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Proprioceptive deficits after ACL injury: are they clinically relevant?

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ABSTRACT

Objective To establish the clinical relevance of proprioceptive deficits reported after anterior cruciate ligament (ACL) injury.
Material and methods A literature search was done in electronic databases from January 1990 to June 2009. Inclusion criteria for studies were ACL deficient (ACL-D) and ACL reconstruction (ACL-R) articles written in English, Dutch or German and calculation of correlation(s) between proprioception tests and clinical outcome measures. Clinical outcome measures were muscle strength, laxity, hop test, balance, patient-reported outcome, objective knee score rating, patient satisfaction or return to sports. Studies included in the review were assessed on their methodological quality.
Results In total 1161 studies were identified of which 24 met the inclusion criteria. Pooling of all data was not possible due to substantial differences in measurement techniques and data analysis. Most studies failed to perform reliability measurements of the test device used. In general, the correlation between proprioception and laxity, balance, hop tests and patient outcome was low. Four studies reported a moderate correlation between proprioception, strength, balance or hop test.
Conclusion There is limited evidence that proprioceptive deficits as detected by commonly used tests adversely affect function in ACL-D and ACL-R patients. Development of new tests to determine the relevant role of the sensorimotor system is needed. These tests should ideally be used as screening tests for primary and secondary prevention of ACL injury.

INTRODUCTION

The anterior cruciate ligament (ACL) is the most commonly injured ligament in the body.[1] Instability of the knee often occurs after ACL injury in pivoting type sports and ACL reconstruction (ACL-R) is often recommended.[2] Nonetheless, despite ACL-R, up to a third of the patients will not reach their preinjury activity level,[3] which may be attributed to the fear of re-injury.[4] Of concern is the incidence of recurrent injury to the operated knee ranging from 3.6%[5] in adults to 17% in patients younger than 18 years.[6] An ACL injury increases the risk of osteoarthritis with a prevalence ranging from 0% to 13% for patients with isolated ACL deficient (ACL-D) knees and 21% to 48% for patients with combined injuries.[7]

Proprioceptive deficits after ACL injury may be a factor related to both giving-way and higher incidence of subsequent injuries, which in turn may contribute to the development of osteoarthritis.[8] Proprioceptive deficits are claimed to adversely affect activity level,[9–11] balance,[12 13] re-establishment of quadriceps strength[14] and increase the risk of further injury.[15] Evidence supporting such claims is not readily available as was revealed by an earlier critical review on this topic.[16] The objective of this review is to analyse the correlations between proprioception in ACL-D and ACL-R patients and common clinical outcome measurements such as objective scores, strength, laxity, balance, hop tests and patient-reported outcomes.

MATERIALS AND METHODS

An electronic search was performed in Medline, Cinahl and Embase on studies published between January 1990 and June 2009. In addition, a manual search was conducted by tracking the reference lists of the included studies. The inclusion criteria in this review were as follows: (1) studies reporting on patients with a rupture of the ACL diagnosed by positive Lachman, pivot shift, KT-1000, MRI or arthroscopy; (2) studies reporting on ACL-R using an autograft or allograft; (3) proprioception measures; (4) full text published in English, Dutch or German; (5) outcome measures classified by the WHO including impairment of body functions (strength, laxity), activity limitation (hop test, balance) and participation restriction (objective or patient-reported outcome) and (6) correlation reported between proprioceptive tests and outcome measurements as listed above. For this review, the two most commonly used methods to quantify proprioception were included. These were defined at the Foundation of Sports Medicine Education and Research Workshop in 1997 as joint position sense (JPS) and threshold to detect passive motion (TTDPM).[17] JPS is assessed by measuring reproduction of passive positioning (RPP) or active repositioning of the knee (RAP). Studies that analysed other forms of proprioception were excluded in this review due to reported decreased accuracy.[18] The search terms are presented in Table 1.

A modified version of the Cochrane Methods Group on Screening and Diagnostic Tests Methodology (CM) was used to assess the methodological quality.[19] The following criteria were modified: questions 1–4 were replaced by Oxford Center for Evidence-based Medicine (http://www.cebm.net/index.aspx?o=1025) to score

Table 1 Search terms used in the databases of Medline, Embase and Cinahl from January 1990 to June 2009 (MeSH, medical subject heading; TI, title; ti, ab, title abstract, MH, medical heading; TX, text)

	Medline	Embase	Cinahl
1	'Proprioception' [MeSH]	'Proprioception' exploded	Proprioception MH
2	'Mechanoreceptors' [MeSH]	'Kinesthesis' exploded	Somatosensory disorders MH
3	'Sensory thresholds' [MeSH]	'somatosensory' exploded	Kinesthesis MH
4	'Kinesthesis' [MeSH]	'Mechanoreceptors' exploded	Receptors, sensory MH
5	Proprioception [TI]	'Proprioception' in ti, ab	Mechanoreceptors MH
6	Mechanoreceptors [TI]	'Proprioceptive' in ti, ab	Proprioception TX
7	Kinesthesis [TI]	'Kinesthesis' in ti, ab	Proprioceptive TX
8	kinesthesia [TI]	'Kinesthesia' in ti, ab	Kinesthesis TX
9	Joint position sense [TI]	Kinesthetic' in ti, ab	Kinesthesia TX
10	'Anterior cruciate ligament' [MeSH]	'Somatosensory' in ti, ab	Kinesthetic TX
11	'Knee joint' [MeSH]	'Mechanoreptors' in ti, ab	Somatosensory disorders TX
12	ACL injury [TI]	'Sensory receptors' in ti, ab	Mechanoreceptors TX
13	ACL deficient [TI]	'Ligament' exploded	Sensory receptors TX
14	ACL reconstruction [TI]	'Knee' exploded	Joint position sense TX
15		'Joint' exploded	Motion perception TX
16			Anterior cruciate ligament MH
17			Knee joint MH
18			Anterior cruciate ligament TX
19			ACL TX
20			ACL deficient TX
21			ACL injury TX
22			ACL reconstruction TX
23	(#1 or #2 or #3 or #4 or #5 or #6 or #7 or #8 or #9) and (#10 or #11 or #12 or #13 or #14)	(#1 or #2 or #3 or #4 or #5 or #6 or #7 or #8 or #9 or #10 or #11) and (#12 or #13 or #14 or #15)	(#1 or #2 or #3 or #4 or #5 or #6 or #7 or #8 or #9 or #10 or #11 or #12 or #13 or #14 or #15) and (#16 or #17 or #18 or #19 or #20 or #21 or #22)

