The Knee 46 (2024) 136–147

Contents lists available at ScienceDirect

The Knee

journal homepage:

Inline dynamometry provides reliable measurements of quadriceps strength in healthy and ACL-reconstructed individuals and is a valid substitute for isometric electromechanical dynamometry following ACL reconstruction

Richard Norris [a,b,*], Scot Morrison [c,d], Alan Price [a], Sian Pulford [e], Erik Meira [f], Seth O'Neill [g], Huw Williams [e], Thomas W. Maddox [b,h], Paul Carter [a], Rachel A. Oldershaw [b,i]

[a] Department of Trauma and Orthopaedics, Aintree University Hospital, Liverpool University Hospitals NHS Foundation Trust, Lower Lane, Fazakerley, Liverpool L9 7AL, United Kingdom
[b] Department of Musculoskeletal and Ageing Sciences, Institute of Life Course and Medical Sciences, Faculty of Health and Life Sciences, University of Liverpool, William Henry Duncan Building, 6 West Derby Street, Liverpool L7 8TX, United Kingdom
[c] Physio Praxis PLLC, University Place, WA, USA
[d] Department of Neuroscience, Biomedicine and Movement Sciences, University of Verona, Piazzale Ludovico Antonio Scuro 10, 37124 Verona, Italy
[e] Department of Medical Therapy and Support Services, Royal Liverpool and Broadgreen University Hospital NHS Trust, Thomas Dr, Liverpool L14 3LB, United Kingdom
[f] Physical Therapy Science Communication Group, Happy Valley, Oregon, USA
[g] School of Healthcare, Life Sciences, University of Leicester, University Road, Leicester LE1 7RH, United Kingdom
[h] Small Animal Teaching Hospital, Institute of Infection, Veterinary and Ecological Sciences, Faculty of Health and Life Sciences, University of Liverpool, Leahurst Campus, Chester High Road, Neston, Wirral CH64 7TE, United Kingdom
[i] MRC-Versus Arthritis Centre for Integrated Research into Musculoskeletal Ageing (CIMA), Institute of Life Course and Medical Sciences, Faculty of Health and Life Sciences, University of Liverpool, William Henry Duncan Building, 6 West Derby Street, Liverpool L7 8TX, United Kingdom

ARTICLE INFO

Article history:
Received 23 August 2023
Revised 11 December 2023
Accepted 12 December 2023

Keywords:
Quadriceps strength testing
Handheld dynamometry
Inline dynamometry
Knee extensor torque
Anterior cruciate ligament

ABSTRACT

Background: Quadriceps strength testing is recommended to guide rehabilitation and mitigate the risk of second injury following anterior cruciate ligament (ACL) reconstruction. Hand-held dynamometry is a practical alternative to electromechanical dynamometry but demonstrates insufficient reliability and criterion validity in healthy and ACL-reconstructed participants respectively. The purpose of this study is to investigate the reliability and concurrent validity of inline dynamometry for measuring quadriceps strength. The hypotheses are that intra-class correlation coefficient (ICC) values will be >0.90 for reliability and concurrent validity.

Methods: This was a cross sectional study using a within-participant, repeated measures design. Isometric quadriceps testing was performed at 60° knee flexion in 50 healthy and 52 ACL-reconstructed participants. Interrater reliability, intrarater reliability, and concurrent validity of inline dynamometry was investigated through calculation of ICCs, Bland-Altman analysis, linear regression, standard error of measurement (SEM) and minimal detectable change (MDC).

Results: The lower bounds of the 95% confidence intervals were >0.90 for all reliability and validity ICCs in healthy and ACL-reconstructed participants, except for intrarater reliability in healthy participants using absolute scores (ICC = 0.936 [95% CI 0.890–0.963]). In ACL-reconstructed participants, Bland-Altman bias was 0.01 Nm/kg for absolute and average

* Corresponding author at: Department of Trauma and Orthopaedics, Aintree University Hospital, Liverpool University Hospitals NHS Foundation Trust, Lower Lane, Fazakerley, Liverpool, L9 7AL, United Kingdom.
E-mail address: Richard.Norris2@liverpoolft.nhs.uk (R. Norris).

https://doi.org/10.1016/j.knee.2023.12.006

scores, limits of agreement were −11.74% to 12.59% for absolute scores, the SEM was 0.13Nm/kg (95% CI 0.10–0.17) and the MDC was 0.36Nm/kg (95% CI 0.28 – 0.47).
Conclusion: Inline dynamometry is a reliable and economical alternative to electromechanical dynamometry for the assessment of quadriceps strength following ACL-reconstruction.
Clinical trial registration number: ClinicalTrials.gov (NCT05109871)

1. Introduction

Anterior cruciate ligament (ACL) injuries are common with a median annual incidence of 0.03% per person overall and up to 3.7% in professional athletes [1]. Surgical reconstruction of a torn ACL is indicated for patients reporting persistent knee instability [2,3], with an estimated 30,000 primary surgical reconstructions performed in England each year [4]. In the United States, approximately 130,000 ACL-reconstructions are performed annually, with an incidence rate that has risen over the last two decades [5,6].

