the meta-analyses. The search process is described in Fig. 1.

The characteristics of the included studies are detailed in Table 1. Several studies were identified from the same institution and contact was made with the authors of these studies to identify any patient overlap. Krych et al. [19] and Souza et al. [20] were identified as the same patient population and were therefore not included in the same meta-analysis. Four studies from the Delaware-Oslo group (Logerstedt et al. [21], Grindem et al. [22], Nawasreh et al. [23] and Wellsandt et al. [24]) were identified as having a minimum of 50% patient overlap and were also not included in the same meta-analysis. Finally, Gokeler et al. [14] and Welling et al. [25] also had more than 50% patient overlap and were not included in the same meta-analysis.

A variety of RTS test batteries was used (Table 1), with the most common elements being quadriceps strength and hop tests for function. A limb symmetry index of ≥ 90 was the most common pass cut-off used. Some studies varied the cut-off according to the type of test or the level of sport that the patient aimed to return to [14, 25, 26]. Of the 18 studies, only five studies [20, 22, 24, 27, 28] had further injury data, and only one [23] assessed whether passing RTS criteria was associated with subsequent return to play. Grindem et al. [22] were contacted and provided subsequent ACL injury data as these raw data were not included in the published manuscript (only raw data for overall knee injuries were provided in the published paper). The most common time for RTS assessment was 6 months post-surgery.

3.1 Quality Assessment

Ten of the 18 studies adequately described the study population in terms of patient selection, age, sex, sports played and graft type used for the reconstruction surgery [19–26, 28, 29]. Only three studies included any form of sample size or power calculation [20, 30, 31]. Three studies did not report the individual elements and cut-off used for the RTS test battery in a way that could be easily replicated [19, 27, 29]. Three of the five studies that had injury data had detailed adequate follow-up of a minimum 2 years post-surgery [20,