the level of evidence from 1 to 5; level 1, the highest score and level 5, the lowest score possible. Questions pertaining to inclusion criteria, study design, setting, previous tests/referral time since injury or surgery, comorbid conditions, description of index test (JPS and TTDPM) and its reproducibility, demographic information, percentage missing were used and a question was added regarding statistical analysis. The maximum score of the modified CM was 16 points. In addition, effect sizes (ES) were calculated where d=0.2–0.5, d=0.5–0.8 and d≥0.8 representing a small, moderate and large effect, respectively.[20] Correlation coefficients were interpreted as r=0–0.25 as 'no correlation', r=0.26–0.49 as 'low', r=0.50–0.69 as 'moderate', r=0.70–0.89 as 'good' and r=0.90–1.0 as 'excellent'. A total of 1161 studies were identified in the databases and 48 duplicates were discarded leaving 1113 studies. Seven studies were retrieved by manual search. Of the total of 1120 studies, four were excluded because of language restrictions.[21–24] From the 1116 studies, 83 were identified as potentially relevant after reading the abstract. The full text of these 83 studies was independently assessed by two observers (AG and AB) after which 59 studies were excluded as they did not meet the inclusion criteria. A consensus meeting was needed on four studies.[25–28] Hence, in total, 24 studies were included; 20 of which were cross-sectional[25 26 28–44] and four had a prospective design.[8 45–47] Reliability was reported in 12 studies,[8 26 29 31 34 39–42 44 47 48] of which six were conducted at the same centre.[8 29 34 41 42 45] In seven studies, the same, or part of the patient population was measured but different outcome measures were presented.[8 26 29 31 41 42 45] In six studies, data on correlation were not provided and the principal author from each study was contacted with a request to provide data: one replied but was not able to provide data,[9] four provided data[29 30 39 41] and one author did not reply despite two contact attempts.[47]

RESULTS

The methodological quality is presented in Table 2.

The mean score on the CM was 8 (SD 2). None of the reviewed studies scored higher than level 5 evidence. Table 3 summarises the characteristics of included patients.

The tests characteristics and correlation between proprioceptive tests and outcome measurements for the ACL-D and ACL-R patients are presented in Tables 4 and 5, for TTDPM and JPS, respectively.

The number of patients ranged between 9 and 56 across all studies. In 12 studies, healthy controls were examined and compared with the patients with ACL injuries.[8 28 32 33 38–40 43–47] In most studies that examined TTDPM, tests speeds were 0.5°/s, whereas two studies used speeds of 0.3°/s and 3°/s.[33 47] JPS was tested in five studies with RAP[28 30 33 35 39] and four studies measured RPP.[36 37 44 46] The range of motion in which the knee was tested ranged between 15° and 45° flexion for TTDPM and between 0° and 100° flexion for JPS. Most studies reported a deficit for the involved ACL-D or ACL-R knee in comparison to the uninvolved leg. Mean deficits in TTDPM for the involved leg in ACL-D patients were 0.4° (SD 0.4) and 0.2° (SD 0.2) in ACL-R patients. A lower (better) TTDPM in ACL-D patients for the involved leg compared with the uninvolved leg ranged between 0.1° and 0.5° in some test positions.[34 44] One study found a lower TTDPM of 0.1° in the involved leg compared with the uninvolved leg 6 weeks after ACL-R.[47] The mean deficit in JPS in ACL-D patients was 0.8° (SD 0.6) and 0.5° (SD 0.4) in ACL-R patients. In two studies examining JPS in ACL-R patients, lower values were found in the involved leg compared with the uninvolved leg (0.1° to 0.6°) in some test positions.[35 39] The mean ES was 0.4 (SD 0.6). In healthy controls, the mean differences for TTDPM between the left and right leg were 0.1° (SD 0.1).[33 38 40 43] In two studies, mean

Table 2 Methodological quality assessment

Authors	Design	Level of evidence	Selection criteria clearly described	Setting	Previous tests/referral filter	Time since injury/surgery	Co-morbid conditions or type of surgery	Demographic information	Description of index test in sufficient detail to permit replication of the test	Statistical analysis	Reliability of index test	Percentage missing	Total score (maximum is 16)
	Prospective (1 point) or retro-spective series	Oxford Centre for Evidence-based Medicine Levels of Evidence (level 1=5 points; level 2=4 points; level 3=3 points; level 4=2 points; level 5=1 point)	In and exclusion criteria reported (1 point)	Enough information to identify setting (1 point)	Details given about clinical and other diagnostic information as to which the index test is being evaluated (symptomatic or asymptomatic patients) (1 point)	Mean or median and SD reported (1 point)	Details given (1 point)	Age (mean or median and SD or range) and gender reported (1 point)	Test device, patient positioning, speed tested, number of trials (two or more items 1 point)	Details given on mean or median, SD or CI and p value proprioceptive tests and p value correlation (1 point)	Reliability reported (1 point)	All included subjects measured and if appropriate: missing data or withdrawals from study reported or explained (1 point)	
Corrigan *et al*[33]	0	1	0	1	1	0	0	0	1	1	0	1	6
Harter *et al*[35]	0	1	0	1	1	1	0	1	1	1	0	1	8
Co *et al*[33]	0	1	0	1	1	0	1	1	1	0	0	1	7
Wright*et al*[43]	0	1	1	1	1	0	1	0	1	0	0	1	7
MacDonald *et al*[38]	0	1	0	1	1	0	0	0	1	1	0	1	6
Borsa *et al*[31]	0	1	0	1	1	1	1	1	1	1	1	1	10
Borsa *et al*[26]	0	1	0	1	1	1	1	1	1	0	1	1	9
Fridén et al[34]	1	1	0	1	1	0	0	0	1	1	1	1	8
Beynnon *et al*[48]	0	1	1	1	1	1	1	1	1	0	1	1	10
Fridèn *et al*[8]	1	1	0	1	1	0	1	0	1	1	1	1	9
Risberg *et al*[40]	0	1	0	1	1	0	1	0	1	0	1	1	7
Fischer-Rasmussen and Jense[28]	0	1	0	1	1	0	0	1	1	1	0	1	7
Fremery *et al* (1998)	1	1	0	1	1	1	1	1	1	0	0	1	9
Birmingham *et al*[30]	0	1	0	1	1	1	0	1	1	1	0	1	8
Adachi *et al*[25]	0	1	0	1	1	0	0	0	1	0	0	1	5
Reider *et al*[47]	1	1	1	1	1	0	1	0	1	0	1	1	9
Katayama *et al*[36]	0	1	0	1	1	0	1	0	1	1	0	1	7
Roberts *et al*[42]	0	1	0	1	1	1	1	0	1	1	1	1	9
Ageberg *et al*[29]	0	1	1	1	1	1	0	1	1	1	1	1	10
Roberts *et al*[41]	0	1	0	1	1	0	1	1	1	1	1	1	9
Ageberg and Fridén[45]	1	1	1	1	1	1	1	1	1	1	1	1	12
Zhou *et al*[44]	0	1	1	1	1	1	1	1	1	1	1	1	11
Lee *et al*[37]	0	1	0	1	1	1	1	1	1	1	0	1	9
Muaidi *et al*[39]	0	1	0	1	1	1	0	1	1	1	1	1	9
Mean (SD)													8 (2)