Following ACL-reconstruction, recovery of quadriceps strength is an important criterion that informs clinical decision making [7–9] including return to running [10] and return to play (RTP) [11,12]. Pre-injury (healthy) values provide the most accurate reference to evaluate post-operative recovery, but these data are rarely available [13]. In the absence of pre-injury data, normative values from matched controls and between-limb strength symmetry are recommended as proxy measures [13–15]. Strength symmetry is typically calculated by dividing the operated limb scores by the unoperated limb scores and converting to a percentage, though other methods exist [16]. Quadriceps strength deficits can persist in patients that pass functional RTP tests (e.g., hop for distance) [17–19], and are associated with an increased risk of second ACL injury [11,12], reduced self-reported knee function [20–22], and knee osteoarthritis [23], highlighting the importance of measuring quadriceps strength specifically.

Electromechanical dynamometry (ED), in either isometric or isokinetic mode, is considered the gold-standard method of quantifying quadriceps strength [24]. Quadriceps strength is expressed as peak knee extensor torque, with peak torque values produced at approximately 60° knee flexion [25,26]. ED can detect small, clinically relevant changes (<10%) in strength [27] but is cost prohibitive, time consuming [28], and lacks portability [29]. 'Push-type' handheld dynamometry (HHD), which measures the pushing force applied to a sensor, is a more affordable and practical option but has been shown to underestimate quadriceps strength by almost 30% at 60° knee flexion when stability is provided by the tester [30]. Belt stabilisation is required for stronger individuals [31,32], which precludes testing at 60° knee flexion due to slippage of the device and non-perpendicular forces being applied to the gauge [24]. For practical purposes, belt-stabilised HHD is therefore performed at 90° knee flexion [24] but this method is not recommended for measuring quadriceps strength in healthy individuals based on estimates of reliability [27,33].

Following ACL-reconstruction, isometric-ED (at 60° knee flexion) or isokinetic-ED are the preferred methods of assessing quadriceps strength [9], with HHD considered an alternative when ED is not accessible [9,34]. Belt-stabilised HHD at 90° knee flexion demonstrates excellent test–retest reliability and 100% specificity for detecting strength asymmetry greater than 10% in ACL-reconstructed patients [35]. However, estimates of criterion validity are considered insufficient [34], with belt-stabilised HHD underestimating isokinetic-ED values by almost 20% [35]. Furthermore, strength symmetry can be misleading and should not be used in isolation to evaluate quadriceps strength recovery [13,36]. Peak knee extensor torque, normalised to body mass, is a stronger predictor of self-reported knee function [20,21], and should be considered alongside symmetry when an individual's pre-injury data are not available for reference [13–15]. A practical and reliable measure of peak knee extensor torque, which also demonstrates high concurrent validity, is therefore required to inform clinical decision-making following ACL-reconstruction, especially when ED is inaccessible.

'Pull-type' inline dynamometers are set up to measure the tensile pulling force passing through a load cell; these devices are also known as traction dynamometers or strain gauges. Inline dynamometry has been shown to demonstrate higher estimates of validity than belt-stabilised HHD in healthy individuals [29], but the reliability and validity of inline dynamometry for measuring peak knee extensor torque has not been investigated in participants following ACL-reconstruction, or at 60° knee flexion. The primary objectives of this study are to investigate the reliability of inline dynamometry in healthy and ACL-reconstructed individuals, and the validity of inline dynamometry in ACL-reconstructed individuals for measuring peak isometric knee extensor torque at 60° knee flexion. Based on previous inline dynamometry studies demonstrating intra-class coefficient (ICC) values above 0.90 [29,37], the hypotheses are that ICC values will be > 0.90 for interrater and intrarater reliability, and concurrent validity. The secondary objectives are to determine whether there is a significant difference in pain, and time taken to perform testing, between the two measurement methods in ACL-reconstructed individuals.

Inline dynamometry will be performed using an operator-independent dynamometer (KForce Link, Kinvent) by two physiotherapists with varying amounts of inline dynamometry experience. Normative reference values will be obtained from healthy participants.

2. Material and methods

2.1. Study design

This was a cross sectional study using a within-participant, repeated measures design that was approved by the Trust and NHS ethics committees. The study was registered *a priori* on ClinicalTrials.gov (NCT05109871), and conducted in accordance with the ethical standards of the World Medical Association Declaration of Helsinki (2002) and Consensus-based Standards for the selection of health Measurement Instruments (COSMIN) recommendations [38]. The study is reported using the Guidelines for Reporting Reliability and Agreement Studies (GRRAS) [39] and CHecklist for statistical Assessment of Medical Papers (CHAMP) [40].

2.2. Sample size

For assessment of reliability, to ensure with 80% power that the width of the 95% confidence interval (CI) is 0.20 when the anticipated ICC value is 0.85 or higher, a sample size of 45 was calculated based on values reported in a previous 'pull-type' dynamometer study [37]. For assessment of validity, to ensure with 80% power that the width of the 95% CI is 0.30 when the anticipated ICC value is 0.75 or higher, a sample size of 45 was calculated. To account for possible participant attrition (10%) and to meet the COSMIN recommendations for a 'good' sample size [38], both samples were increased to a minimum of 50 participants (total $\geq$100).

2.3. Study population

For interrater and intrarater reliability in healthy individuals, a quota sample of healthy staff, of different age and sporting activity levels, was recruited from Liverpool University Hospitals, NHS Foundation Trust (LUHFT). For intrarater reliability and concurrent validity in an ACL-reconstructed cohort, consecutive patients presenting to an orthopaedic outpatient clinic following ACL-reconstruction were recruited from LUHFT.