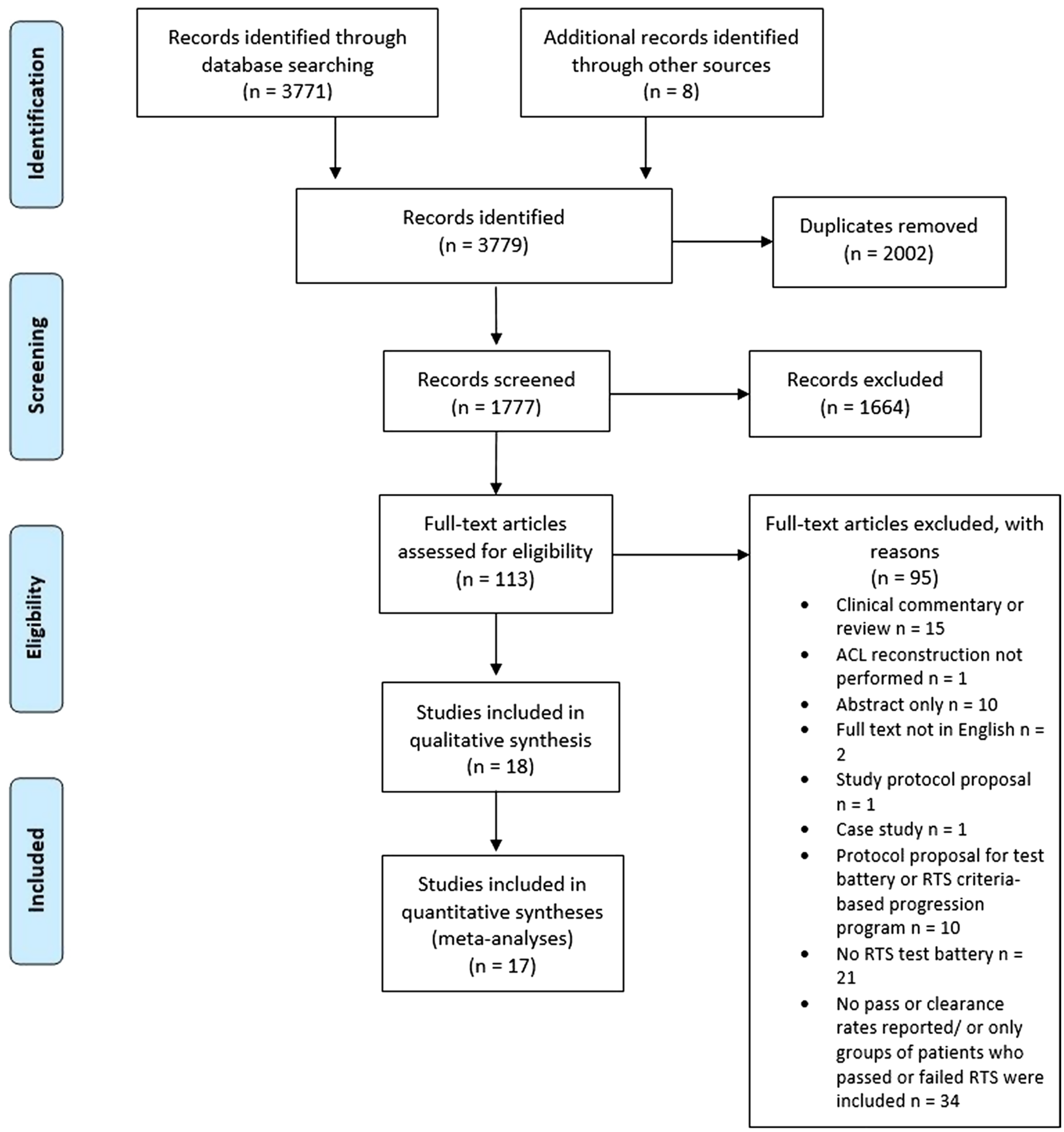

Fig. 1 PRISMA flow diagram for inclusion of studies. *RTS* return to sport, *ACL* anterior cruciate ligament

22, 24] (see Electronic Supplementary Material Table S1 for assessment ratings).

3.2 Proportion of Patients Who Pass Return-to-Sport (RTS) Test Batteries Before Return to Sport

From eight studies with 876 patients, a proportional meta-analysis showed that 23% (95% CI 8–43%, $I^2 = 97.5\%$) passed RTS test batteries before return to sport (Fig. 2). There was heterogeneity amongst studies with pass rates that ranged from 0 to 79%. All studies that were included in the meta-analysis tested patients between 5 and 10 months post-surgery. If a study also tested patients at a later time point (i.e. 12 months) only the earlier time point was used in the analysis. For Herbst et al. [15] the pass rates for return to non-competitive sport were used and for Thomee et al. [33] data for the > 90 LSI cut-off was used as this was most consistent with the other papers.

3.3 RTS Test Battery Pass Rates in Patients Who Have Returned to Strenuous Sports

From three studies with 234 patients, a proportional meta-analysis showed that 23% (95% CI 18–29%, $I^2 = 0\%$) passed

Table 1 Characteristics of included studies

Reference	Participants	Return-to-sport (RTS) test battery	RTS test time and pass rate	Injury data
Beischer et al. 2018 [30]	$N = 220$ (117F, 103M)	Strength (knee flexor and extensor) and 3 hop tests (vertical, distance and side hop)	RTS testing 8 and 12 months post-surgery	Not included
	Age between 15–30 years	LSI ≥ 90 to pass	Pass rate of 25% (25/100) reported for patients who had returned to strenuous sports at 8 months post-surgery	
	> 6 Tegner level			
Di Stasi et al. 2013 [31]	$N = 42$ (12F, 30M) Mean 29.3 years (14–50 years) cutting or pivot sports	Two self-report (KOS-ADLS; global rating scale), quadriceps strength, 4 hop tests (distance, timed, triple hop and triple crossover) LSI ≥90 to pass	6 months; 48% (20/42) pass rate	Not included
Ebert et al. 2018 [32]	$N = 111$	Strength (knee flexor and extensor) and 4 hop tests (distance, timed, triple hop and triple crossover) LSI ≥ 90 to pass	Mean 12.5 months (median 11 months)	Not included
	Mean 27.3 years (14–51 range)		Pass rate of 26% (15/57) reported for patients who had returned to strenuous sports	
	Level 1 sports; hamstring graft			
Falstrom et al. 2016 [26]	$N = 77$ Female	Star excursion, hop for distance, 5-jump test, side hop, DVJ, tuck jump	Median 18 months (6–36 months)	Not included
	Mean 20.1 years		Pass rate of 18% (14/77) for patients who had returned to strenuous sports	
	Soccer 96% hamstring grafts	Various cut-offs reported		
Gokeler et al. 2017 [14]	$N = 28$ (6F, 22M)	Jump landing (LESS), 3 hop tests (single, triple, side) and strength (knee flexor and extensor), IKDC subjective, ACL-RSI	Mean 6.5 months; 7% (2/28) pass rate	Not included
	Mean 25.4 years			
	Level I and II athletes			
	HS (68%), PT (29%) allograft (3%)	Various cut-offs used depending on measure		
Graziano et al. 2017 [27]	$N = 42$ skeletally immature (12F, 30M), mean age 12 years (10–15)	Stability, strength, hop for distance	From 5 months, unclear if all measured before RTS; pass rate of 90% (37/41)	Pass group: 14% knee injury and 11% second ACL injury. Fail group: 25% knee injury and 25% second ACL injury
	Various sports	Pass cut-off not reported	One patient had playground accident at 3 months and reinjured knee	
Grindem et al. 2016 [22]	$N = 100$ (54F, 46M)	Two self-report (KOS-ADLS; global rating scale), quadriceps strength, 4 hop tests (distance, timed, triple hop and triple crossover)	Between 3 and 23 months	6% of pass group knee injury and 38% fail group knee injury
	24.3 years	LSI ≥ 90 to pass	24% (18/74) pass rate for those who RTS	
	Level I or II sports			
	67% HS; 33% PT			
Herbst et al. 2015 [15]	$N = 69$ (27F, 42M)	Stability tests, counter movement jump, speedy jumps, plyometric jumps, quick feed test	Mean 5.6 months and 8 months	Not included
	21.2 years	Criteria based on normative data and LSI >90% for dominant leg and >80% for non-dominant	16% (11/69) pass rate for return non-competitive sport at 5.6 months and 17% (12/67) at 8 months	
	68% HS, 17% quadriceps, 15% PT, 18% revisions		1 patient passed for return to competitive sport at 8 months	