Table 3 Demographics of patients

Author	n ACL	Age (SD)	n C	Age (SD)	Design	Time from injury (SD)	Additional injury
ACL-D							
Corrigan *et al*[33]	20 (11 Analysed)	30 (NR)	17	28 (NR)	c	5.3 (NR) years	NR
Wright *et al*[43]	9	18–40 (NR)	15	18–40 (NR)	c	8.7 (NR) months	1 Meniscus lesion
Borsa *et al*[31]	29	28.7 (1.7)			c	41.7 (11.7) Months	5 Meniscus and 2 MCL grade III lesions
Borsa *et al*[26]	29	28.7 (NR)			c	41.7 (11.7) Months	5 Meniscus and 2 MCL grade III lesions
Fridén *et al*[34]	17	28 (NR)	40	25 (NR)	c	NR	NR
Beynnon *et al*[48]	20	40 (7.4)			c	5.5 (6.5) Years	6 Meniscus lesions
Fridèn *et al*[8]	16	26 (NR)			l	1,2 and 8 (NR) months	15 Meniscus, 8 MCL and 4 chondral lesions
Fischer-Rasmussen and Jensen[28]	20	27.0 (5.0)	20	27.0 (4.0)	c	NR	NR
Fremery *et al* (2000)	10 Acute, 20 chronic	22.7 (3.2) Acute 28.4 (4.4) chronic	20	26.4 (4.8)	p	6.3 (3.0) And 12.4 (3.7) months	12 Meniscus lesions
Adachi *et al*[25]	29	Median 27 (NR)			c	Median 8 (NR) months	NR
Katayama *et al*[36]	32	25.6 (NR)			c	NR	7 Meniscus lesions
Roberts *et al*[42]	54	28 (NR)			c	2.7 (2.7) Years	39 Meniscus, 7 MCL and 7 chondral lesions
Ageberg *et al*[29]	36 (35 Analysed)	26 (5.0)			c	3.8 (3.0) Years	NR
Roberts *et al*[41]	36	26 (5.4)			c	3.8 (NR) years	19 Meniscus, 6 MCL and 5 chondral lesions
Ageberg and Fridén[45]	67 (56 Analysed)	43 (8)	28	42 (9)	c	15 (1.4) Years	31 Meniscus, 25 MCL, 11 chondral lesions
Lee *et al*[37]	12 (10 Analysed)	23.1 (1.8)				12.8 (3.9) Months	No
Muaidi *et al*[39]	20	30.4 (1.4)	20	29.5 (1.8)	c	n=20, 5 weeks; n=1, 10 weeks; n=1, 7 months; n=1, 5 years	13 Injuries, mostly meniscus
ACL-R							
Harter *et al*[35]	48	27.6 (6.9)	–	–	c	4.1 (1.7) Years	NR
Co *et al*[33]	10	27 (NR)	10	24 (NR)	c	31.6 (NR) months	8 Meniscus and 2 MCL lesions
MacDonald *et al*[38]	16	26.1 (NR)	6	30 (NR)	c	27.5 (NR) months	NR
Risberg *et al*[40]	20	35 (NR)	10	33 (NR)	c	24 (NR)	9 Menscius and 2 MCL lesions
Birmingham *et al*[30]	30	27.2 (11.3)	–	–	c	19.4 (14.5) months	NR
Reider *et al*[47]	26 (21 Analysed)	25 (NR)	26	25 (NR)	p	Preop to 3 weeks, 6 weeks and 6 months (NR)	17 Meniscus and 10 chondral lesions
Zhou *et al*[44]	36	26 (5.8)	13.0	26.4 (3.9)	c	189 (11.2) Days	NR
Muaidi *et al*[39]	15 (3 Months) 14 (6 months)	30.4 (1.4)	20	29.5 (1.8)	c	3 and 6 (NR) months	13 Injuries, mostly meniscus

ACL-D, anterior cruciate ligament deficient; ACL-R, anterior cruciate ligament reconstruction; C, control subjects; c, cross-sectional; MCL, medial collateral ligament; n, number; NR, no correlation.

results of TTDPM for left and right leg were combined to a value of 0.9° (SD 0.2)[34] and 1.5° (SD, not reported)[47] with the statement that there was no significant difference between the two legs. The mean difference between right and left leg in healthy controls for JPS was 0.1° (SD 0.1).[28 33 46] Two studies reported only values for one leg in the control group and involved leg without side-to-side comparison.[44 47]

STRENGTH

A correlation between proprioception and quadriceps strength was calculated in five studies.[26 32 33 44 45] In two studies, isometric strength[26 33] was tested whereas three studies examined isokinetic strength.[32 44 45] The two papers on isometric strength showed a good correlation with hamstring/quadriceps ratio and JPS ($r=-0.74$, $p<0.01$)[33] but a low correlation with isometric quadriceps strength and TTDPM ($r=-0.29$, p=NR).[26] The three studies on isokinetic quadriceps strength found no correlation with TTDPM although p values were not provided,[32] the second found no correlation ($r=0.06$, $p=0.58$),[45] whereas for JPS a low correlation ($r=-0.41$, $p<0.05$)[44] was reported in the third.