2.4. Inclusion and exclusion criteria

Potential participants were approached by direct invitation and deemed eligible for inclusion if they were willing and able to give informed consent, and aged 18 years or above. For the healthy cohort, participants must have reported no current or previous history of significant lower limb injury, no history of previous minor injury that was symptomatic at the time of recruitment/testing, and no previous lower limb surgery on the leg to be tested. For the ACL-reconstructed cohort, participants must have undergone ACL-reconstruction surgery, with or without additional meniscal repair or excision; participants with concomitant knee ligament reconstruction or non-meniscal surgical procedures (e.g., osteotomy, microfracture) were excluded.

Participants could not enter the study if they had any medical condition that might hinder their ability to perform maximal strength testing or put themselves at risk by participating (**Supplemental Section 1**). Participants that failed to attend any of the designated testing sessions or reported unacceptable pain during testing, defined as $\geq$ 6/10 on a visual analogue scale (VAS) [9], were excluded. Once informed consent was obtained, relevant testing sessions were conducted in an LUHFT physiotherapy department.

2.5. Testing procedure

Inline dynamometry was performed using the KForce Link (300 kg [2942 N] force capacity) and KForce Pro iOS application (Kinvent, Montpellier, France). Isometric-ED was performed using the HUMAC NORM Cybex with HUMAC 2015 software (CSMI Medical Solutions, Stoughton, MA, USA). The procedure for inline dynamometry (**Supplemental Video 1**) and isometric-ED was standardised. The order of testing between assessors and devices was randomised to control for potential sources of systematic error including fatigue [37] and a learning effect [30] using an online random number generator (https://www.random.org/lists).

For healthy participants, the dominant leg was used for testing; if the participant was unsure of leg dominance, this was determined by asking which leg they would use to kick a ball [41]. For ACL-reconstructed participants, the operated leg was used for testing as documented in the operation notes and confirmed during clinical examination. Testing was not performed until at least 12-weeks after ACL-reconstruction, to allow adequate time for the resolution of pain and effusion, and to coincide with criterion-based milestones (e.g., return to running) [9].

2.5.1. Inline dynamometry (*Figure 1**A and Supplemental Video 1***)

A three-panel, height-adjustable plinth (AKRON, Ipswich, UK) was placed side on against a wall with the end panels removed to allow the participant to grip the sides. The participant sat on the centre panel of the plinth with a six-inch, soft plyometric box (Jordan, Norfolk, UK) placed behind them acting as a back rest. A dense foam pad (green TheraBand® stability

trainer, Akron, OH, USA) and small folded towel was placed under the distal thigh to maintain a horizontal thigh position and maximise comfort during testing. An 11 cm wide Velcro ankle strap with double D-rings (Kinvent, Montpellier, France) was attached securely to the leg with the distal end of the straps resting immediately proximal to the medial malleolus. Via two carabiners (Kinvent, Montpellier, France), one end of the dynamometer was connected to the D-rings of the ankle strap and the other end to an adjustable, rigid strap (Kinvent, Montpellier, France) that was looped around the furthest perpendicular metal bar of the plinth, in line with the leg.

Whilst sat in an upright position, gripping the sides of the plinth to prevent the pelvis from lifting [29,30], the participant was asked to slowly extend their knee until all slack was taken up in the straps. The plinth height and strap length were adjusted until the knee was positioned at 70° flexion and the rigid strap at an angle of 100° to the shin, measured by a plastic 30 cm goniometer. These angles were chosen to account for the small decrease in knee flexion (approximately 10°) noted during maximal-effort isometric knee extension [42]. The practice trials were used to confirm that the knee was at 60° flexion, and the inline dynamometer/strap perpendicular to the shin, during the 100% maximal effort. If the angles were not correct, the plinth height and straps were adjusted accordingly. The moment arm was recorded by measuring the distance from the lateral epicondyle of the femur [43] to the centre of the ankle strap, to the nearest half centimetre. These measurements were obtained with the knee relaxed over the edge of the bed, using a tape measure, and converted to metres.

2.5.2. Isometric-ED (*Figure 1**B***)

Isometric-ED was performed using the relevant testing mode (isometric knee extension at 60°) with gravity correction. The participant sat on the chair with trunk, pelvis and thigh straps fastened securely. The backrest was adjusted until the back of the knee was overhanging the end of the seat by approximately 2 cm (finger width), as measured by the assessor's hand. To ensure the axis of the knee was aligned with the axis of the device during maximal testing, the dynamometer and seat were adjusted until the lateral epicondyle of the femur was positioned approximately 2.5 cm above, and in front of, the axis of the dynamometer. This was to account for the small change in knee position (downwards and backwards) during maximal-effort isometric knee extension [42]. The pad of the lever arm was positioned 2 cm above the lateral malleolus, checked for comfort, and adjusted if required. The limb was then weighed for gravity correction. The participant was instructed to grab the handles to prevent the pelvis from lifting during testing.

2.5.3. Measurement of peak knee extensor torque

For both testing methods, three practice trials (50%, 75% and 100% maximal effort) were performed to familiarise the participant with the procedure and to screen for pain. If pain was reported as ≥6/10 on a VAS, no further testing was performed, and they were excluded from the study.