Table 1 (continued)

Reference	Participants	Return-to-sport (RTS) test battery	RTS test time and pass rate	Injury data
Krych et al. 2015 [19]	$N = 224$ (131F, 93M)	Strength and three functional tests (vertical jump, single hop, triple jump)	6 months	Not included
	Median 22 years (12–59)	LSI ≥ 85 for strength and ≥ 90 function. Overall pass if pass 6 of 7 tests	23% (52/224) pass rate	
	Median Tegner = 6 (2–10)			
	PT autograft (60%) PT allograft (28%) HS (12%)			
Kyritsis et al. 2016 [28]	$N = 158$ male professional athletes various sports	Quadriceps strength, 3 hop tests (single, triple, triple crossover), on field rehabilitation, running t-test	Unclear if all measured before RTS; pass rate of 73% (116/158)	10% of pass group ACL rupture
	21.5 years, HS (68%) PT (32%)	Quadriceps deficit <10%, LSI >90 (single, triple, crossover hop, running t test <11 s; completed on field sport specific rehabilitation		33% fail group ACL rupture
Logerstedt et al. 2014 [21]	$N = 158$	Two self-report (KOS-ADLS; global rating scale), quadriceps strength, 4 hop tests (distance, timed, triple hop and triple crossover)	6 and 12 months 29% (14/158) pass rate at 6 months	Not included
	Level I/II athletes	LSI ≥ 90 to pass	52% (74/141) pass rate at 12 months	
	HS (42%) PT (15%) soft tissue allograft (32%) unknown (10%)			
Luo et al. 2015 [29]	$N = 124$ (68F, 56M)	Strength and three functional tests (vertical jump, single hop, triple jump)	6 months	Not included
	18 and younger (mean 16)	LSI ≥ 85 for strength and ≥ 90 function. Overall pass if pass 6 of 7 tests	79% (98/124) pass rate	
	Mean Tegner 8.3			
	HS (68%) PT (32%)			
Nawasreh et al. 2018 [23]	$N = 95$ (32F, 63M) 15–55 years	Two self-report (KOS-ADLS; global rating scale), quadriceps strength, 4 hop tests (distance, timed, triple hop and triple crossover)	6 months; (48/95) pass rate 81% (30/37) who passed RTS tests at 6 months returned at 12 months	Not included
	Level I/II sports		44% (19/43) who failed RTS tests at 6 months returned at 12 months	
	38% autograft, 62% allograft	LSI ≥ 90 to pass	84% (27/32) who passed RTS tests at 6 months returned at 24 months	
			46% (13/28) who failed RTS tests at 6 months returned at 24 months	
Sousa et al. 2017 [20]	$N = 223$ (131F, 92M)	Strength and three functional tests (vertical jump, single hop, triple jump)	6 months	21% of pass group second ACL injury
	Median 22 years (12–59)	LSI ≥ 85 for strength and ≥ 90 function. Overall pass if pass 6 of 7 tests	23% (52/223) pass rate	9% fail group second ACL injury
	Median Tegner = 6 (2–10)			
	PT autograft (59%) PT allograft (28%) HS (13%)			

Table 1 (continued)