Table 4 Results proprioception: threshold to detect passive motion (TTDPM)

Author	Reliability (*)	Speed (°/s)	Direction (°)	TTDPM ACL-I (SD)	TTDPM ACL-U (SD)	Diff I-U	ES	TTDPM C left (SD)	TTDPM C right (SD)	Diff C left-right	Outcome measurements	Correlation with TTDPM (p value)
ACL-D												
Corrigan *et al*[33]	NR	0.3	TE 35 and TF 35 mean 2.6 (1.8)	1.9 (1.2)	0.7	0.5	1.2 (0.4)	1.0 (0.5)	0.2	Strength – isometric H/Q ratio	Involved leg r=−0.74 (<0.01) Controls r=0.25 (0.41)	Uninvolved leg no correlation (NR)
Wright *et al*[43]	NR	0.5	TE 40	3.2 (1.6)	3.3 (1.9)	0.1	−0.1	3.4 (1.5)	3.5 (2.1)	0.1	Laxity – KT-1000	Difference involved-uninvolved: r=−0.005 (NR)
											Patient-reported outcome – Cincinnati knee rating	Difference involved-uninvolved: r=−0.40 (NR)
Borsa *et al*[31]	ICC 0.92	0.5	TE 15	0.9 (0.1)	0.8 (0.1)	0.1	2.5				Hop test – index single leg hop test distance	Involved leg TE 15 r=−0.46 (<0.05)
			TE 45	1.1 (0.1)	1.0 (0.1)	0.1	1.1					Involved leg TE 45 r=−0.56 (<0.01)
			TF 15	1.1 (0.1)	0.9 (0.1)	0.2	1.9					Involved leg TF 15 r=−0.37 (NR)
			TF 45	1.1 (0.1)	0.9 (0.1)	0.2	1.4					Involved leg TF 45 r=−0.47 (NR)
Borsa *et al*[26]	ICC 0.92	0.5	Index score	65 (NR)							Strength – isometric quadriceps	Involved leg r=−0.29 (NR)
											Hop test – index single leg hop test distance	Involved leg r=−0.40 (NR)
											Balance – KAT 2000	Involved leg r=−0.07 (NR)
											Patient-reported outcome – Cincinnati Knee Rating	Involved leg r=−0.34 (NR)
											Lysholm	Involved leg r=−0.19 (NR)
Fridén *et al*[34]	CI 0 to 0.38	0.5	TE 20	1.1 (0.9)	1.1 (0.9)	0.0	−0.1	0.8 (0.5)			Hop test – single leg hop test distance	Involved leg TE 20 r=−0.42 (NR)
	CI 0 to 0.63		TE 40	0.9 (0.7)	1.4 (1.6)	−0.5	−0.4	1.0 (0.6)				Involved leg TE 40 r=−0.58 (NR)
	CI 0 to 0.25		TF 20	0.8 (0.5)	1.2 (0.9)	−0.4	−0.5	1.1 (0.9)				Involved leg TF 20 r=−0.32 (NR)
	CI 0 to 0.13		TF 40	0.8 (0.7)	0.6 (0.2)	0.2	0.5	0.7 (0.4)				Involved leg TF 40 r=−0.46 (NR)
Beynnon *et al*[48]	Analysis variance 0.57	0.5	TE45 and TF 45	1.5 (0.7)	1.2 (0.5)	0.3	0.5				Laxity – KT-1000	Involved leg r=0.15 (NR)
						Laxity – pivot shift					Laxity – pivot shift	Involved leg r=0.22 (NR)
Fridèn *et al*[8]	CI 0 to 0.38	0.5	TE 20	1.3 (1.3)	1.0 (1.2)	0.3	0.2				Patient-reported outcome – subjective rating knee function (1=recently injured; 10=healthy without any limitation)	Involved leg TE 20 at 8 months r=0.61 (<0.01)

Continued

Table 4 Continued

Author	Reliability (*)	Speed (°/s)	Direction (°)		TTDPM ACL-I (SD)	TTDPM ACL-U (SD)	Diff I-U	ES	TTDPM C left (SD)	TTDPM C right (SD)	Diff C left-right	Outcome measurements		Correlation with TTDPM (p value)
	CI 0 to 0.63		TE 40		1.2 (1.0)	1.0 (0.7)	0.5	0.2						Involved leg TE 40 at 2 months r=0.64 (<0.01)
	CI 0 to 0.25		TF 20		2.3 (4.0)	1.1 (1.0)	0.8	0.4						Involved leg TF 20 at 2 months r=0.44 (<0.01)
	CI 0 to 0.13		TF 40		1.4 (2.2)	0.8 (0.5)	0.6	0.4						Involved leg TF 40 at 1 month r=0.65 (<0.008)
Roberts *et al*[42]	CI 0 to 0.63	0.5	Index score	Only ACL	4.5 (1.1)	3.6 (1.1)	0.9	0.8				Laxity – Lachman		Proprioceptive index r=0.33 (0.02)
				ACL+chondral lesion	15.2 (3.1)	13.9 (0.7)	1.2	0.6				Patient-reported outcome	Tegner	Propriocpetive index r=−0.26 (0.06)
													Subjective rating knee function (1=recently injured; 10=healthy without any limitation)	Propriocpetive index r=−0.35 (<0.01)
Ageberg *et al*[29]	CI 0 to 0.63	0.5	Index score		4.0 (2.0)							Balance	Movements exceeding 10 mm mean of centre of pressure	Proprioceptive index r=0.41 (0.81)
													Speed of movement centre of pressure	Proprioceptive index r=−0.27 (0.10)
												Patient-reported outcome	VAS Subjective Rating knee function (0=total disability; 100=good knee function – as prior to injury)	Proprioceptive index r=−0.29 (0.08)
													Tegner	Proprioceptive index r=−0.36 (0.03)
Roberts *et al*[41]	CI 0 to 0.63	0.5	Index score		4.1 (2.2)								Hop test – single leg hop test distance	Proprioceptive index r=−0.40 (0.014)
													Patient-reported outcome-Subjective Rating knee function (0=total disability; 100=good knee function – as prior to injury)	Proprioceptive index r=−0.30 (0.06)
Ageberg and Fridén[45]	CI 0 to 0.63	0.5	Index score		3.3 (3.8)				2.3 (0.7)				Strength – isokinetic quadriceps	Proprioceptive index r=0.06 (0.58)
													Hop test – single leg hop test distance	Proprioceptive index r=−0.11 (0.32)

