OPEN ACCESS

Poor functional performance 1 year after ACL reconstruction increases the risk of early osteoarthritis progression

Brooke Patterson ,¹ Adam Geoffrey Culvenor ,^{1,2} Christian J Barton ,¹ Ali Guermazi ,³ Joshua Stefanik,⁴ Hayden G Morris,⁵ Timothy S Whitehead,⁶ Kay M Crossley ¹

► Additional material is published online only. To view, please visit the journal online (<http://dx.doi.org/10.1136/bjsports-2019-101503>).

¹Sport and Exercise Medicine Research Centre, La Trobe University, Melbourne, Victoria, Australia

²Institute of Anatomy, Paracelsus Medical University, Salzburg & Nuremberg, Salzburg, Austria

³Department of Radiology, School of Medicine, Boston University, Boston, Massachusetts, USA

⁴Department of Physical Therapy, Movement and Rehabilitation Sciences, Northeastern University, Boston, Massachusetts, USA

⁵The Park Clinic, St Vincent's Private Hospital, Melbourne, Victoria, Australia

⁶Orthosport Victoria, Epworth HealthCare, Richmond, Victoria, Australia

Correspondence to

Professor Kay M Crossley, Sport and Exercise Medicine Research Centre, La Trobe University, Melbourne, VIC 3086, Australia; k.crossley@latrobe.edu.au

Accepted 17 January 2020
Published Online First
13 February 2020

© Author(s) (or their employer(s)) 2020. Re-use permitted under CC BY-NC. No commercial re-use. See rights and permissions. Published by BMJ.

To cite: Patterson B, Culvenor AG, Barton CJ, et al. *Br J Sports Med* 2020;**54**:546–555.

ABSTRACT

Background Not meeting functional performance criteria increases reinjury risk after ACL reconstruction (ACLR), but the implications for osteoarthritis are not well known.

Objective To determine if poor functional performance post-ACLR is associated with risk of worsening early osteoarthritis features, knee symptoms, function and quality of life (QoL).

Methods Seventy-eight participants (48 men) aged 28±15 years completed a functional performance test battery (three hop tests, one-leg-rise) 1 year post-ACLR. Poor functional performance was defined as <90% limb symmetry index (LSI) on each test. At 1 and 5 years, MRI, Knee injury Osteoarthritis Outcome Score (KOOS) and International Knee Documentation Committee (IKDC) subjective form were completed. Primary outcomes were: (i) worsening patellofemoral and tibiofemoral MRI-osteoarthritis features (cartilage, bone marrow lesions (BMLs) and meniscus) and (ii) change in KOOS and IKDC scores, between 1 and 5 years.

Results Only 14 (18%) passed (≥90% LSI on all tests) the functional test battery. Poor functional performance on the battery (all four tests <90% LSI) 1 year post-ACLR was associated with 3.66 times (95% CI 1.12 to 12.01) greater risk of worsening patellofemoral BMLs. A triple-crossover hop <90% LSI was associated with 2.09 (95% CI 1.15 to 3.81) times greater risk of worsening patellofemoral cartilage. There was generally no association between functional performance and tibiofemoral MRI-osteoarthritis features, or KOOS/IKDC scores.

Conclusion Only one in five participants met common functional performance criteria (≥90% LSI all four tests) 1 year post-ACLR. Poor function on all four tests was associated with a 3.66 times increased risk of worsening patellofemoral BMLs, and generally not associated with decline in self-reported outcomes.

INTRODUCTION

Rupture and subsequent reconstruction of the ACL (ACLR) substantially increases the risk of knee osteoarthritis (OA) development and poor quality of life (QoL).^{1–2} Yet not everyone after ACLR develops OA; radiographic OA is evident in approximately one-in-two,^{3–4} and one-in-three will have symptomatic radiographic OA within 10–15 years of injury.^{3–4} MRI can detect OA features within 5 years of ACLR,^{5–7} and can be used to

identify individuals who may be on an accelerated trajectory towards radiographic, symptomatic OA.⁸ Understanding modifiable factors associated with structural changes early after ACLR is a priority to inform secondary OA prevention strategies.

Impaired functional performance, often measured through hop tests, is common following ACLR,⁹ and may influence the development of early knee OA and symptoms. Quadriceps weakness is a risk factor for the development of radiographic and/or symptomatic OA, based on the theory of impaired shock absorption, consequent excessive load to joint structures, initiating a degenerative process.¹⁰ Hop-test batteries provide a clinically feasible method to assess multiple aspects of lower-limb muscle function (including quadriceps strength, sensorimotor control) and may indicate reduced ability to control mechanical loading in the knee,^{11–13} thus influencing joint degeneration and/or potential symptoms. Functional performance impairments may represent lack of confidence in the limb,¹⁴ and be reflected in reduced physical activity and worse patient-reported outcomes (PROs).

Following ACLR, the link between functional performance and worsening symptomatic and early structural OA outcomes is unclear. While a single hop-for-distance test at 1 year post-ACLR was associated with the presence of tibiofemoral radiographic OA at 10 years,¹⁵ other studies have reported minimal association between postoperative functional performance and future radiographic OA 5–15 years post-ACLR.^{4 16 17} Prior studies focus on radiographic tibiofemoral OA, and do not evaluate early structural change (ie, worsening) in individual joint features. Despite the patellofemoral joint being burdensome post-ACLR,^{18 19} few studies consider the patellofemoral joint structure. Radiographic measures lack the sensitivity to detect early structural changes which are identifiable on MRI over shorter follow-up.^{20 21} No studies have reported the relationship between functional performance and early (<5 years) structural changes on MRI in an ACLR population.

Evaluation of risk factors for early OA after ACLR should also include concurrent assessment of change in PROs, given the discordance between knee imaging findings and symptoms.^{22 23} Functional performance may possess differing relationships with change in individual early OA features and PROs. Functional performance deficits at the time of return to sport (RTS) are often associated

with worse PROs 2–3 years after ACL injury,^{16 24–28} with few studies evaluating the change in PROs beyond 3 years, due to cross-sectional design. It is this change in PROs and structural outcomes that equates to the problematic accelerated trajectory of symptomatic OA in young adults post-ACLR.

If early functional impairments are related to worsening structural or symptomatic OA, functional deficits can be targeted through exercise therapy to halt or slow the trajectory towards radiographic, symptomatic OA. The aims of the current study were to determine if functional performance 1 year post-ACLR is associated with risk of worsening patellofemoral and tibiofemoral MRI-OA features and change in PROs between 1 and 5 years.

METHODS

Study design and participants

A longitudinal prospective cohort study assessed the trajectory of PROs, functional performance and early OA features 1–5 years post-ACLR. Individuals assessed 1 year post-ACLR (ie, baseline for the current study) ($n=111$; 64% male, median age 27 (range 19–51) years)⁵ were eligible for 5-year follow-up. Descriptions of baseline eligibility criteria, ACLR technique and postoperative rehabilitation have been published.⁵ Briefly, all participants underwent a primary single-bundle hamstring-tendon autograft ACLR. Exclusion criteria were: knee injury/symptoms prior to ACL injury, >5 years between ACL injury and reconstruction and any secondary injury/surgery to the ACLR knee (between ACLR and 1 year post-ACLR). Participants with a secondary injury between 1 and 5 years were invited to participate in the 5-year assessment, as this is common occurrence and represents

the wider ACLR population. Of the 112 participants who completed baseline PROs, 81 (72%) completed PROs at 5 years. Of the 111 who underwent baseline MRI evaluation, 78 (70%) were re-imaged at 5 years (figure 1).