Reference	Participants	Return-to-sport (RTS) test battery	RTS test time and pass rate	Injury data
Thomee et al. 2012 [33]	$N = 82$ (26F, 56M)	3 muscle strength (knee flexor and extensor, and leg press) 3 hop tests (vertical jump, distance, side hop)	3, 6, 12 and 24 months	Not included
	Mean 28 years	Various LSI values (80, 85, 90, 95, 100) used and compared	0% pass (LSI ≥ 90) at 6 months	
	HS (56%) PT (44%)		10% pass (LSI ≥ 90) at 12 months	
	Mean Tegner = 8		24% pass (LSI ≥ 90) at 24 months	
Toole et al. 2017 [34]	$N = 115$ (88F, 27M)	IKDC subjective, strength (knee flexor and extensor) single leg hop (single, triple, cross-over and 6m timed); LSI ≥90 and IKDC ≥90 to pass	Mean 8 months (6–10)	Not included
	Mean 17.7 years		14% (16/115) pass rate	
	PT (43%) HS (50%) allograft (7%)			
Welling et al. 2018 [25]	$N = 62$ (17F, 45M)	Jump landing (LESS), 3 hop tests (single, triple, side) and strength (knee flexor and extensor), IKDC subjective form, ACL-RSI scale. Various cut-off used depending on measure and sex.	Mean 6.5 and 9.5 months	Not included
	24.2 years, mixed sports		3% (2/62) pass rate at 6.5 months and 11% (7/62) pass rate at 9.5 months	
	HS (58%) PT (40%) allograft (2%)			
Wellsandt et al. 2017 [24]	$N = 70$ (4–55)	Quadriceps strength, 4 hop tests (distance, timed, triple hop and triple crossover)	6 months	20% of pass group second ACL injury
	Cutting and pivot sports		57% (40/70) LSI	
	HS (40%) soft tissue allograft (60%)	LSI ≥ 90 to pass	29% (20/70) EPIC	10% fail group second ACL injury
		EPIC ≥ 90 to pass (using pre-surgery uninvolved limb as comparator)		

All autograft unless stated otherwise

LSI Limb Symmetry Index, *KOS-ADLS* knee outcome survey activities of daily living, *DVJ* drop vertical jump, *PT* patellar tendon graft, *HS* hamstring tendon graft, *LESS* landing error scoring system, *IKDC* International Knee Documentation Committee, *ACL-RSI* anterior cruciate ligament return to sport after injury, *EPIC* estimated preinjury capacity, *M* male, *F* female

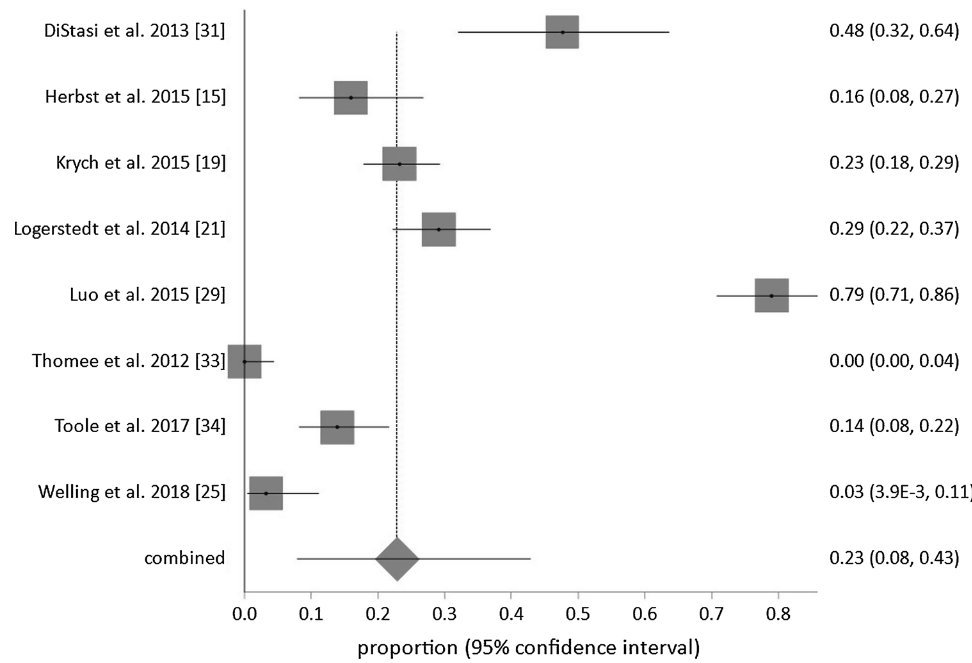

Fig. 2 Pooled rate of passing return to sport criteria before a return to sport

RTS test batteries despite having already returned to strenuous sports (Fig. 3).

3.4 Passing RTS Test Batteries and Rates of RTS

Only one study determined whether passing an RTS test battery was related to a subsequent return to sport. Nawasreh et al. [23] showed that patients who passed RTS criteria at 6 months were significantly more likely to have returned to play at both 12 and 24 months post-surgery. Specifically, in the group who had passed RTS testing, over 80% of that group had returned to sport at 12 months, whereas only 44% of the group who had not passed had returned at the same time. Sousa et al. [20] showed that there was no difference in the proportion of patients who met or exceeded their pre-injury Tegner score at a minimum 2-year follow-up, as 51% of the pass group and 52% of the fail group achieved this.