Continued

Table 4 Continued

Author	Reliability (*)	Speed (°/s)	Direction (°)	TTDPM ACL-I (SD)	TTDPM ACL-U (SD)	Diff I-U	ES	TTDPM C left (SD)	TTDPM C right (SD)	Diff C left-right	Outcome measurements		Correlation with TTDPM (p value)
											Patient-reported outcome	KOOS Pain	Proprioceptive index r=−0.15 (0.17)
												KOOS Symptoms	Proprioceptive index r=−0.12 (0.24)
												KOOS ADL	Proprioceptive index r=−0.13 (0.23)
												KOOS Sport	Proprioceptive index r=−0.13 (0.22)
												KOOS Quality of life	Proprioceptive index r=−0.12 (0.25)
												Tegner	Proprioceptive index r=−0.18 (0.08)
Lee *et al*[37]	NR	0.5	TE 45 and TF 45 mean	3.8 (2.6)	2.6 (2.0)	0.8	0.5				Balance – tilt angle dynamic balance		Involved leg r=0.58 (0.04)
													Uninvolved leg r=0.58 (0.05)
ACL-R													
Co et al[33]	NR	0.5	TE 40	1.3 (0.8)	1.2 (0.4)	0.1		1.7 (0.8)	2.0 (1.0)	−0.3	Strength – isokinetic quadriceps		Involved leg no correlation (NR)
											Gait – heel strike transient		Involved leg no correlation (NR)
MacDonald *et al*[38]	NR	0.5	TE 30–40 TF 30–40 mean	0.8 (0.2)	0.7 (0.2)	0.1	0.5	0.8 (0.1)	0.8 (0.1)	0.0	Laxity – KT-1000 40N		Involved leg no correlation (NR)
											Patient-reported outcome- Patient satisfaction (grade 0 to 5, with 5 representing 100% satisfied)		Involved leg no correlation (NR)
Risberg *et al*[40]	CI 0 to 0.63	0.5	TE 15 TF 15 mean	1.1 (0.6)	1.1 (0.8)	0.0	0.1	1.6 (0.9)	1.5 (0.6)	0.1	Patient-reported outcome		Involved leg Uninvolved leg
												KOOS Pain	0.21 (NR) 0.34 (NR)
												KOOS Symptoms	0.17 (NR) 0.22 (NR)
												KOOS ADL	0.09 (NR) 0.17 (NR)
												KOOS Sport	0.14 (NR) 0.27 (NR)
												KOOS Quality of life	0.33 (NR) 0.32 (NR)
												Cincinnati Knee Rating	0.21 (NR) 0.34 (NR)
											Hop test	Single leg hop test distance	0.40 (NR) 0.55 (NR)
												Stair hop test	0.15 (NR) 0.30 (NR)
											Laxity – KT-1000 134N		0.03 (NR) 0.12 (NR)
Reider *et al*[47]	ANOVA variance component analysis r=0.96	3.0	TE 15 TF 15 mean 3 Weeks	2.3 (NR)	1.8 (NR)	0.5		1.5 (NR)			Laxity – KT-2000 40N		Involved leg no correlation (NR)
			6 Weeks	1.8 (NR)	1.9 (NR)	−0.1							
			3 Months	1.6 (NR)	1.6 (NR)	0							
			6 Months	1.6 (NR)	1.5 (NR)	0.1					Patient-reported outcome – Lysholm		Involved leg no correlation (NR)

ACL, anterior cruciate ligament; ACL-D, ACL deficient; ACL-I, ACL involved; ACL-R, ACL reconstruction; ACL-U, ACL uninvolved; ES, effect sizes; H/Q, Hamstrings and Quadriceps (isokinetic strength ratio); ICC, International Coordinating Committee; TE, towards extension.

Table 5 Results proprioception: joint position sense (JPS)

Author	Reliability	Test mode (°/s)	Direction (°)	JPS ACL-I (SD)	JPS ACL-U (SD)	Diff I-U	ES	JPS C left (SD)	JPS C right (SD)	Diff C left-right	Outcome measurements	Correlation with JPS (p value)
ACL-D												
Corrigan *et al*[33]	NR	RAP	35 to extension and to flexion	5.3 (2.4)	4.9 (2.4)	0.4	0.2	2.8 (1.1)	2.5 (0.9)	0.3	Strength – H/Q ratio	Controls r=−0.25 (0.40)
												Uninvolved leg no correlation (NR)
												Involved leg r=−0.77 (<0.01)
Fremery *et al* (1998)	NR	RPP (0.5)	0–20 flexion	Acute 5.8 (1.9) chronic 3.5 (1.5)				1.9 (0.5)	2.1 (0.7)	−0.2	Laxity – KT-1000 max force in 30° flexion	Involved leg r=−0.21 (NR)
			80–100 flexion	8.1 (2.5)				2.2 (0.7)	2.3 (0.8)	−0.1	Patient-reported outcome – patient satisfaction	Involved leg r=0.76 (NR)
											Patient-reported outcome – Lysholm	Involved leg r=0.6 (NR)
Fischer-Rasmussen and Jensen[28]	NR	RAP	0	3.1 (1.0)	3.1 (0.9)	0.0	0.0	3.1 (1.1)	3.2 (1.0)	−0.1	Patient-reported outcome – assessment performance (score 0–3)	Involved leg rs=0.6 (<0.05)
			60 flexion	4.1 (1.2)	3.1 (0.8)	1.0	0.9	3.0 (1.1)	3.1 (1.2)	−0.1		
Katayama *et al*[36]	NR	RPP (10)	between 5 and 25 flexion	5.2 (1.9)	3.6 (1.5)	1.6	0.9				Hop tests – Vertical hop	Uninvolved leg r=−0.31 (NR)
												Involved leg r=−0.33 (NR)
											Single leg hop distance	Uninvolved leg r=−0.20 (NR)
												Involved leg r=−0.50 (<0.001)
Lee *et al*[37]	NR	RPP (0.5)	45–0 extension	4.6 (1.7)	3.5 (1.3)	0.9	0.7				Balance – tilt angle dynamic balance	Involved leg r=0.024 (0.947)
			45–90 flexion									Uninvolved leg r=0.13 (0.723)
Muaidi *et al*[39]	ICC=0.6	RAP	0–15, 16.5, 18, 19.5 IR	1.6 (0.1)	1.5 (0.1)	0.1	0.8				Laxity – pivot shift	Involved leg no correlation (>0.50)
				0–20, 21.5, 23, 24.5 ER							Laxity – KT-1000 max force	Involved leg r=0.35 (0.205)
												Uninvolved leg r=0.09 (0.762)
											Hop tests – single leg hop distance	Involved leg r=0.37 (0.191)
												Uninvolved leg r=0.10 (0.724)
											Patient-reported outcome – IKDC 2000	Involved leg r=0.42 (0.115)