Demographic, injury and surgical factors

Participant age, sex, height, weight, injury history, activity level (defined as level 1 pivoting/jumping sports to level 4 sedentary²⁹) was obtained at the 1-year and 5-year assessments. Participants were classified as having a ‘combined injury’ if they had (at the time of ACLR): (i) significant cartilage defect identified arthroscopically (Outerbridge grade ≥ 2)³⁰ or (ii) surgical resection or repair of meniscus. To determine the presence of tibiofemoral and patellofemoral OA in the ACLR limb, posteroanterior and lateral weightbearing, and non-weightbearing skyline views were taken, and graded according the Osteoarthritis Research Society International atlas definitions.³¹ Radiographic OA was defined as joint space narrowing of grade ≥ 2 , sum of osteophytes ≥ 2 or grade 1 osteophyte in combination with grade 1 joint space narrowing.³¹

Functional performance

At 1 and 5 years post-ACLR, participants completed a battery of functional tests in the following order: single-hop, triple-crossover hop, side-hop and one-leg rise. The left leg was always tested first after two to three practice trials. The single-hop assessed the maximum distance (cm) achieved from a stationary position with a balanced landing (≥ 2 s without placing the other foot to the floor).³² The triple-crossover hop assessed

Figure 1 Flow chart of participant recruitment into the study. IKDC, International Knee Documentation Committee; KOOS, Knee injury Osteoarthritis Outcome Score; OA, osteoarthritis. *Participant at 1 year was involved in research team at 5 years.

the cumulative distance (cm) achieved with three consecutive hops with a balanced landing, with each hop crossing over two parallel lines 15 cm apart.³³ Hops were repeated for the single-hop and triple-crossover until three successful trials were recorded, and until no increase in distance was seen, due to the known learning effects.³⁴ The side-hop assessed the number of hops over two parallel lines 40 cm apart in 30 s.³² The one-leg rise is the maximum number of times (up to 50) the participant can rise on one leg from 90° knee flexion, at a consistent speed of 45 beats per minute (using a metronome).³⁵ A hop test or one-leg rise test was scored zero if the participant was unable (due to lack of strength/balance/confidence) to perform one successful trial. The one-leg rise test was stopped if the participant received three warnings for deviating from speed or touching the ground with opposite foot. The one-leg rise was added to the traditional battery of hops as it also assesses endurance, and has been associated with the development of radiographic OA in those with chronic knee pain.³⁵

The raw score (ie, distance hopped) and limb symmetry index (LSI) (% score of ACLR knee/contralateral knee) were recorded for each test. Poor functional performance on an individual test was defined as <90% LSI, a common benchmark used to define return-to-sport readiness,^{9,36} and is associated with risk of reinjury.^{37,38} Poor function on the battery was defined as <90% LSI on all four tests, to specifically capture individuals with poor function.

MRI-OA features

At 1 and 5 years post-ACLR, participants had unilateral (index) knee MRI scans acquired using a single 3T system (Philips Achieva, The Netherlands), as previously described.^{5,7} The three-dimensional proton density-weighted VISTA sequence was acquired at 0.35 mm isotropically (repetition time/echo time (TR/TE) 1300 ms/27 ms, field of view (FOV) 150 mm² and echo train length 64 ms) and reconstructed in coronal and axial planes. The sagittal short-tau inversion-recovery sequence was at 2.5 mm thickness, 1.2 mm slice gap and an inversion time of 180 ms was applied with TR/TE 3850 ms/30 ms, FOV 160 mm² and voxel size 0.45 × 0.50 × 2.5 mm. The axial proton-density turbo spin-echo sequence was obtained with imaging parameters of TR/TE 3850 ms/34 ms, slice thickness 2.5 mm, slice gap 2.0 mm, corresponding voxel size 0.5 × 0.55 × 2.5 mm and FOV 140 mm². All MRI scans were evaluated using the MRI-OA Knee Score (MOAKS) by a musculoskeletal radiologist (AG) with 19 years' experience of semi-quantitative MRI analysis of knee OA, and established inter-rater and intrarater reliability (kappa=0.61–0.80).³⁹ The 1-year and 5-year images were read paired (not blinded to time-points), but blind to clinical information. The MOAKS divides the knee into subregions to score specific OA features. For the current study, cartilage defects, bone marrow lesions (BMLs) and meniscal lesions were semi-quantitatively graded.

Four subregions defined the patellofemoral joint (medial and lateral patella, medial and lateral trochlea) and 10 subregions defined the tibiofemoral joint (medial and lateral: femur central and posterior, tibia anterior, central and posterior). For grading of meniscal lesions, six subregions (medial and lateral: anterior, posterior and central) were combined. Cartilage defects and BMLs were graded from 0 to 3 based on size (percentage of surface area relative to each subregion, where 0=none, 1=<33%, 2=33%–66%, 3=>66%). Cartilage defects were also scored on severity based on depth of the lesion (percentage of lesion which is full thickness; 0=no full-thickness loss; 1=<10%; 2=10%–75%;

3=>75%). A meniscal tear was defined as an area of abnormal signal that extends to both meniscal articular surfaces, and meniscal macerations were defined as loss of morphological substance of the meniscus. Meniscal lesions were described as absent or present, and by type (a tear was either vertical, horizontal or complex; and maceration was partial, progressive or complete). These abnormalities were scored according to MOAKS scoring system. Meniscal extrusion was graded by size 0 (<2 mm); 1 (2–2.9 mm); 2 (3–4.9 mm) or 3 (>5 mm) in each of the subregions. Meniscal extrusion, while based on the amount of extrusion in mm, was also scored using the MOAKS.

Worsening OA features in each subregion was defined as any increase in the size or severity of the feature. Therefore, either progression of an OA feature (ie, increase in severity) or a new OA feature (ie, from absent to present) from 1 year to 5 years was classified as worsening. New OA features were defined as those with size=0 at baseline, and size ≥1 at follow-up. Increase in severity was defined as an increase in size or depth of an existing OA feature at 1 year by ≥1 point on the MOAKS. Worsening OA features in the patellofemoral and tibiofemoral compartment was defined as worsening in any corresponding subregion for that compartment, as previously described.^{7,40} This definition of worsening is reliable and sensitive to change in ACL-injured patients.^{6,7}

Patient-reported outcomes

Participants completed the Knee injury Osteoarthritis Outcome Score (KOOS) and the International Knee Documentation Committee (IKDC) subjective knee form 1 and 5 years post-ACLR, with respect to their knee condition during the previous week. The KOOS and IKDC have established reliability and validity in people with ACL injuries.⁴¹ Four of the five subscales of the KOOS were assessed (activities of daily living subscale excluded due to ceiling effects in ACL populations). They were completed in by pen and paper or via an online portal (MySQL, Oracle, California, USA and Promptus, DS PRIMA, Melbourne, Australia) with matching instructions to the original paper version, as previously described.^{22,26} The KOOS and IKDC raw scores were recorded and converted to a percentile score, with 100 being the best possible score (ie, no knee problems). The absolute change (5-year score minus 1-year score) was calculated for each subscale (a negative value indicating worsening knee problems).