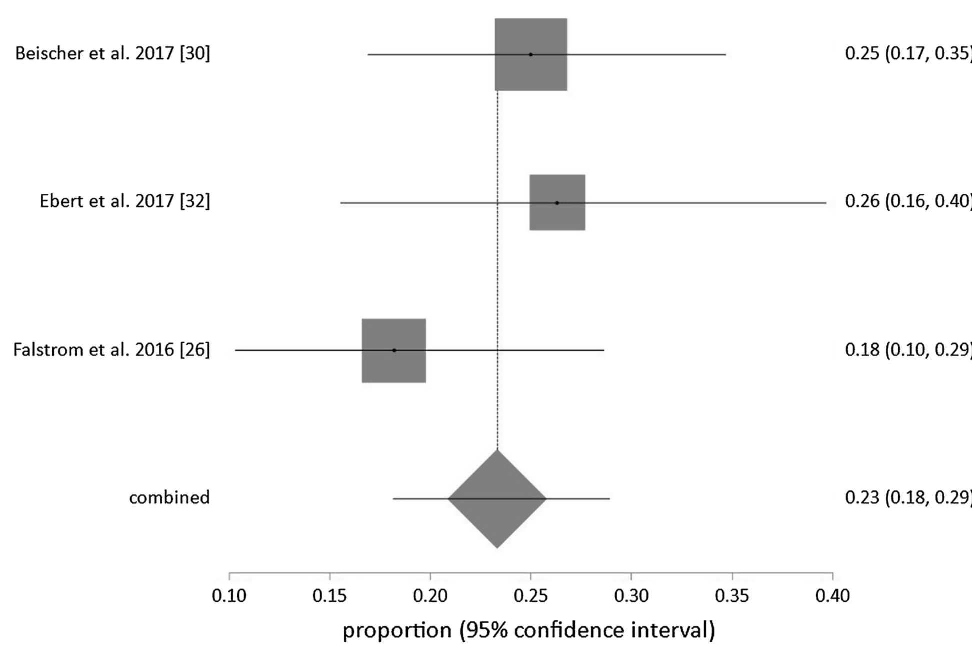

Fig. 3 Pooled rate of passing return to sport criteria in patients who had returned to strenuous sports

3.5 Passing RTS Test Batteries and Re-injury

Five studies that utilized test batteries reported subsequent re-injury rates; two of these reported any subsequent knee injury in 114 patients and five reported ACL injuries in 565 patients (four studies [20, 22, 24, 27] reported all second ACL injuries and one [28] reported only graft ruptures). For all knee injuries, there was no significant reduction in risk for those who passed RTS criteria (RR = 0.28 (95% CI 0.04–0.94), $p=0.09$; $I^2=13\%$; Fig. 4).

Passing an RTS test battery had minimal effect on reduction of the risk of all subsequent ACL injuries (RR = 0.80 (95% CI 0.27–2.3), $p=0.7$; $I^2=79\%$; Fig. 5). However, for graft ruptures, those who passed a test battery had a significantly reduced risk of a subsequent graft rupture (RR=0.40 (95% CI 0.23–0.69), $p<0.001$; $I^2=0\%$; Fig. 6), whereas for contralateral ACL injury, passing the test battery significantly increased the risk of a subsequent contralateral ACL injury (RR=3.35 (95% CI 1.52–7.37), $p=0.003$; $I^2=0\%$; Fig. 7). Note that one patient in Graziano et al. [27] sustained a graft rupture at 3 months from an accidental playground injury and was excluded from all meta-analyses as they did not complete RTS testing.

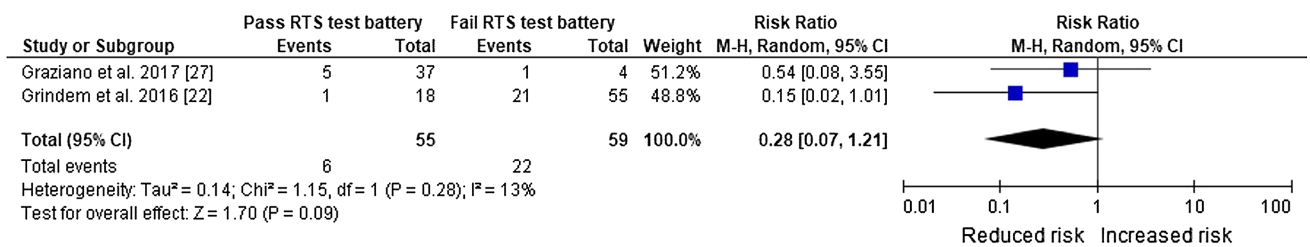

Fig. 4 Meta-analysis showing the risks for subsequent knee injury after passing an RTS test battery. The risk ratio and 95% CI data from individual studies in addition to the pooled data are shown. RR < 1 indicates a reduced risk of re-injury if the patient passes an RTS test battery. *RTS* return to sport, *M-H* Mantel-Haenszel, *RR* risk ratio