Continued

Table 5 Continued

Author	Reliability	Test mode (°/s)	Direction (°)	JPS ACL-I (SD)	JPS ACL-U (SD)	Diff I-U	ES	JPS C left (SD)	JPS C right (SD)	Diff C left-right	Outcome measurements	Correlation with JPS (p value)
ACL-R												
Harter *et al*[35]	NR	RAP	15 flexion	5.6 (4.1)	4.7 (3.9)	0.9	0.2				Laxity – KT-1000 90N	Involved leg r=−0.22 (0.13)
			20 flexion	5.9 (4.8)	5.6 (3.9)	0.3	0.1				Laxity – pivot shift	Involved leg r=0.15 (0.16)
			25 flexion	5.0 (4.0)	4.4 (4.0)	0.6	0.2				Laxity – Slocum	Involved leg r=−0.13 (0.18)
			30 flexion	4.7 (4.7)	5.3 (4.1)	−0.6	−0.1					
			35 flexion	5.4 (4.3)	5.4 (2.7)	0.0	0.0					
Birmingham *et al*[30]	NR	RAP	Between 30 and 60 flexion	3.5 (1.7)							Balance – on firm platform/eyes open	Involved leg r=0.00–0.19 (0.32)
											Balance – on foam/eyes closed	Involved leg r=0.14 (>0.50)
Zhou *et al*[44]	NR	RPP (2)	0 to flexion	5.6 (2.6)				4.3 (1.1)			Strength – isokinetic strength	Involved leg r=−0.41 (<0.05)
											Strength – presurgical H/Q peak torque	Involved leg no correlation (0.152)
Muaidi *et al*[39]	ICC=0.6	RAP	0 to 15, 16.5, 18, 19.5 IR	3 Months	1.3 (0.1)	1.4 (0.1)	−0.1	−0.4 to −0.7			Patient-reported outcome – Cincinnati sport activity rating	Involved leg (3 mo) r=0.63 (0.021)
	ICC=0.6	RAP	0 to 20, 21.5, 23, 24.5 ER	6 Months	1.3 (0.1)	1.3 (0.1)	0.0					Involved leg (6 mo) r=0.22 (0.44)
												Involved leg (3 mo) r=0.23 (0.408)
											Patient-reported outcome – IKDC 2000	Involved leg (6 mo) r=0.05 (0.867)

ACL, anterior cruciate ligament; ACL-D, ACL deficient; ACL-R, ACL reconstruction; ER, external rotation; H/Q, Hamstrings and Quadriceps (isokinetic strength ratio); IKDC, International Knee Documentation Committee; IR, internal rotation; RAP, repositioning of the knee.

GAIT

One study reported no correlation between TTDPM and vertical ground reaction force at heel strike, although a statistical analysis of the data was not presented.[32]

LAXITY

Seven of the 10 studies found either no (five)[35 40 43 46 48] or a low (two)[39 42] correlation between proprioception and laxity. However, statistical significance was only achieved in one study with a low correlation (r=0.33, p=0.02)[42] whereas in two studies the correlations were not significant.[35 39] Four studies did not report p values.[40 43 46 48] Three studies reported a nonsignificant correlation although data were not provided.[25 38 47] Two of the principal authors of these studies[25 38] responded to the request to provide the data but stated that data were no longer available, whereas the other author did not respond.[47]

HOP TESTS

Of the seven studies examining the correlation between proprioception and hop tests, one found no correlation (r=−0.11, p=NR),[45] four generally low[26 34 39 40] and two moderate correlations.[31 36] Borsa *et al* reported on the same cohort in two separate studies, but used different calculations of proprioceptive deficits, which resulted in a low correlation (no p value) in one study[26] and a moderate correlation in the other.[31] A moderate correlation was found for TTDPM only at 40° of flexion whereas all other test positions demonstrated low correlations (no p values reported).[49]

BALANCE

Of the four studies[26 29 30 37] that examined balance, one study found a moderate correlation with proprioception (r=0.58, p=0.04).[37] In the remaining three studies, low to no correlations (r=0.00 to 0.41) were found.[26 29 30] The study that found a moderate correlation with TTDPM, did not find a correlation when examining JPS in the same patient population (r=0.024, p=0.947).[37]

PATIENT-REPORTED OUTCOMES

Correlation between proprioception and patient-reported outcomes was examined in 15 studies. In four studies, the correlation ranged between none and low for knee injury and Osteoarthritis Outcome Score (KOOS) or Cincinnati score.[26 40 43 45] The fifth study found a moderate correlation between proprioception and Cincinnati score at 3 months after ACL-R (r=0.63, p=0.021) whereas at 6 months no correlation was observed (r=0.22, p=0.44).[39] At 3 months, there was no correlation with International Knee Documentation Committee (IKDC) (r=0.23, p=0.408) and changed to a low correlation at 6 months (r=0.44, p=0.807). In three studies, the correlation between proprioception and Lysholm was examined and no correlation (r=−0.19, p=NR),[26 47] or a moderate correlation (r=0.6, p=NR) was found.[28] No correlation was found for Tegner score (r ranging from −0.18 to −0.36 and p ranging from 0.03 to 0.08).[29 42 45] Four studies used a visual analogue score for subjective knee rating and found, in general, low correlations.[8 29 41 42] The remaining three studies used patient satisfaction or performance rating questionnaires.[28 38 46] Studies that examined objective scores were not found.