Statistical analyses

Generalised linear models with Poisson regression and generalised estimating equations (GEE) (accounting for correlations between subregions within the same participant) assessed whether functional performance at 1 year post-ACLR (both as a dichotomous (poor function ≤90% LSI) and a continuous (ACLR limb raw score in cm/repetitions) variable) was associated with risk of worsening MRI-OA features. Risk ratios (RR) and 95% CIs were calculated. A RR >1.0 represents an increased risk of worsening OA features in the presence of poor functional performance (<90% LSI) or a lower functional performance score (ie, fewer repetitions). The GEE regression was adjusted for presence of a combined injury (noted at time of ACLR, or secondary injury to the index knee), 1-year age, sex, height and weight, due to their potential influence on function and MRI-OA features.⁷ Linear regression (β, 95% CI) determined the relationship between 1-year functional performance, and change in KOOS/IKDC scores between 1 and 5 years (adjusted for combined injury (noted at time of ACLR, or secondary injury to

Table 1 Participant characteristics at 1 and 5 years post-ACLR*

	Participants at 1 year post-ACLR (n=81)	Participants at 5 years post-ACLR (n=81)
Age, median±IQR years	28±14	32±14
Male sex, no. (%)	50 (62)	50 (62)
Body mass index, median±IQR kg/m ²	25.7±4.2	26.4±5.0
Preinjury activity level 1 sport†, no. (%)	56 (69)	56 (69)
Time injury to surgery, median±IQR weeks	14±20	14±20
Combined injury,‡ no. (%)	40 (49)	46 (57)
New knee injuries, no. (%)	0 (0)§	16 (20)
ACLR limb¶	0 (0)§	10 (11)
Contralateral limb**	0 (0)§	6 (7)
Returned to level 1 sports,† no. (%)	20 (25)	26 (32)
Radiographic OA, no. (%)††	5 (6)	15 (19)
Patellofemoral	4 (5)	14 (18)
Tibiofemoral	2 (3)	6 (8)

*Participant demographics of n=81 completed PROs at 1 and 5 years.

†Level 1 sport=jumping, cutting pivoting as per Sports Activity Classification based on the study by Grindem *et al.*²⁹

‡Participants were defined as a combined injury at 1 and 5 years if they had a significant cartilage defect³⁰ and/or meniscectomy assessed/performed at the time of ACLR. Those who had a secondary injury/surgery to the index knee between 1 and 5 years follow-up were added to the combined injury group at 5 years.

§No new knee injuries were reported at 1 year as this was an exclusion criterion at baseline.

¶5-year new ACLR limb knee injuries/surgery n=10 (n=3 ACLR revision, n=6 meniscectomy, n=1 lateral collateral ligament sprain).

**5-year new contralateral limb knee injuries/surgery n=6 (combined: n=2 ACLR, n=1 meniscectomy, isolated: n=1 ACLR, n=1 meniscectomy, n=1 lateral collateral sprain).

††n=78 completed X-ray evaluation at 1 and 5 years, demographics of these participants have been reported previously.⁷

the index or contralateral knee), 1-year age, sex, height, weight and baseline KOOS/IKDC score, due to their potential to influence function and PROs²²). Analyses were performed using Stata V.14.2 with $\alpha=0.05$.

RESULTS

Demographics of the 81 participants who completed PROs at 1 and 5 years are presented in table 1. Of the 81 participants, 10 (12%) had poor functional performance (<90% LSI) on all four tests, while only 14 (18%) would have passed the test battery ($\geq 90\%$ on all four tests) at 1 year post-ACLR. The proportion of participants with <90% LSI on individual tests, and functional performance outcomes are presented in table 2. Of the 78 participants with radiographs at 5 years, the prevalence of any radiographic OA increased from 6% to 19% between 1 and 5 years (table 1). In those with poor function on the battery at 1 year (n=9/78), 33% (n=3) had patellofemoral or tibiofemoral radiographic OA at 5 years.

Imaging outcomes

Worsening compartment-specific MRI-OA features and radiographic OA prevalence are reported in detail previously.⁷ Briefly, patellofemoral and tibiofemoral cartilage worsening (34 (44%) and 16 (21%) participants, respectively) was more common than BML worsening (14 (18%) and 12 (15%) participants, respectively). Seventeen (22%) participants displayed worsening meniscal lesions. Five (6%) participants displayed worsening

Table 2 Functional performance 1 year post-ACLR*

	Raw score	LSI %
Single HFD, median±IQR (range) cm	108±40 (3 to 169)	92±15 (4 to 109)
$\geq 90\%$ LSI (n=50/81)	119±27 (71 to 169)	96±6 (90 to 109)
<90% LSI (n=31/81)	85±34 (3 to 142)	79±17 (4 to 88)
Triple-crossover HFD, median±IQR (range) cm	337±130 (0 to 569)†	95±11 (0 to 129)
$\geq 90\%$ LSI (n=55/81)	383±119 (146 to 569)	98±5 (90 to 129)
<90% LSI (n=26/81)	262±83 (0 to 403)	79±11 (0 to 89)
Side-hop, median±IQR (range) reps	25±17 (0 to 63)†	83±28 (0 to 156)
$\geq 90\%$ LSI (n=29/81)	29±13 (14 to 63)	100±11 (90 to 155)
<90% LSI (n=52/81)	23±18 (0 to 51)	70±20 (0 to 89)
OLR, median±IQR (range) reps	26±39 (0 to 50)†	96±40 (0 to 167)
$\geq 90\%$ LSI (n=40/76)	50±8 (5 to 50)	100±0 (92 to 325)
<90% LSI (n=36/76)	12±15 (0 to 43)	59±36 (0 to 89)

*n=81 completed functional performance assessment at 1 year and PROs at 1 and 5 years. n=76 for the one-leg rise as five participants were not included, as they could not perform a valid test on both ACLR and contralateral limb.

†Number of participants with a score of zero for the ACLR limb for the triple-crossover hop (n=1), side-hop (n=5) and one-leg rise (n=8).

ACLR, ACL reconstruction; HFD, hop for distance; LSI, limb symmetry index; OLR, one-leg rise; PRO, patient-reported outcome.

of all three features, while 20 (26%), 4 (5%) and 7 (9%) had isolated cartilage, BML and meniscal worsening, respectively. Worsening osteophytes were not included in the current study due to low numbers in the patellofemoral (n=7) and tibiofemoral (n=9) compartments.⁷

Functional performance and risk of worsening early OA features

Poor functional performance on the test battery (<90% on all four tests) resulted in an increased risk of worsening patellofemoral BMLs (RR 3.66; 95% CI 1.12 to 12.01) (table 3). The majority (86%) of those with a worsening patellofemoral BML had <90% LSI on the side-hop (figure 2). Individuals with <90% LSI on the triple-crossover hop-for-distance had an increased risk of worsening patellofemoral cartilage lesions (RR 2.09; 95% CI 1.15 to 3.81). Individuals with <90% LSI on the single hop-for-distance, side-hop and one-leg rise had an increased risk of worsening patellofemoral BMLs (RR 4.17, 95% CI 1.37 to 12.72; RR 3.77, 95% CI 1.15 to 12.43 and RR 2.92, 95% CI 1.19 to 7.18, respectively). Fewer side-hop repetitions was associated with an increased risk of worsening patellofemoral BMLs (RR 1.08; 95% CI 1.01 to 1.15). In contrast, fewer one-leg rises was associated with a small reduction in risk of worsening tibiofemoral cartilage lesions (RR 0.96; 95% CI 0.94 to 0.99) (table 3).