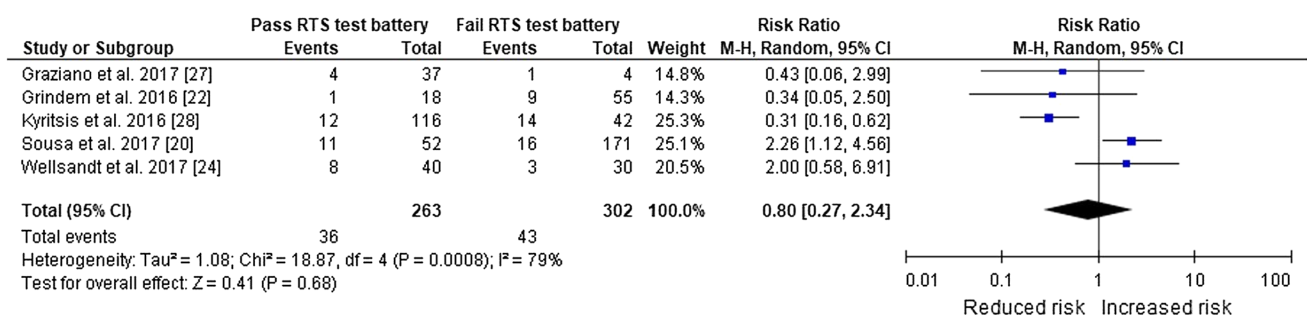

Fig. 5 Meta-analysis showing the risk for ACL injury after passing an RTS test battery. The risk ratio and 95% CI data from individual studies in addition to the pooled data are shown. RR < 1 indicates a reduced risk of injury if the patient passes an RTS test battery. *RTS* return to sport, *M-H* Mantel-Haenszel, *RR* risk ratio

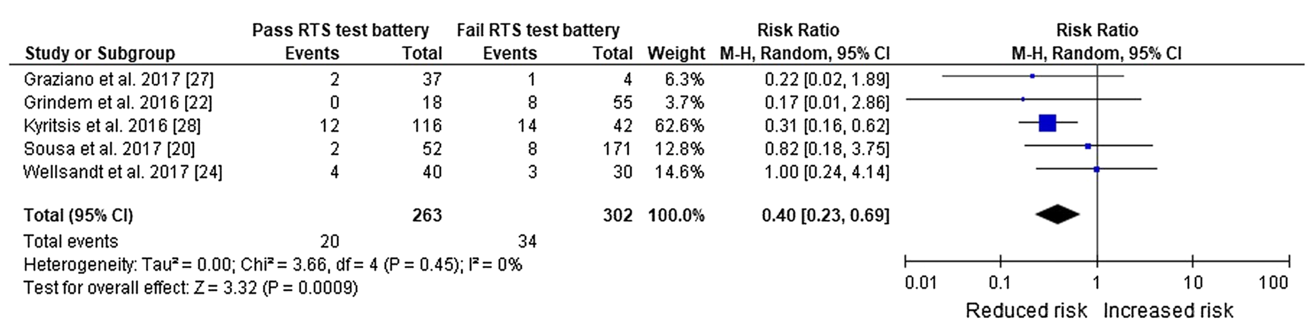

Fig. 6 Meta-analysis showing the risk for graft rupture after passing an RTS test battery. The risk ratio and 95% CI data from individual studies in addition to the pooled data are shown. RR < 1 indicates a reduced risk of graft rupture if the patient passes an RTS test battery. *RTS* return to sport; *M-H* Mantel-Haenszel, *RR* risk ratio

4 Discussion

This study summarizes the current evidence for the RTS test batteries that are frequently used to clear patients for a return to sport after ACL reconstruction surgery. Overall it was found that few patients passed test batteries and that there was limited evidence that passing an RTS test battery reduced the risk for any subsequent knee injury as well as all ACL injures. Interestingly, passing an RTS test battery was shown to significantly reduce the risk of subsequent graft rupture; however, passing RTS criteria also increased the risk of a contralateral ACL injury.

Whilst there was noted variation between studies, overall the proportion of patients who passed RTS test batteries was a low 23%. RTS testing was typically conducted between 5 and 10 months post-surgery, with the most common time being 6 months. Only one study had a pass rate above 50% [29]. For this study, in which the pass rate was 76%, the patient cohort were all 18 years and younger at surgery [29]. This is consistent with other recent research that has shown that younger patients have significantly higher pass rates for hop tests and other clinical outcomes than older patients [35]. However, the pass rate in another study that was included in the review, with a similar young athlete population, was only 14% [34]. One study in elite level athletes also had a high pass rate (73%) but was not included in the meta-analysis as it was unclear whether the RTS testing was conducted before all athletes had returned to play [28].