During testing, the participant was asked to extend their knee as hard as possible for five seconds, with standardised verbal encouragement. To avoid jolting the leg during inline dynamometry testing, the knee was passively extended by the assessor, until all slack was taken up in the strap, before the participant exerted maximal effort. A 30-second rest period was used between trials [44], monitored by the K-Force Pro iOS application (inline dynamometry) and HUMAC software (isometric-ED), with three maximal-effort trials completed per assessor and device. Force-time curves were inspected visually after each testing procedure to confirm peak torque had been achieved. If the force–time curve was still rising at the 5-second mark, testing was repeated after a 5-minute rest period and the individual was advised to push faster.

Peak force measurements for inline dynamometry were extracted from the KForce Pro iOS application in Newtons (N), multiplied by the moment arm to calculate peak torque (Nm) then divided by body mass (Nm/kg). For isometric-ED, peak

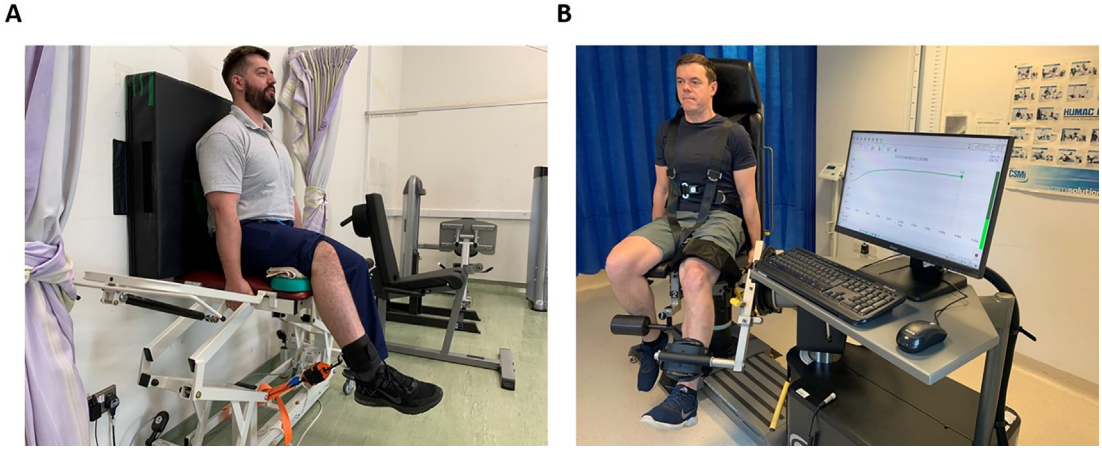

Figure 1. Representation of the testing setup. Representative images illustrating the testing setup for (A) inline dynamometry and (B) isometric electromechanical dynamometry.

torque normalised to body mass (Nm/kg) was extracted from the test summary. The sampling rate for inline dynamometry and isometric-ED were 75 Hertz (Hz) and 100 Hz respectively.

2.5.4. Measurement of time and pain

The time taken to complete each testing procedure was recorded on an iPhone stopwatch, and individuals were asked to record their pain during testing on a VAS immediately after each assessment.

2.6. Reliability

In the context of this study, reliability is defined as the extent to which scores for individuals who have not changed are the same for repeated measurement [38]. Interrater reliability reflects the variation between two or more raters who measure the same group of participants, while intrarater reliability reflects the variation of data measured by one rater across two or more trials [45].

For interrater reliability in healthy individuals, inline dynamometry was performed by Assessors A and B at the index testing session (within-session reliability). Assessor A is a physiotherapist with 19-years' clinical experience and three-years' experience using inline dynamometry. Assessor B is a physiotherapist with six-years' clinical experience but no previous experience using dynamometry. Assessor B received adequate training from Assessor A before data collection was initiated. A 5-minute rest period was used between assessors to allow adequate recovery [29].

For intrarater reliability in healthy individuals, the testing procedure was repeated by Assessor A seven days after the index test (between-session reliability). This timeframe was considered appropriate to maintain the independence of administrations [46] whilst precluding significant changes in strength. All participants were encouraged to continue their usual weekly activities between testing sessions, but to avoid significant changes in load, which may affect fatigue levels and subsequent ability to generate force. Consistent activity levels were confirmed by each participant via direct questioning before retesting.

The three maximal-effort test scores were used to determine the intrarater reliability of inline dynamometry in ACL-reconstructed individuals, which were 30-seconds apart (within-session reliability). This timeframe was considered suitable as 30-seconds has been shown to allow sufficient recovery between repetitions when measuring peak quadriceps torque [44] and a one-week interval may result in changes in scores that could be attributed to the volatility of recovery rather than measurement error.

2.7. Concurrent validity

Inline dynamometry and isometric-ED were performed within the same testing session by Assessors A and C respectively (within-session validity). Assessor C is an assistant practitioner with a degree in sports and exercise science, eight-years' experience using ED, and six-years' clinical experience. A 5-minute rest period was used between devices to allow adequate recovery [29].

2.8. Blinding

Knee extensor torque scores were obtained independently with each assessor blinded to the other assessor's measurements until testing was complete. Participants were also blinded to their scores until all testing was complete. For intrarater reliability in healthy participants, Assessor A was blinded to the force values during retesting by using the auditory cues from the KForce Pro iOS application only.

2.9. Data analysis

All statistical analyses were performed using SPSS 25.0 (SPSS Inc, Chicago, Illinois, USA) and R (R version 3.2.0, The R Foundation for Statistical Computing). Continuous variables were assessed for normality using graphical analysis (construction of histograms and normal Q-Q plots), and through the Kolmogorov-Smirnov and Shapiro-Wilk tests. Data are presented for absolute (maximum of three trials) and average scores (mean of three trials) as average scores provide a more reliable measure [47] but absolute values are often used to quantify strength and inform clinical decision making [14].