Functional performance relationship with KOOS and IKDC

The 1-year and 5-year KOOS and IKDC scores (n=81) have been reported in detail previously.²² Significant ($p<0.05$) improvement (ie, less knee symptoms, better function and QoL) was observed for all KOOS subscales (except KOOS-Symptoms) and IKDC between 1 and 5 years.²² The mean±SD changes were: pain: 2.8±9; symptoms: 0.5±16.1; sport: 6.0±18.2; QoL: 10.0±18.9 and IKDC: 4.7±10.9. Generally, functional performance 1 year post-ACLR was not associated with change in KOOS or IKDC scores between 1 and 5 years (table 4). Participants with <90% LSI for the side-hop test had a mean

Table 3 Functional performance at 1 year and risk of worsening early osteoarthritis features up to 5 years*

		Worsening early osteoarthritis features on MRI				
		PF cartilage	PF BML	TF cartilage	TF BML	TF meniscal
		n=34/78 (44%)	n=14/78 (18%)	n=16/78 (21%)	n=12/78 (15%)	n=17/78 (22%)
Single HFD						
Raw score (cm)†	No. (%)	1.00 (0.99 to 1.01)	1.01 (0.98 to 1.03)	0.98 (0.96 to 1.01)	1.00 (0.97 to 1.03)	0.98 (0.96 to 1.02)
Poor function (ref ≥90% LSI)‡	31 (38%)	1.26 (0.66 to 2.41)	4.17 (1.37 to 12.72)	0.69 (0.21 to 2.35)	0.68 (0.20 to 2.31)	1.65 (0.62 to 4.44)
Triple-crossover HFD						
Raw score (cm)†		1.00 (1.00 to 1.01)	1.00 (0.99 to 1.01)	1.00 (0.99 to 1.00)	1.00 (0.99 to 1.01)	0.99 (0.98 to 1.00)
Poor function (ref ≥90% LSI)‡	25 (32%)	2.09 (1.15 to 3.81)	2.60 (0.79 to 8.62)	1.02 (0.31 to 3.38)	1.02 (0.29 to 3.57)	1.76 (0.52 to 6.01)
Side-hop						
Raw score (repetitions)†		1.01 (0.98 to 1.05)	1.08 (1.01 to 1.15)	0.96 (0.91 to 1.02)	1.00 (0.95 to 1.06)	0.97 (0.92 to 1.02)
Poor function (ref ≥90% LSI)‡	49 (63%)	1.02 (0.51 to 2.03)	3.77 (1.15 to 12.43)	1.10 (0.47 to 2.60)	1.69 (0.34 to 8.45)	0.89 (0.35 to 2.28)
One-leg rise						
Raw score (repetitions)†		1.01 (0.99 to 1.02)	1.02 (0.99 to 1.05)	0.96 (0.94 to 0.99)	0.99 (0.94 to 1.04)	0.98 (0.95 to 1.02)
Poor function (ref ≥90% LSI)‡	35 (48%)§	1.32 (0.72 to 2.41)	2.92 (1.19 to 7.18)	0.30 (0.08 to 1.05)	0.58 (0.19 to 1.78)	0.98 (0.33 to 2.93)
Functional battery† (ref ≥90% LSI ≥any one test)						
Poor function all four tests§	9 (12%)	1.99 (0.92 to 4.30)	3.66 (1.12 to 12.01)	NA¶	1.32 (0.30 to 5.78)	1.25 (0.32 to 4.88)

Bold values indicate a statistically significant association ($p < 0.05$).

*Values are RR (95% CIs). Analysis performed in $n=78$ who completed functional assessment at 1 year and MRI and X-ray evaluation at 1 and 5 years. $n=73$ for the one-leg rise and battery LSI as five participants were not included, as they could not perform a valid one-leg rise on both ACLR and contralateral limb.

†For continuous exposure variables (raw score in cm or repetitions in ACLR limb), a RR >1 represents greater risk of the MRI-OA feature worsening in the presence of lower functional performance (ie, less distance or fewer repetitions). For example, a one repetition decrease on the side-hop test could be interpreted as having a 8% increased risk of worsening patellofemoral BMLs.

‡For dichotomous exposure variables (poor function defined as <90% LSI), a RR >1 represents a greater risk of the MRI-OA feature worsening in the presence of poor functional performance. For example, individuals with <90% LSI on the one-leg rise were 2.92 times more likely to have worsening patellofemoral BMLs, than those with >90% LSI.

§Poor functional performance was defined as <90% LSI.

¶Unable to perform analysis as all participants with <90% on the functional performance battery had TF cartilage defect worsening.

ACLR, ACL reconstruction; BML, bone marrow lesion; LSI, limb symmetry index; n, number of subregions with feature; N, total number of subregions; PF, patellofemoral; RR, risk ratio; TF, tibiofemoral.

8-points higher KOOS-QoL change value (β : 8.08; 95% CI 1.56 to 14.61).

DISCUSSION

Only one in five participants met common functional performance criteria ($\geq 90\%$ LSI on all hopping, one-leg rise tests)

1 year following ACLR—a time when function is typically expected to be restored. In this first evaluation of the implications of not meeting functional performance criteria on early OA outcomes after ACLR, poor function (<90% LSI) was consistently associated with 2–4 times increased risk of worsening patellofemoral BMLs. While performance on the triple-crossover

Figure 2 Individuals with and without change in patellofemoral BMLs and respective side-hop limb symmetry index.* *LSI scores are presented in categories of 0%–5%, 5%–10% in increasing increments of 5% for purposes of visualisation. BML, bone marrow lesion; LSI, limb symmetry index.

Table 4 Functional performance at 1 year post-ACL: relationship with change in KOOS and IKDC between 1 and 5 years*