One problem with these test batteries is the 'penalty' of multiple tests [34]. With a test battery, multiple tests across a number of domains are required to be passed at a required pass rate, which was most often set at 90%. If athletes meet the pass rate for one test and a second test with a 90% pass requirement is added, the percentage of athletes who pass will almost certainly drop [34]. For example, even if 80% of athletes pass each test of a test battery, the overall pass rate for the test battery will be dependent on the total number of tests such that the pass rate for the first test will be 80%, but then only 64% (0.8 × 0.8) for two tests, 51% (0.64 × 0.8) for three, 40% (0.5 × 0.8) for four, and so on. Fortunately, this problem is correctable. Testing should be administered at multiple time points and once an athlete passes a test of the battery, that test pass requirement may be able to be dropped from the battery requirement. However, caution should still be exercised as athletes who pass a criterion at one time point may fail it at another [11].

Even when RTS testing was conducted over a longer time frame (1–2 years) [21] and once the patient had returned to sport [26, 30, 32], the pass rate was still only 23%. This is of concern from an injury prevention perspective as it highlights that many patients may have returned without acceptable knee function and control. Beischer et al. [30] showed that only 29% of adolescent (15–20 years) patients achieved a limb symmetry index of > 90% on five tests of muscle function despite having already returned to strenuous sports at 8 months. When these findings are considered in parallel with the high rates of reinjury that have been reported in younger patients, it is reasonable to suggest that poor knee function combined with high exposure was a contributing cause of reinjury in this younger patient group. From a practical point of view, the overall low pass rates should also lead us to question how such tests can be utilized if the majority of patients fail (i.e. the test batteries have large floor effects). A fundamental question is whether RTS test batteries are designed to determine whether the patient is capable of return to play at a specific performance level or are they designed to determine whether return is safe.

In terms of capability of return to play, passing an RTS test battery at 6 months post-surgery was shown to lead to significantly higher RTS rates at both 12 and 24 months in the only study included that investigated the relationship between passing RTS criteria and subsequent return rates [23]. The group that passed had signifiantly more male patients and was overall of younger age. However, Sousa et al. [20] showed that a similar proportion of patients who had passed RTS testing at 6 months compared to those who failed, reached or exceded their pre-injury Tegner activity

Study or Subgroup	Pass RTS test battery Events	Pass RTS test battery Total	Fail RTS test battery Events	Fail RTS test battery Total	Weight	Risk Ratio M-H, Random, 95% CI
Graziano et al. 2017 [27]	2	37	0	4	7.4%	0.66 [0.04, 11.83]
Grindem et al. 2016 [22]	1	18	1	55	8.4%	3.06 [0.20, 46.40]
Sousa et al. 2017 [20]	9	52	8	171	76.7%	3.70 [1.50, 9.10]
Wellsandt et al. 2017 [24]	4	40	0	30	7.5%	6.80 [0.38, 121.74]
Total (95% CI)		**147**		**260**	**100.0%**	**3.35 [1.52, 7.37]**
Total events	16		9			

Heterogeneity: Tau² = 0.00; Chi² = 1.51, df = 3 (P = 0.68); I² = 0%
Test for overall effect: Z = 3.01 (P = 0.003)

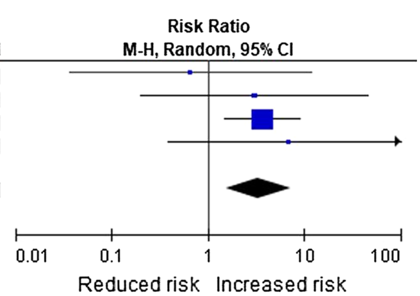

Fig. 7 Meta-analysis showing the risk for contralateral ACL injury after passing an RTS test battery. The risk ratio and 95% CI data from individual studies in addition to the pooled data are shown. RR > 1 indicates an increased risk of contralateral ACL injury if the patient passes an RTS test battery. *RTS* return to sport, *M-H* Mantel-Haenszel, *RR* risk ratio

score at a mid-term follow-up (minimum 2 years). Despite this, the pass group had an overall higher activity level at mid-term and also had significantly better knee function. Therefore these combined results indicate that 6-month RTS test results may be indicative of latter-term function.