DISCUSSION

In general, low to moderate correlations between proprioception as measured with TTDPM and JPS and strength, hop tests and balance in ACL-D or ACL-R patients were found. No correlations were found between proprioception and laxity except for one study with a low correlation. The correlation with patient-reported outcomes was, in general, not evident.

METHODOLOGICAL QUALITY

A modified version of the CM methodology was used to assess the methodological quality.[19] The mean methodology quality score was 8 (SD 2) on the modified CM scoring checklist. Common flaws in methodological design were lack of reliability testing, incomplete statistical data, poor description of time since injury, inclusion and exclusion criteria of patients and their demographic data. All studies had a low level of evidence on the Oxford Center for Evidence-based Medicine Levels of Evidence. A maximum of five points could be scored on this item, but no study scored more than one point because no reference test was presented. Specific checklists for the current topic of interest are not available to the knowledge of the authors. It is recognised that this modified scoring system is arbitrary. However, the authors felt that weighing the included studies' scoring was necessary to compare across studies. To add insight relative to the strength of the relationship between the variables of interest, ES was also calculated. The mean ES was 0.4 (SD 0.6) and can be considered small.[20]

OUTCOME MEASUREMENTS

Strength

Muscle strength can be considered an important factor in maintaining joint stability. Joint stability can be defined as effectively resisting joint displacements and accomplished through a relationship between static and dynamic components. Static stability is measured through clinical joint stress testing in order to evaluate the integrity of the ligamentous structures and is not synonymous with functional stability. If static stability is compromised, such as with an ACL injury, compensation by dynamic components may become important in order to maintain functional stability of the knee. The dynamic components reflect the unconscious activation of the muscles in preparation for and in response to joint loading for the purpose of maintaining functional stability.[50]

The contention is that injury of the ACL results in altered proprioceptive input and subsequently leads to functional instability.[51] The sensorimotor system involves the mechanisms responsible for the acquisition of a sensory stimulus along with transmission of the signal via afferent pathways to the central nervous system (CNS). At the CNS, the signal is processed by the various centres of the motor cortex and results in a motor response, which is required for maintenance of joint stability. The somatosensory system encompasses all of the mechanoreceptive, thermoreceptive and nociceptive information gathered from the periphery.[50] Hence, proprioception is a subcomponent of the somatosensory system and involves the acquisition of stimuli by articular, cutaneous and muscular and tendinous receptors. Therefore, proprioception involves only the afferent pathway of sensory information and is not involved in the motor response.[50] This may explain why four of the five studies in this review found either no or a low correlation between strength and proprioception. Although, the authors of this review do not refute the importance of strength in generating sufficient functional stability, the relationship of strength with proprioception was not convincing.

Laxity

Nine of the 10 studies found no correlation between proprioception and laxity.[25 35 38 40 42 43 46–48] except a low correlation in one study.[39] Roberts *et al* speculated that a proprioceptive deficit leads to an increase in laxity as a result of giving-way episodes.[42] A ligament-muscle reflex stimulating α- and/or γ-motor neuron pathway has been reported[52] and, theoretically, following ACL injury, this ligament-muscle reflex is altered. The theory may lead to the assumption that ACL-R should therefore improve proprioception. Interestingly, the studies that examined ACL-R patients included in this review did not find a correlation with laxity and proprioception.[35 38 40 47] Preoperative baseline data were only presented in one study that showed improvement of proprioception after ACL-R, yet no correlation with laxity could be established.[47] The debate regarding the cause and effect relationship between laxity and proprioception may be fuelled by the fact that a lack of significant relationship between laxity and functional stability has been demonstrated in patients with ACL-D.[53] It is believed that proprioceptive deficits after ACL injury are caused by loss of mechanoreceptors located in the ACL.[32 33] This seems plausible, however, critical discussion points can be raised. First, there is the issue of validity. Although it is commonly accepted that proprioception is assessed by JPS and TTDPM, no golden reference test has been presented thus far that would support this assumption. Pincivero *et al*[16 54] were one of the first to raise critical concerns pertaining the validity of current proprioception test methods. JPS and TTDPM do not differentiate between mechanoreceptors from the ACL and those arising from other mechanoreceptors in and around the knee joint.[55] Second, it has recently been demonstrated that besides the afferent information from mechanoreceptors, the CNS can also contribute to JPS even when the CNS is deprived of peripheral afferent input. This illustrates a far more complex system than the contention that only peripheral information is essential.[56] The CNS may play a more important role after ACL injury than previously thought. This can be exemplified by the existence of two distinct groups of ACL-D patients, the copers and non-copers. Both have an injury to the ACL, but only the non-copers experience instability. Better proprioception has been reported in non-copers versus copers.[57] Interestingly, copers had altered somatosensory-evoked potentials compared with non-copers, which may indicate that central somatosensory changes are the critical elements in development of an effective strategy to the stabilise the ACL-D knee and not proprioception.[57] It seems plausible that efficient CNS plasticity allows copers to maintain high athletic activity without instability of the knee whereas non-copers may lack this compensatory mechanism.[58] Third, the fact that proprioception is still altered after ACL-R is often related to the fact that the graft does not contain receptors. This has recently been challenged, as reinnervation of the graft occurred as early as 3 months following ACL reconstruction.[10] Lee *et al*[37] recently found a positive relationship between TTDPM and knee function at 3 months but not at 6 months postsurgery, highlighting the difficulty of interpreting the differences reported. Proprioceptive deficits persist after ACL-R,[12 38] however, baseline data are required to substantiate these claims. Only two studies included in this review provided baseline data which indicated that proprioception improves slightly after ACL-R.[46 47] The changes were relatively small and the authors of this review question their clinical relevance.