Change in KOOS and IKDC between 1 and 5 years					
		KOOS-Symptoms	KOOS-Pain	KOOS-Sport	KOOS-QoL
Single HFD					
	No. (%)				IKDC
Raw score (cm)†		0.05 (−0.09 to 0.19)	−0.06 (−0.13 to 0.01)	−0.11 (−0.27 to 0.05)	−0.03 (−0.18 to 0.12)
Poor function (ref >90% LSI)‡	31 (38%)	1.35 (−5.70 to 8.41)	−2.57 (−6.08 to 0.94)	−1.68 (−9.04 to 5.67)	−1.81 (−9.01 to 5.41)
Triple-crossover HFD					
Raw score (cm)†		0.02 (−0.02 to 0.07)	−0.02 (−0.05 to 0.00)	−0.03 (−0.08 to 0.02)	−0.01 (−0.05 to 0.04)
Poor function (ref >90% LSI)‡	26 (32%)	2.56 (−4.30 to 9.42)	−3.14 (−6.65 to 0.37)	−3.14 (−6.65 to 0.37)	−3.40 (−10.27 to 3.46)
Side-hop					
Raw score (repetitions)†		0.22 (−0.08 to 0.52)	0.06 (−0.22 to 0.10)	−0.07 (−0.40 to 0.27)	0.08 (−0.24 to 0.40)
Poor function (ref >90% LSI)‡	52 (64%)	5.50 (−1.23 to 12.24)	2.97 (−0.43 to 6.37)	2.96 (−0.44 to 6.37)	8.08 (1.56 to 14.61)
One-leg rise					
Raw score (repetitions)†		−0.08 (−0.11 to 0.26)	0.00 (−0.10 to 0.10)	−0.04 (−0.25 to 0.18)	0.09 (−0.10 to 0.29)
Poor function (ref >90% LSI)‡	36 (47%)§	2.92 (−3.72 to 9.58)	0.45 (−3.07 to 3.97)	0.45 (−3.08 to 3.97)	6.19 (−0.75 to 13.15)
Functional battery‡ (ref ≥90% LSI ≥ any 1 test)					
Poor function all four tests§	10 (13%)	−2.78 (−12.44 to 6.88)	−3.00 (−7.80 to 1.79)	0.30 (−11.23 to 11.83)	0.47 (−9.66 to 10.61)

Bold values indicate a statistically significant association ($p < 0.05$).

*Values are beta-coefficient (95% CIs). Analysis performed in $n=81$ completed functional assessment at 1 year, KOOS and IKDC at 1 and 5 years. $n=76$ for the one-leg rise and battery LSI% as five participants were not included, as they could not perform a valid one-leg rise on both ACLR and contralateral limb.

†The beta-coefficient represents the adjusted difference in KOOS or IKDC change score per unit decrease in the continuous exposure variables. (ie, cm or number of side-hop repetitions, ACLR limb).

‡The beta-coefficient represents the adjusted difference in KOOS or IKDC in the presence of the dichotomous exposure variables (ie, poor function defined as <90% LSI), eg, those with <90% LSI had on average 8.08 points greater improvement on the KOOS-QoL than those with >90%.

§Poor functional performance was defined as <90% LSI.

ACL, ACL reconstruction; HFD, hop for distance; IKDC, International Knee Documentation Committee; KOOS, Knee injury and Osteoarthritis Outcome Score; LSI, limb symmetry index; QoL, quality of life.

hop was also associated with worsening patellofemoral cartilage over the subsequent 4 years, weak/no associations were generally observed between poor function and tibiofemoral cartilage, bone marrow and meniscal lesions and changes in PROs.

Poor function and risk of worsening patellofemoral OA features

Poor functional performance was associated with an increased risk of worsening patellofemoral OA features, particularly BMLs. An LSI <90% on all four tests in the battery was associated with 3.66 times greater risk of worsening patellofemoral BMLs. When considered as a continuous variable (ie, number of repetitions), the side-hop test was associated with worsening patellofemoral BMLs—each one repetition decrease on the side-hop test could be interpreted as having an 8% increased risk of worsening patellofemoral BMLs (RR: 1.08). Given the association of BMLs with incident symptoms, future damage to adjacent features (ie, cartilage) and incident radiographic OA,^{8 42 43} these findings may help identify individuals on an accelerated trajectory towards radiographic OA.⁸ There is need to validate these findings in larger cohorts and to confirm which factors influence functional recovery. Previous cross-sectional evaluation of this cohort at 1 year post-ACLR found worse hop-test performance at 1 year post-ACLR was associated with patellofemoral pain, kinesiophobia, lower psychological readiness for RTS and worse knee confidence.^{14 19} Other factors that have been linked to functional recovery after ACLR, such as motivation, stress and self-efficacy,⁴⁴ may also be important to target during supervised rehabilitation⁴⁵ to optimise function. Future interventional studies should determine if improving functional performance can positively impact long-term patellofemoral joint health.

Do tibiofemoral and patellofemoral post-traumatic OA have different risk profiles?

Functional performance 1 year post-ACLR had little association with worsening tibiofemoral OA features in the following 4 years, concurring with other studies reporting minimal association between greater postoperative function or muscle strength and tibiofemoral radiographic OA 5–15 years later.^{4 17} The tibiofemoral and patellofemoral compartment may have a different association with function for the development of post-traumatic OA. Our results extend those from non-traumatic older OA populations, where lower-limb function (ie, quadriceps muscle strength) was more strongly associated with risk of patellofemoral disease progression than tibiofemoral.⁴⁶ In contrast to patellofemoral disease worsening, our results indicate that poorer function (fewer one-leg rises) reduced the risk of tibiofemoral disease worsening. The mechanism underpinning this inverse (and unexpected) relationship is uncertain but is consistent with results in military recruits (aged 18 years), where lower quadriceps strength reduced the incidence of tibiofemoral OA 20 years later.⁴⁷ Taken together with demographic and surgical-related factors which display compartment-specific relationships with post-traumatic OA progression,^{7 22 48} future studies should evaluate the patellofemoral and tibiofemoral compartments independently to determine distinct risk profiles—particularly as they may have differing impacts on disease burden.¹⁸ For example, patellar alignment (lateral patellar displacement) was weakly associated with worsening patellofemoral cartilage in this cohort,⁴⁹ although when added as a covariate to the current statistical models, the relationship between function and worsening patellofemoral bone marrow and cartilage lesions did not change (data not shown). There is emerging appreciation of the

greater risk of early^{5 7} and long-term radiographic patellofemoral OA,⁵⁰ and potential contribution to symptoms,¹⁸ compared with tibiofemoral OA.

Challenges in predicting PROs

Functional performance 1 year post-ACLR was mostly not associated with change in PROs between 1 and 5 years. The only significant finding was that individuals with poor function (<90% LSI) for the side-hop test had an 8-point greater improvement in KOOS-QoL compared with those with good function (<90% LSI). Due to a low proportion (12%) scoring <90% LSI on all four tests, a sensitivity analysis calculated the RRs for poor function (<90% LSI) on *any* one, two or three tests, or *at least* one, two or three tests (ie, at least 2=all participants with two, three or four tests <90% LSI) (see online supplementary file 1). Similarly, poor function at 1 year on *any* or *at least* two tests was associated with 8–12 points greater improvement in KOOS scores. While 8–12 points approaches a clinically meaningful difference for the KOOS (≥ 8 –10 points),⁴¹ these results should be interpreted with caution. Individuals with poor function 1 year post-ACLR have greater potential for future improvement in physical and self-reported function, compared with those who have already restored good function. Only seven (9%) had a KOOS-QoL >90 at 1 year, demonstrating majority of the cohort had not reached a ceiling point, and may continue to improve between 1 and 5 years.