Reliability and concurrent validity were assessed through calculation of the ICC with 95% CIs reported. For interrater reliability and concurrent validity, a two-way random effects model for absolute agreement based on single ratings ($ICC_{2,1}$) was used for absolute scores and multiple ratings ($ICC_{2,3}$) for average scores [45]. For intrarater reliability, a two-way mixed effects model for absolute agreement based on single ratings ($ICC_{3,1}$) was used for absolute scores and multiple ratings ($ICC_{3,3}$) for average scores [45]. The ICCs were categorised as 'poor' if less than 0.50, 'moderate' between 0.50–0.75, 'good' between 0.75–0.90, and 'excellent' if greater than 0.90 [45].

Scatter plots were created to illustrate the spread of data on the X and Y axes, relative to a 45° line of 'perfect fit', with a regression line overlayed and R^2 values calculated. Bland-Altman plots were constructed with bias and limits of agreement (LOA) reported. Evidence for fixed and proportional bias was assessed via ordinary least squares (OLS) regression of the difference in scores on the mean of scores [48], with the null hypothesis that the slope of this line equals zero, and the 95% CIs

for the Y intercept and slope coefficients would include zero. Measurement error was also expressed as standard error of measurement (SEM) [46] and calculated as SD $\times\sqrt{}$(1-ICC), where SD is the standard deviation of the test and retest scores combined. The minimal detectable change (MDC) was calculated as 1.96 $\times\sqrt{}2 \times$ SEM [46].

The difference between pain during inline dynamometry and ED was determined using a paired t-test. The difference between time taken to complete each method was determined using a related-samples Wilcoxon Signed Rank test, with median values and interquartile ranges (IQR) provided.

3. Results

Fifty participants were recruited to determine the interrater and intrarater reliability of inline dynamometry in a healthy cohort (Table 1); no participants were excluded from the study (0%). Fifty-six participants were recruited to determine the intrarater reliability and concurrent validity of inline dynamometry following ACL-reconstruction. Four (7.1%) participants were excluded due to non-attendance; therefore 52 participants were included in the study (Table 1). For both cohorts, no adverse events were reported during testing and no data were missing (0%). There was no significant difference in age, mass, height, or BMI between the healthy and ACL-reconstructed cohorts, except for age in female participants ($p = 0.042$) (Table 1).

The median Tegner Actvity Scale level for healthy participants was 5.5 (IQR 3.0 [4.0 – 7.0]) (**Supplemental Table 1**). Hamstrings (semitendinosus/gracilis) grafts were used for all ACL-reconstructions with 23 (44.2%) participants undergoing concomitant meniscal procedures (**Supplemental Table 2**). The median time from surgery was 15.9-weeks (IQR 29.0 [13.1–42.1]). Inline dynamometry and isometric-ED torque values, normalised to body mass, are presented in Table 2 with corresponding force and torque values presented in **Supplemental Table 3**.

3.1. Interrater reliability

The ICC values in healthy participants were excellent for absolute (0.967 [95% CI 0.943–0.981]) and average inline dynamometry scores (0.976 [95% CI 0.958–0.986]). Linear regression R^2 was 0.94 for absolute scores and 0.91 for average scores (**Supplemental Figure 1A and Supplemental Figure 2A**). Bland-Altman bias was 0.02 Nm/kg for absolute (Figure 2**A**) and average scores (Figure 2**B**) with LOA between −10.17% to 11.94% for absolute scores and −11.37% to 13.26% for average scores (**Supplemental Figure 3**A **and B**). The 95% CIs for the Y axis intercept and slope coefficients of the OLS regression lines contained zero, therefore no fixed or proportional bias was evident for absolute or average scores (**Supplemental Table 4**).

3.2. Intrarater reliability

In healthy participants, ICC values were good-to-excellent for absolute inline dynamometry scores and excellent for average inline dynamometry scores (Table 3). In ACL-reconstructed participants, ICC values were excellent for inline dynamometry and isometric-ED scores (Table 3). The SEM and MDC of inline dynamometry were lower for average scores than absolute scores in healthy participants (Table 3).

Linear regression R^2 was 0.88 for absolute scores and 0.86 for average scores (**Supplemental Figure 1B and Supplemental Figure 2B**). Bland-Altman bias was −0.05 Nm/kg for absolute scores (Figure 3**A**) and −0.04 Nm/kg for average scores (Figure 3**B**), with LOA between −17.24% to 13.27% for absolute scores and −16.64% to 13.80% for average scores (**Supplemental Figure 4A and B**). The 95% CIs for the Y axis intercept and slope coefficients of the OLS regression lines contained zero, therefore no fixed or proportional bias was evident for absolute or average scores (**Supplemental Table 4**).

3.3. Validity

The ICCs for validity were excellent for absolute (0.969 [95% CI 0.947–0.982]) and average scores (0.977 [95% CI 0.960–0.987]). Linear regression R^2 was 0.94 for absolute scores and 0.91 for average scores (**Supplemental Figure 1C and Supple-**

Table 1
Demographics for healthy and ACL-reconstructed participants. Data of participant demographics are presented as mean values with standard deviations in parentheses.