Hop tests

In general, no or a low correlation between proprioception and hop tests was found in five studies[26 39 40 45 49] and a moderate correlation in two studies.[31 36] Six studies reported on ACL-D patients and the remaining study on ACL-R patients.[40] Borsa *et al* reported on the same patients in two separate studies, but used different calculations of proprioceptive deficits, which resulted in low correlation in one study[26] and a moderate correlation in the other.[31] Fridén *et al*[49] reported generally low correlations between hop tests and TTDPM, except at 40° of flexion showing a moderate correlation. In summary, the results are inconsistent and the correlation between hop tests and proprioception cannot be established from the available data.

Balance

Three studies found no correlation between proprioception and balance.[26 29 30] The fourth study found a moderate correlation with TTDPM, but no correlation with JPS.[37] There appears to be no correlation between proprioception and balance in ACL-D patients. Balance deficits that persist up to 2 years after ACL-R are thought to be related to proprioceptive deficits.[59] However, proprioception in this context continues to be a frequently misused term. Balance has been incorrectly used synonymously with proprioception.[50] It is known that balance exercises may improve outcome after ACL injury.[15] However, clear definitions are needed. Balance is defined as when postural equilibrium during all motor activities is achieved.[60] With respect to balance, pertinent afferent information arises from vestibular, visual and somatosensory sources. The afferent information gathered from these three sources must be integrated and processed to determine the necessary motor commands. The motor commands are then executed by muscles along the entire kinetic chain. Hence, it seems reasonable to conclude that the resultant outcome of exercises should be stated in exactly those terms such as improvement of balance, and not as improvement of proprioception.[61] Hypothetically, skill training may allow a patient to improve the probability of detecting knee motion. The question remains if this would have any clinical relevance in terms of improved knee function or reduction of knee injury. It may be that the patient has improved the ability to respond to the standard cues provided by the current tests of proprioception by improved cognitive awareness and not by increased mechanoreceptor gain of the knee.

Patient-reported outcome

The current validated patient outcome such as KOOS, IKDC or Cincinnati[62–64] were only presented in five studies.[26 39 40 43 45] Four studies found no or a low correlation between proprioception and KOOS and or Cincinnati score, whereas one study reported a moderate correlation at 3 months after surgery.[39] Interestingly, this changed to no correlation at 6 months after surgery. The IKDC had a low correlation 6 months after surgery.[39] Therefore, the correlation between proprioception and patient-reported outcome scores cannot be judged with certainty. Roberts *et al* have noted larger proprioceptive deficits in patients with symptoms versus asymptomatic patients, although the Tegner scores were not different between both groups.[11] Deficits are reportedly higher in patients with a cartilage and/or meniscus injury in addition to an ACL injury.[49] However, there was no adverse effect on the Tegner score. The authors of this review recommend the use of validated patient outcome questionnaires for future research to provide accepted evaluation tools for comparison of studies.

Clinical relevance of proprioceptive deficits

The mean reported proprioceptive deficits for TTDPM and JPS were small in patients with a mean deficit for the involved leg of, respectively, 0.4° and 0.8° for ACL-D and 0.2° and 0.5° for ACL-R patients. The mean side-to-side differences in healthy subjects were 0.1° for TTDPM and 0.1° for JPS measurements. Therefore, even in comparison to healthy subjects, the differences are small and do not likely represent any clinical relevance. For example, one may ask if a mean proprioceptive deficit of 0.4° for TTDPM and 0.8° for JPS could discern between non-copers and copers in ACL-D patients. Conversely, given the lack of reliability measurements in more than half of all included studies and the small differences observed, which likely fall within the range of measurement error, we view these differences as not clinically relevant. Jensen *et al* examined proprioception between copers and non-copers and found no difference between both groups.[65] Bilateral deficits in proprioception were reported to exist after ACL injury, in which case use of the uninvolved leg as an internal control might result in underestimation of the proprioceptive deficit.[66] ACL-D patients may have had a proprioceptive deficit prior to injury, which predisposed them to this injury. Scientific evidence to substantiate this claim is not available to the best knowledge of the authors. The use of passive tests for assessment of proprioception sense can be challenged. Under normal circumstances, the sensorimotor system gathers information from an active musculoskeletal system. In addition, there may not be a sound physiological rationale to justify using these extremely slow rates of knee displacement of 0.5°/s as used in most studies. The detection of movement at these rates may not truly assess proprioception as it relates to its functional activities.

From this review, it is now possible to evaluate the clinical relevance of reported proprioceptive deficits after ACL injury. However, there are some limitations associated with this review. This review only included studies in English, German and Dutch and could potentially cause language bias.

What is already known on this topic

ACL injury and surgical reconstruction have been shown to alter proprioception of the knee. The current accepted test methods consisting of JPS and TTDPM reveal deficits for the involved knee.

What this study adds

Proprioceptive deficits as measured with the current methods have only a low-to-moderate clinically relevant correlation with function. However, subsequent studies with higher methodological qualities are needed. Development of more valid tests is required to investigate the precise role of the changes in the sensorimotor system after ACL injury.

Nonetheless, only four studies were excluded on language restrictions, indicating that outcome would not be considerably different if these would have been included. Only the two most commonly used measurement techniques to quantify proprioception were included. Proprioception assessed by TTDPM has been found to be more repeatable and precise than JPS, and other methods of assessing proprioception have even lower accuracy.[18] It is recognised that the modified scoring system may be controversial. For instance, weighing of the items in the modified scoring system is arbitrary. This has to be taken into consideration when interpreting the results. A formal meta-analysis was not feasible due the heterogeneous data reported in the included studies.

CONCLUSION AND FUTURE DIRECTIONS

Although proprioception has been examined thoroughly after injury of the ACL, this review indicates that proprioception testing to date has, in general, only a low-to-moderate correlation with function after ACL injury. However, it should be noted that the methodological quality of included studies was, in general, not high, which may indicate that higher quality studies, as well as newer, more accurate and precise methodologies, may change the conclusions as drawn from the current review. In light of the increasing rate of ACL injuries, as well as relative high recurrent injury rate after ACL-R, the authors advise on development of new tests to determine the relevant role of the sensorimotor system. These tests should ideally be used as screening tests for primary and secondary prevention of ACL injury.

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