The only other study to evaluate the relationship between function at the time of RTS and PROs beyond 2 years reported conflicting findings.⁵¹ Greater between limb asymmetry on the one-leg rise test 6–15 months post-ACL injury was associated with worse KOOS scores at 5 years.⁵¹ Due to the multifactorial fluctuating nature of life for a young active adult, it is likely many other subjective factors influence change in KOOS and IKDC scores, hence predicting PROs post-ACLR is challenging.^{16 52} Further research should consider potential psychosocial and contextual influences on PROs such as fear avoidance, confidence, coping and healthcare utilisation.^{53–57}

Limitations

This prospective study lost 31 (28%) participants between 1 and 5 years. However, there were no significant differences in preinjury activity level, age, sex, body mass index or combined injury presence at the time of ACLR, between those who did and did not participate in follow-up.⁷ The current study included six (8%) participants who did not participate in jumping or cutting sports preinjury (ie, level 3 or 4),²⁹ which may influence the raw hop-test scores at 1 year. The current study may have been underpowered to detect potential relationships with functional performance for some outcome variables (ie, tibiofemoral worsening), affecting the statistical stability of some regression models. Future approaches should combine large sets of individual level data from multiple sites to provide sufficient power to detect risk factors and develop a risk profile for early OA development and progression in this young active population. Mechanical (eg, movement patterns,⁵⁸ physical activity,^{59–61} time from injury to ACLR⁷) and systemic factors (eg, adiposity)⁶² may influence the development of post-traumatic OA⁶¹ and warrant consideration in future risk profiles.

The LSI has inherent limitations and may overestimate knee function due to the bilateral neuromuscular deficits observed post-ACLR.⁶³ Also, discrete cut-offs (ie, >90% LSI) as an independent risk factor may result in overestimation of risk estimates.⁶⁴ Therefore, we considered both magnitude of performance as a

continuous outcome (repetitions or distance), as well as symmetry (LSI%), with generally a closer association observed between worsening OA features and dichotomised outcomes (<90% LSI). A floor effect for the functional performance tests should be noted as some participants scored zero on their ACLR limb (table 2), with reasons (anecdotally reported) as lack of physical capability (strength/power/control) or confidence to attempt the task. Future studies should explore reasons for poor functional performance, to better direct intervention strategies.

Clinical considerations

Despite the limitations of the LSI, better limb symmetry in hop tests has been associated with greater likelihood of return-to-sport, and reduced reinjury risk.^{38 65} Our results show restoring limb symmetry is also an attractive intervention target, given only 18% 'passed' the test battery (>90% LSI all four tests), and poor function was associated with increased risk of worsening patellofemoral bone marrow and cartilage lesions. Our sensitivity analysis (see online supplementary file 1) demonstrated the highest RRs for worsening patellofemoral cartilage, patellofemoral BMLs, tibiofemoral meniscal lesions were observed when *any* three tests, or *at least* two or three tests were failed (<90% LSI). A battery of tests assessing multiple functional domains (ie, strength, endurance, balance) may better categorise individuals with poor functional performance, and be more predictive of clinical outcomes.³⁸ Multifaceted neuromuscular deficits may affect joint loading,¹² and consequently joint health. Regardless of return-to-sport aspirations, continuing rehabilitation to achieve 'functional criteria' on a test battery may optimise future joint health. Future studies should continue to investigate the relationship between symptomatic and structural changes in a post-traumatic OA population after ACLR. Underlying early stages of OA without the presence of symptoms may not be 'incidental' in those at risk of OA, and may lead to future symptomatic radiographic OA.⁸

What are the findings?

- Individuals with poor functional performance 1 year following ACL reconstruction (ACLR) had 2–4 times increased risk of worsening patellofemoral bone marrow lesions (BMLs) in the following 4 years.
- Less than one in five passed the functional performance battery ($\geq 90\%$ limb symmetry index on all four tests) 1 year after ACLR, highlighting a need to implement treatments capable of improving functional recovery.
- Poor functional capacity on hop testing and a one-leg rise at 1 year post-ACLR may help identify individuals at an increased risk of worsening patellofemoral BMLs, and developing early onset post-traumatic patellofemoral osteoarthritis.

How might it impact on clinical practice in the future?

- Clinicians should evaluate patient-specific barriers and enablers to implement evidence-based rehabilitation, given only 18% passed the functional test battery at 1 year post-ACLR.
- Regardless of an individual's desire to return-to-sport, restoring lower-limb function may be important to mitigate the risk of future joint degeneration.

CONCLUSION

Only one in five participants met common functional performance criteria ($\geq 90\%$ LSI all four tests) 1 year post-ACLR. Poor function was consistently associated with 2–4 times increased risk of worsening patellofemoral (but not tibiofemoral) BMLs. These results highlight the importance of optimising function beyond the short-term re-injury risk, as functional performance may help identify individuals on an accelerated trajectory towards (patellofemoral) radiographic OA.

Patient and public involvement

There were no funds or time allocated for patient and public involvement so we were unable to involve patients. We have invited patients to our knowledge translation events, to help inform our dissemination strategy and future research questions.

Twitter Brooke Patterson @Knee_Howells and Christian J Barton @DrChrisBarton

Acknowledgements The authors would like to thank all the participants, Imaging@Olympic Park for assistance in obtaining all MRIs and Olympic Park Sports Medicine Centre for use of their facility for clinical data collection.

Contributors BP, AG and KAC conceived and designed the study. HGM and TSW assisted with recruitment of participants. BP, JS and AGC conducted the statistical analysis and interpretation of data, with input from CB and KMC. BP drafted the manuscript with input from AG, CJB, KAC, JS, HGM, TSW and KAC. All authors have read and approved the final manuscript.

Funding Support for this study was provided by Arthritis Australia, La Trobe University Sport, Exercise and Rehabilitation Research Focus Area, the Queensland Orthopaedic Physiotherapy Network, the University of Melbourne (Research Collaboration grant) and the University of British Columbia Centre for Hip Health and Mobility (Society for Mobility and Health). BP was the recipient of the Felice Rosemary-Lloyd Travel Scholarship, which assisted with travel and data analysis to visit coauthor JS at the University of Delaware. BP, AC and CB are recipients of National Health and Medical Research Council awards (post-graduate scholarship No. 1114296, Neil Hamilton Fairley Clinical Fellowship No. 1121173 and MRFF Translating Research into Practice No. 11163250, respectively). JS is supported by a NIH/NIGMS grant U54-GM104941.

Competing interests AG received consulting fees for grading of MRI images at baseline and follow-up. He is a shareholder of Boston Imaging Core Lab (BICL) and a consultant to Merck Serono, Pfizer, GE Healthcare, Galapagos, Roche and TissueGene.

Patient consent for publication Not required.

Ethics approval Ethical approval was granted by the La Trobe University Human Ethics Committee (HEC15-100) and all participants signed informed consent.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request. The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request. Reuse will be permitted by the corresponding author, and can occur up until 2027, which corresponds with the conditions of the La Trobe University Human Ethics committee that indicates data will be kept for at least 10 years following completion of data collection.

Open access This is an open access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited, appropriate credit is given, any changes made indicated, and the use is non-commercial. See: <http://creativecommons.org/licenses/by-nc/4.0/>.

ORCID iDs

Brooke Patterson <http://orcid.org/0000-0002-6570-5429>
Adam Geoffrey Culvenor <http://orcid.org/0000-0001-9491-0264>
Christian J Barton <http://orcid.org/0000-0002-3545-5094>
Ali Guerhazi <http://orcid.org/0000-0002-9374-8266>
Kay M Crossley <http://orcid.org/0000-0001-5892-129X>

REFERENCES

- 1 Lohmander LS, Östenberg A, Englund M, *et al*. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum* 2004;50:3145–52.