	Healthy cohort			ACL reconstruction cohort			p value	
	All (n = 50)	Female (n = 25)	Male (n = 25)	All (n = 52)	Female (n = 5)	Male (n = 47)	Female	Male
Age [years]	26.8 (5.2)	26.7 (6.2)	26.9 (4.2)	28.3 (8.0)	28.0 (12.2)	28.3 (7.6)	0.042	0.773
Mass [kg]	71.1 (12.3)	63.7 (9.1)	78.4 (10.6)	82.1 (16.4)	68.4 (15.9)	83.6 (15.9)	0.364	0.173
Height [m]	1.74 (0.10)	1.67 (0.06)	1.80 (0.09)	1.80 (0.07)	1.69 (0.07)	1.81 (0.06)	0.430	0.586
BMI [kg/m^2]	23.5 (3.2)	22.9 (3.5)	24.1 (2.9)	26.3 (5.2)	25.0 (5.7)	26.4 (5.2)	0.276	0.044

ACL: anterior cruciate ligament, BMI: body mass index, kg: kilograms, m: metres.

Table 2
Absolute and average peak knee extensor torque divided by body mass.

Cohort	Testing session	Absolute peak torque/BM **[Nm/kg]** (SD)			Average peak torque/BM **[Nm/kg]** (SD)		
		All	Female	Male	All	Female	Male
Healthy	ID Assessor A (*n = 50*)	**3.12** (0.66)	**2.81** (0.52)	**3.44** (0.64)	**2.99** (0.62)	**2.72** (0.52)	**3.27** (0.60)
	ID Assessor B (*n = 50*)	**3.10** (0.68)	**2.79** (0.53)	**3.41** (0.67)	**2.97** (0.65)	**2.69** (0.54)	**3.24** (0.64)
	ID Re-test (*n = 50*)	**3.17** (0.64)	**2.88** (0.50)	**3.46** (0.65)	**3.03** (0.63)	**2.76** (0.52)	**3.30** (0.63)
ACLR	ID (n = 52)	**2.66** (0.66)	**2.39** (0.72)	**2.69** (0.66)	**2.56** (0.63)	**2.24** (0.64)	**2.60** (0.63)
	Isometric-ED (n = 52)	**2.65** (0.66)	**2.34** (0.57)	**2.69** (0.67)	**2.55** (0.63)	**2.27** (0.57)	**2.58** (0.63)

ACLR: ACL reconstruction, BM: body mass, ED: electromechanical dynamometry, ID: inline dynamometry, Nm/kg: Newton-metres per kilogram, SD: standard deviation.

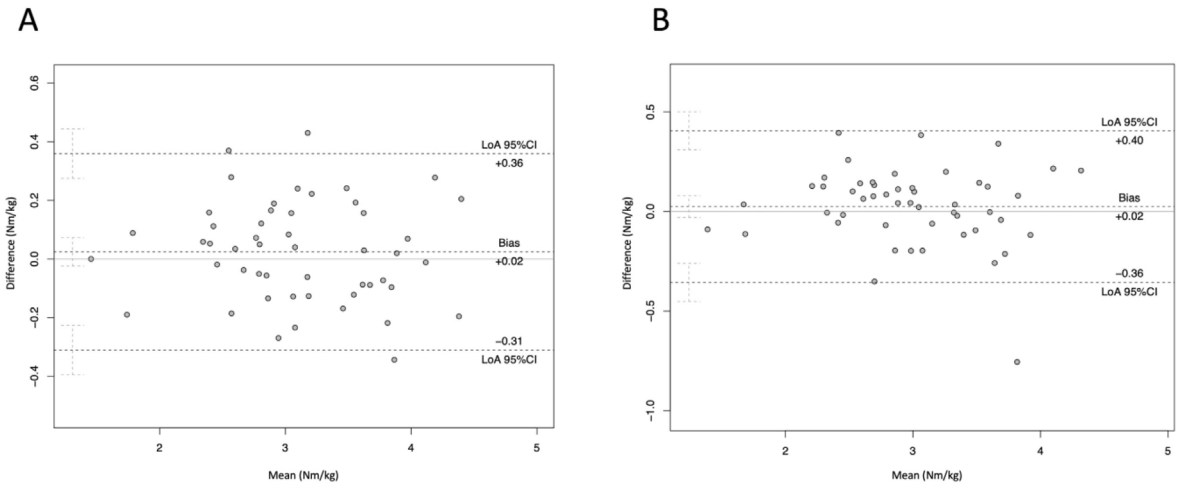

Figure 2. Interrater reliability of inline dynamometry in healthy participants. (A) Bland-Altman plot of absolute scores and (B) average scores. LOA: limits of agreement. Nm/kg: Newton-metres per kilogram.

Table 3
Intrarater reliability of inline dynamometry and isometric electromechanical dynamometry (ED) in healthy participants and ACL-reconstructed participants.