With regard to whether RTS testing can determine whether it is safe to return to sport, five studies were included in this review that investigated subsequent injury [20, 22, 24, 27, 28]. Two of these recorded all knee injuries and showed that passing an RTS test battery resulted in an overall 72% reduction in risk for any subsequent knee injury [22, 27]. However, this reduction was not statistically significant, and the risk estimate should be considered imprecise due to a large 95% CI (from 93% reduction in risk to 21% increase in risk), mainly due to the low number of studies and small subject numbers (only 114 patients in total). Nonetheless, as both studies showed the same trend, further research is both encouraged and required to confirm this finding. In these two studies, Grindem et al. [22] noted that patients should wait at least 9 months before return to play as the risk for further knee injury was significantly reduced for each month the athlete delayed return until the 9-month mark. Graziano et al. [27] similarly noted that none of their young patient cohort was ready to return before 9 months.

Passing an RTS test battery led to a significant 60% reduction in risk for graft rupture; however, it also led to a significant 235% increase in risk of contralateral ACL injury compared to not passing the test battery. Therefore, passing a test battery did not change the risk for all subsequent ACL injuries, which is similar to findings of a recent review of four studies that showed a nonsignificant 3% reduction in risk [36].These current findings highlight the need to consider the outcome and rehabilitation of both knees as, for the athlete, any further ACL injury is a devastating outcome. Of the five studies included in this analysis there were two with significant results, and these were the only two studies with a total sample size of more than 100 patients. Kyritsis et al. [28] recorded graft ruptures in elite male athletes and reported that those who did not meet all RTS criteria had a four times greater risk of graft rupture. The hamstring-to-quadriceps ratio of the involved leg alone was also highly associated with graft rupture, with a ten times greater risk for every 10% difference in strength. In comparison, Sousa et al. [20] did not find a reduced risk for graft rupture in their group who passed RTS criteria; they did, however, find a significantly increased risk for contralateral injuries. The authors suggested that this may be related to an increased activity level in their patients as they had been cleared for an earlier return to play. In addition, biomechanical and epidemiological findings demonstrated increased loading of the contralateral limb at the time of return to sport and beyond [37, 38]. This increased loading of the contralateral limb may also account for the increased risk in contralateral injury post-release to return to play.

Whilst this review has shown that RTS test batteries currently have limited validity in the reduction of overall second ACL injury risk, we cannot conclude that they have no benefit. They can be used to provide the patient with important feedback with regard to their rehabilitation progress and may also, for example, boost confidence for when the patient returns to play. However, these test batteries have the potential to decrease confidence as well. Due to the heterogeneity of tests that were conducted in the studies included in this review, as well as those in the wider literature, it is apparent that there is still a high level of uncertainly as to what tests are best to include, the value of any specific test and when they should be used.

4.1 Limitations

There are a number of limitations that need to be considered. There was only one study that assessed whether passing RTS criteria was associated with subsequent return to play, so it is difficult to draw firm conclusions from the data. The definition of RTS has also varied and is not always clearly defined in any one study. A recent consensus statement has attempted to provide a working definition [39], but this was not adopted in any of the included studies. The sample sizes in most of the studies were limited and the inclusion criteria were broad. For example, the age limits typically ranged from 14 to 50 years, some studies had greater than 50% allografts [23, 24], and there was a mixture of the types of sports played. All these factors have been related to second ACL injury and have not been specifically controlled for in the included studies. In addition, no study reported on player exposure, so it is unclear whether the group who passed RTS criteria actually had a higher level of exposure as suggested by Sousa et al. [20], and also whether this affects the risk of subsequent injury. Measurement of exposure is of course a challenging undertaking. Finally, whilst a minimum 2-year follow-up time was used in the studies that reported further injury, and this length of follow-up is considered a strength for capture of all further injuries, it also means that over this time frame factors other than passing an RTS test battery come into play. There has been little discussion in the literature as to what may be an appropriate follow-up time period following RTS testing. For instance, if a patient is reinjured during his/her first couple of games/matches after return to play it would be logical to see if he/she had passed RTS testing or not. However, if a player has made a successful return to play and played for at least two full seasons, it may not be meaningful to relate an injury that occurs after this time point back to an RTS test that occurred many years earlier.

5 Summary and Conclusions

In conclusion, this review showed that less than a quarter (23%) of patients pass RTS test batteries irrespective of whether or not they have already returned to sport, though patients who pass test batteries earlier may have better RTS outcomes in terms of participation. Passing RTS test batteries did not significantly reduce the risk for further knee injuries in general or ACL injuries specifically. A highly interesting finding was observed in terms of graft rupture and contralateral ACL injury, where passing significantly decreased the risk for graft rupture by 60%, but significantly increased the risk for contralateral ACL injury by 235%. Therefore, given these mixed and equivocal results, the information that can be gained from these current RTS test batteries may be hard to apply in clinical practice as there is a high level of uncertainly as to their validity for providing advice to patients regarding their risk for subsequent injury should or when they choose to return to play.

Data availability All the data in these studies are available in the figures and tables.

Compliance with Ethical Standards

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