- 2 Poulsen E, Goncalves GH, Bricca A, *et al.* Knee osteoarthritis risk is increased 4-6 fold after knee injury – a systematic review and meta-analysis. *Br J Sports Med* 2019;53:1454–63.
- 3 Lie MM, Risberg MA, Storheim K, *et al.* What's the rate of knee osteoarthritis 10 years after anterior cruciate ligament injury? An updated systematic review. *Br J Sports Med* 2019;53:1162–7.
- 4 Øiestad BE, Holm I, Gunderson R, *et al.* Quadriceps muscle weakness after anterior cruciate ligament reconstruction: a risk factor for knee osteoarthritis? *Arthritis Care Res* 2010;62:1706–14.
- 5 Culvenor AG, Collins NJ, Guermazi A, *et al.* Early knee osteoarthritis is evident one year following anterior cruciate ligament reconstruction: a magnetic resonance imaging evaluation. *Arthritis Rheumatol* 2015;67:946–55.
- 6 van Meer BL, Oei EHG, Meuffels DE, *et al.* Degenerative changes in the knee 2 years after anterior cruciate ligament rupture and related risk factors: a prospective observational follow-up study. *Am J Sports Med* 2016;44:1524–33.
- 7 Patterson BE, Culvenor AG, Barton CJ, *et al.* Worsening knee osteoarthritis features on magnetic resonance imaging 1 to 5 years after anterior cruciate ligament reconstruction. *Am J Sports Med* 2018;46:2873–83.
- 8 Sharma L, Nevitt M, Hochberg M, *et al.* Clinical significance of worsening versus stable preradiographic MRI lesions in a cohort study of persons at higher risk for knee osteoarthritis. *Ann Rheum Dis* 2016;75:1630–6.
- 9 Abrams GD, Harris JD, Gupta AK, *et al.* Functional performance testing after anterior cruciate ligament reconstruction. *Orthop J Sports Med* 2014;2:232596711351830.
- 10 Øiestad BE, Juhl CB, Eitzen I, *et al.* Knee extensor muscle weakness is a risk factor for development of knee osteoarthritis. A systematic review and meta-analysis. *Osteoarthritis Cartilage* 2015;23:171–7.
- 11 Palmieri-Smith RM, Lepley LK. Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. *Am J Sports Med* 2015;43:1662–9.
- 12 Gardinier ES, Di Stasi S, Manal K, *et al.* Knee contact force asymmetries in patients who failed return-to-sport readiness criteria 6 months after anterior cruciate ligament reconstruction. *Am J Sports Med* 2014;42:2917–25.
- 13 Roos EM, Arden NK. Strategies for the prevention of knee osteoarthritis. *Nat Rev Rheumatol* 2016;12:92–101.
- 14 Hart HF, Culvenor AG, Guermazi A, *et al.* Worse knee confidence, fear of movement, psychological readiness to return-to-sport and pain are associated with worse function after ACL reconstruction. *Physical Therapy in Sport* 2019.
- 15 Pinczewski LA, Lyman J, Salmon LJ, *et al.* A 10-year comparison of ACLR with hamstring tendon and patellar tendon autograft: a controlled, prospective trial. *Am J Sports Med* 2007;35:564–74.
- 16 Losciale JM, Bullock G, Cromwell C, *et al.* Hop testing lacks strong association with key outcome variables after primary anterior cruciate ligament reconstruction: a systematic review. *Am J Sports Med* 2019;363546519838794.
- 17 Wellsandt E, Axe MJ, Snyder-Mackler L. Poor performance on Single-Legged hop tests associated with development of posttraumatic knee osteoarthritis after anterior cruciate ligament injury. *Orthop J Sports Med* 2018;6:232596711881077.
- 18 Culvenor AG, Lai CCH, Gabbie BJ, *et al.* Patellofemoral osteoarthritis is prevalent and associated with worse symptoms and function after hamstring tendon autograft ACL reconstruction. *Br J Sports Med* 2014;48:435–9.
- 19 Culvenor AG, Collins NJ, Vicenzino B, *et al.* Predictors and effects of patellofemoral pain following hamstring-tendon ACL reconstruction. *J Sci Med Sport* 2016;19:518–23.
- 20 Pollard TC, Gwilym SE, Carr AJ. The assessment of early OA. *J Bone Joint Surg Br* 2008;90:411–21.
- 21 Hunter DJ, Zhang W, Conaghan PG, *et al.* Responsiveness and reliability of MRI in knee osteoarthritis: a meta-analysis of published evidence. *Osteoarthritis Cartilage* 2011;19:589–605.
- 22 Patterson BE, Culvenor AG, Barton CJ, *et al.* Patient-reported outcomes 1 to 5 years after ACL reconstruction: effect of combined injury, and associations with MRI-defined osteoarthritis features. *Arthritis Care Res* 2019. doi:10.1002/acr.23854. [Epub ahead of print: 14 Feb 2019].
- 23 Yusuf E, Kortekaas MC, Watt I, *et al.* Do knee abnormalities visualised on MRI explain knee pain in knee osteoarthritis? A systematic review. *Ann Rheum Dis* 2011;70:60–7.
- 24 Logerstedt D, Grindem H, Lynch A, *et al.* Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction. *Am J Sports Med* 2012;40:2348–56.
- 25 Grindem H, Logerstedt D, Eitzen I, *et al.* Single-legged hop tests as predictors of self-reported knee function in nonoperatively treated individuals with anterior cruciate ligament injury. *Am J Sports Med* 2011;39:2347–54.
- 26 Culvenor AG, Collins NJ, Guermazi A, *et al.* Early Patellofemoral osteoarthritis features one year after anterior cruciate ligament reconstruction: symptoms and quality of life at three years. *Arthritis Care Res* 2016;68:784–92.
- 27 Menzer H, Slater LV, Diduch D, *et al.* The utility of objective strength and functional performance to predict subjective outcomes after anterior cruciate ligament reconstruction. *Orthop J Sports Med* 2017;5:232596711774475.
- 28 Bodkin S, Goetschius J, Hertel J, *et al.* Relationships of muscle function and subjective knee function in patients after ACL reconstruction. *Orthop J Sports Med* 2017;5:232596711771904.
- 29 Grindem H, Eitzen I, Snyder-Mackler L, *et al.* Online registration of monthly sports participation after anterior cruciate ligament injury: a reliability and validity study. *Br J Sports Med* 2014;48:748–53.
- 30 Marx RG, Connor J, Lyman S, *et al.* Multirater agreement of arthroscopic grading of knee articular cartilage. *Am J Sports Med* 2005;33:1654–7.
- 31 Altman RD, Hochberg M, Murphy WA, *et al.* Atlas of individual radiographic features in osteoarthritis. *Osteoarthritis Cartilage* 1995;3:3–70.
- 32 Gustavsson A, Neeter C, Thomeé P, *et al.* A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. *Knee Surg Sports Traumatol Arthr* 2006;14:778–88.
- 33 Reid A, Birmingham TB, Stratford PW, *et al.* Hop testing provides a reliable and valid outcome measure during rehabilitation after ACLR. *Phys Ther* 2007;87:337–49.
- 34 Munro AG, Herrington LC. Between-session reliability of four hop tests and the agility t-test. *J Strength Cond Res* 2011;25:1470–7.
- 35 Thorstenson CA, *et al.* Reduced functional performance in the lower extremity predicted radiographic knee osteoarthritis five years later. *Ann Rheum Dis* 2004;63:402–7.
- 36 Burgi CR, Peters S, Ardern CL, *et al.* Which criteria are used to clear patients to return to sport after primary ACL reconstruction? A scoping review. *Br J Sports Med* 2019;53:1154–61.
- 37 Grindem H, Snyder-Mackler L, Moksnes H, *et al.* Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med* 2016;50:804–8.
- 38 Kyritsis P, Bahr R, Landreau P, *et al.* Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *Br J Sports Med* 2016;50:946–51.
- 39 Hunter DJ, Guermazi A, Lo GH, *et al.* Evolution of semi-quantitative whole joint assessment of knee oa: MOAKS (MRI osteoarthritis knee score). *Osteoarthritis Cartilage* 2011;19:990–1002.
- 40 Runhaar J, Schiphof D, van Meer B, *et al.* How to define subregional osteoarthritis progression using semi-quantitative MRI osteoarthritis knee score (MOAKS). *Osteoarthritis Cartilage* 2014;22:1533–6.
- 41 Collins NJ, Misra D, Felson DT, *et al.* Measures of knee function: international knee documentation Committee (IKDC) subjective knee evaluation form, knee injury and osteoarthritis outcome score (KOOS), knee injury and osteoarthritis outcome score physical function short form (KOOS-PS), knee outcome survey activities of daily living scale (KOS-ADL), Lysholm knee scoring scale, Oxford knee score (OKS), Western Ontario and McMaster universities osteoarthritis index (WOMAC), activity rating scale (ARS), and Tegner activity score (Tas). *Arthritis Care Res* 2011;63:S208–28.
- 42 Lo GH, McAlindon TE, Niu J, *et al.* Bone marrow lesions and joint effusion are strongly and independently associated with weight-bearing pain in knee osteoarthritis: data from the osteoarthritis initiative. *Osteoarthritis Cartilage* 2009;17:1562–9.
- 43 Hunter DJ, Zhang Y, Niu J, *et al.* Increase in bone marrow lesions associated with cartilage loss: a longitudinal magnetic resonance imaging study of knee osteoarthritis. *Arthritis Rheum* 2006;54:1529–35.
- 44 Everhart JS, Best TM, Flanigan DC. Psychological predictors of anterior cruciate ligament reconstruction outcomes: a systematic review. *Knee Surg Sports Traumatol Arthrosc* 2015;23:752–62.
- 45 Ebert JR, Edwards P, Yi L, *et al.* Strength and functional symmetry is associated with post-operative rehabilitation in patients following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2018;26:2353–61.
- 46 Culvenor AG, Segal NA, Guermazi A, *et al.* Sex-Specific influence of quadriceps weakness on worsening Patellofemoral and Tibiofemoral cartilage damage: a prospective cohort study. *Arthritis Care Res* 2019;71:1360–5.
- 47 Turkiewicz A, Timpka S, Thorlund JB, *et al.* Knee extensor strength and body weight in adolescent men and the risk of knee osteoarthritis by middle age. *Ann Rheum Dis* 2017;76:1657–61.
- 48 van Meer BL, Meuffels DE, van Eijlsden WA, *et al.* Which determinants predict tibiofemoral and patellofemoral osteoarthritis after anterior cruciate ligament injury? A systematic review. *Br J Sports Med* 2015;49:975–83.
- 49 Macri EM, Patterson BE, Crossley KM, *et al.* Does patellar alignment or trochlear morphology predict worsening of patellofemoral disease within the first 5 years after anterior cruciate ligament reconstruction? *Eur J Radiol* 2019;113:32–8.
- 50 Culvenor AG, Cook JL, Collins NJ, *et al.* Is patellofemoral joint osteoarthritis an under-recognised outcome of anterior cruciate ligament reconstruction? A narrative literature review. *Br J Sports Med* 2013;47:66–70.
- 51 Ericsson YB, Roos EM, Frobell RB. Lower extremity performance following ACL rehabilitation in the KANON-trial: impact of reconstruction and predictive value at 2 and 5 years. *Br J Sports Med* 2013;47:980–5.
- 52 An VV, Scholes C, Mhaskar VA, *et al.* Limitations in predicting outcome following primary ACL reconstruction with single-bundle hamstring autograft - A systematic review. *Knee* 2017;24:170–8.
- 53 Ardern CL, Österberg A, Sonesson S, *et al.* Satisfaction with knee function after primary anterior cruciate ligament reconstruction is associated with self-efficacy, quality of life, and returning to the Preinjury physical activity. *Arthroscopy* 2016;32:1631–8.