Cohort	**Testing method**	**ICC** [95% CI]	**SEM (Nm/kg)** [95% CI]	**MDC (Nm/kg)** [95% CI]
Healthy	ID (absolute scores)	**0.936** [0.890–0.963]	**0.16** [0.12–0.21]	**0.45** [0.35–0.59]
(n = 50)	ID (average scores)	**0.961** [0.932–0.978]	**0.12** [0.09–0.16]	**0.34** [0.26–0.45]
ACLR	ID	**0.958** [0.930–0.975]	**0.13** [0.10–0.17]	**0.36** [0.28–0.47]
(n = 52)	Isometric-ED	**0.967** [0.947–0.980]	**0.12** [0.09–0.15]	**0.32** [0.25–0.41]

ACLR: anterior cruciate ligament reconstruction, CI: confidence intervals, inline dynamometry (ID), ICC: intra-class correlation coefficient, MDC: minimal detectable change, Nm/kg: Newton-metres per kilogram, SEM: standard error of measurement.

mental Figure 2C). Bland-Altman bias was 0.01 Nm/kg for absolute (Figure 4**A**) and average scores (Figure 4**B**) with LOA between −11.74% to 12.59% for absolute scores and −14.28% to 15.25% for average scores (**Supplemental Figure 5A and B**). The 95% CIs for the Y axis intercept and slope coefficients of the OLS regression lines contained zero, therefore no fixed or proportional bias was evident for absolute or average scores (**Supplemental Table 4**).

3.4. Pain

No participants recorded pain ≥ 6/10 on a VAS. Any pain experienced was at the knee, with no pain reported at the interface/ankle strap. There was no significant difference (p = 0.164) in pain scores between inline dynamometry (median 1.0, IQR 2.0 [0.0–2.0]) and isometric-ED (median 1.0, IQR 3.0 [0.0–3.0]). One participant (1.9%) reported increased pain and effusion in the ACL-reconstructed knee within 24-hours of testing, which resolved with appropriate management. This individual was 12-weeks and 2-days following isolated ACL-reconstruction (ipsilateral hamstrings autograft), with a VAS of 5/10 on both devices.

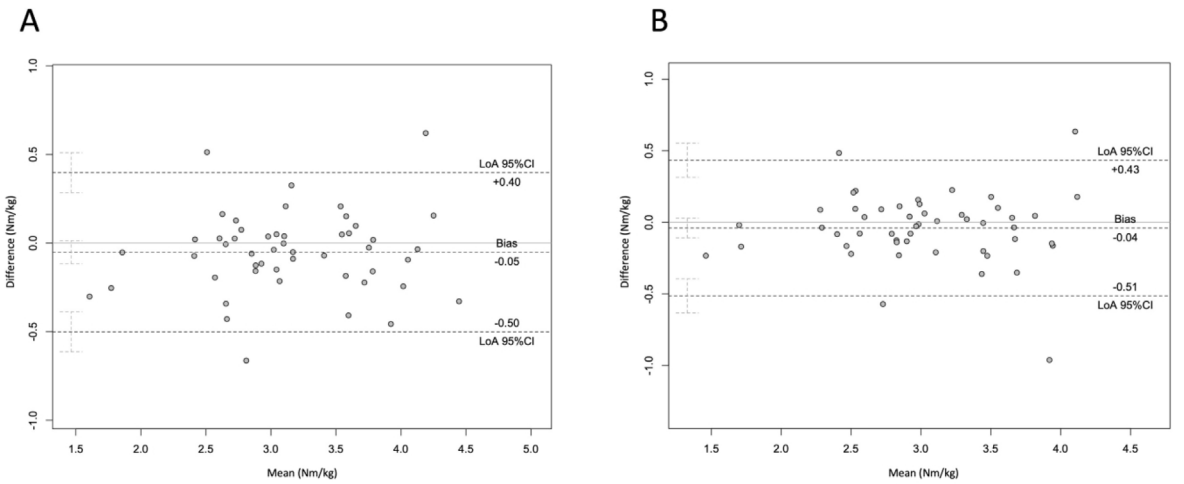

Figure 3. Intrarater reliability of inline dynamometry in healthy participants. (A) Bland-Altman plot of absolute scores and (B) average scores. LOA: limits of agreement. Nm/kg: Newton-metres per kilogram.

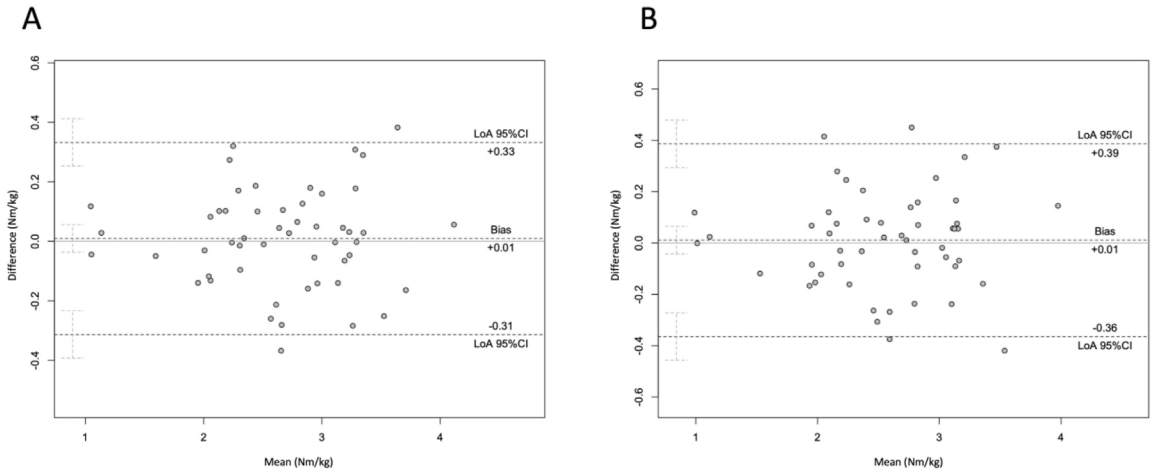

Figure 4. Validity of inline dynamometry in ACL-reconstructed participants. (A) Bland-Altman plot of absolute scores and (B) average scores. LOA: limits of agreement. Nm/kg: Newton-metres per kilogram.