- 54 Ardern CL, Österberg A, Tagesson S, *et al.* The impact of psychological readiness to return to sport and recreational activities after anterior cruciate ligament reconstruction. *Br J Sports Med* 2014;48:1613–9.
- 55 Feucht MJ, Cotic M, Saier T, *et al.* Patient expectations of primary and revision anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2016;24:201–7.
- 56 Hart HF, Collins NJ, Ackland DC, *et al.* Is impaired knee confidence related to worse kinesiophobia, symptoms, and physical function in people with knee osteoarthritis after anterior cruciate ligament reconstruction? *J Sci Med Sport* 2015;18:512–7.
- 57 Grindem H, Arundale AJ, Ardern CL. Alarming underutilisation of rehabilitation in athletes with anterior cruciate ligament reconstruction: four ways to change the game. *Br J Sports Med* 2018;52:1162–3.
- 58 Culvenor AG, Perraton L, Guermazi A, *et al.* Knee kinematics and kinetics are associated with early patellofemoral osteoarthritis following anterior cruciate ligament reconstruction. *Osteoarthritis Cartilage* 2016;24:1548–53.
- 59 Culvenor AG, Patterson BE, Guermazi A, *et al.* Accelerated return to sport after anterior cruciate ligament reconstruction and early knee osteoarthritis features at 1 year: an exploratory study. *PM R* 2018;10:349–56.
- 60 Øiestad BE, Holm I, Risberg MA. Return to pivoting sport after ACL reconstruction: association with osteoarthritis and knee function at the 15-year follow-up. *Br J Sports Med* 2018;52:1199–204.
- 61 Whittaker JL, Roos EM. A pragmatic approach to prevent post-traumatic osteoarthritis after sport or exercise-related joint injury. *Best Pract Res Clin Rheumatol* 2019;33:158–71.
- 62 Toomey CM, Whittaker JL, Nettel-Aguirre A, *et al.* Higher fat mass is associated with a history of knee injury in youth sport. *J Orthop Sports Phys Ther* 2017;47:80–7.
- 63 Wellsandt E, Failla MJ, Snyder-Mackler L. Limb symmetry indexes can overestimate knee function after anterior cruciate ligament injury. *J Orthop Sports Phys Ther* 2017;47:334–8.
- 64 Carey DL, Crossley KM, Whiteley R, *et al.* Modeling training loads and injuries: the dangers of Discretization. *Med Sci Sports Exerc* 2018;50:2267–76.
- 65 Ardern CL, Taylor NF, Feller JA, *et al.* Sports participation 2 years after anterior cruciate ligament reconstruction in athletes who had not returned to sport at 1 year: a prospective follow-up of physical function and psychological factors in 122 athletes. *Am J Sports Med* 2015;43:848–56.