3.5. Time

The mean time taken to complete testing was 3-minutes 43 seconds (SD = 42.9 seconds) for inline dynamometry and 6-minutes 20 seconds (SD = 39.0 seconds) for isometric-ED; the difference in time was statistically significant ($p < 0.001$).

4. Discussion

The most important findings from the current study are inline dynamometry, performed at 60° knee flexion, provides reliable measurements of quadriceps strength in healthy and ACL-reconstructed individuals. Based on the estimates for concurrent validity, this method can also be recommended as a valid alternative to isometric-ED following ACL-reconstruction. There was no evidence of fixed or proportional bias for inline dynamometry. Since all ICC scores for reliability and concurrent validity exceed 0.90, the hypotheses were accepted.

Clinical practice guidelines advocate quadriceps strength measurement following ACL-reconstruction to guide rehabilitation and mitigate the risk of second ACL injury [8,9]. Despite this, fewer than half of physiotherapists use instrumented strength testing [49,50]. This is understandable as gold-standard ED is cost prohibitive [28] and the only published systematic review with meta-analysis suggests that current HHD methods demonstrate insufficient criterion validity in ACL-reconstructed patients [34]. A practical and reliable method of measuring quadriceps strength, which also demonstrates suf-

ficient concurrent validity, is therefore required to make valid clinical decisions, and facilitate compliance with clinical practice guidelines when gold-standard methods are inaccessible.

Reliability is a characteristic of an instrument used in a population, not just the instrument itself, and should therefore be investigated in a sample in which the measurement instrument is to be used [47]. The reliability of inline dynamometry was evaluated in both healthy and ACL-reconstructed individuals as routine collection of pre-injury (healthy) data is recommended to determine rehabilitation status following ACL-reconstruction [13]. Where pre-injury data is not available, pre-operative uninvolved (healthy) limb scores and normative (healthy control) data can be used alongside post-operative values (peak knee extensor torque and symmetry) to inform clinical decision-making [13–15].

In healthy individuals, interrater reliability ICCs were excellent for average and absolute scores with Bland-Altman analysis demonstrating very small mean bias and LOA <15%, indicating that this method of testing is not affected by assessor experience. Intrarater reliability ICCs were excellent for average scores and good-to-excellent for absolute scores, the latter of which is consistent with previous inline dynamometry studies performed at 90° knee flexion [29,37]. The highest mean scores were obtained at the retest session, which might indicate a learning effect. Healthy male and female absolute scores combined were consistent with target values following ACL-reconstruction (≥3.0–3.1 Nm/kg) [20,21] but female scores (2.8 Nm/kg) were lower than male scores (3.4 Nm/kg), suggesting normative values may be gender-specific. The MDC was 0.45 Nm/kg for absolute scores, which is consistent with the MDC previously reported for inline dynamometry at 90° knee flexion (0.42 Nm/kg) [29].

In ACL-reconstructed participants, ICCs for intrarater reliability and concurrent validity were excellent. Bland-Altman analysis demonstrated very small mean bias and LOA <15% for absolute scores. A recent systematic review with meta-analysis suggests that strength assessment tools should demonstrate LOA <15% before being recommended for use [27]; this is the first 'push' or 'pull-type' dynamometer study to demonstrate LOA <15% in participants following ACL-reconstruction. However, these thresholds are arbitrary and specific values should be established for quadriceps strength testing methods [34]. The MDC for inline dynamometry was 0.36 Nm/kg, which was comparable with isometric-ED (0.32 Nm/kg). The MDC for belt-stabilised HHD in ACL-reconstructed participants has previously been reported as 2.8 Nm/kg, which most likely reflects an error in calculation/reporting as the MDC was greater than the mean score [35].

Previous studies have shown that HHD positioning impacts comfort during quadriceps strength testing [51]. No participants reported pain at the interface during inline dynamometry, which may be due to the wide (11 cm) ankle strap. There were no adverse events during testing, indicating that inline dynamometry at 60° knee flexion is safe from 12-weeks following ACL-reconstruction. This is not unexpected as open chain knee extension places minimal strain on the ACL at 60° knee flexion [52]. Peak loading of the ACL occurs between 10-30° of knee flexion [52], prompting caution when introducing resisted knee extension within this range following ACL-reconstruction [53]. However, 2–3 times more strain is placed on the ACL during walking [54] and the introduction of full range resisted knee extension from 4-weeks after ACL-reconstruction has not been shown to increase hamstrings graft laxity versus closed chain exercises alone [55].

The difference in time taken to perform inline dynamometry and isometric-ED was statistically significant; for every two legs tested with isometric-ED, three legs could be tested with inline dynamometry. This time-efficient method of testing quadriceps strength may be particularly beneficial for practitioners working in sports and health care settings, where time is often constrained. Inline dynamometry is also more portable than ED, allowing quadriceps strength to be measured at point of contact, thereby avoiding any delays associated with onward referral for ED. This is particularly beneficial as testing the uninjured side as soon as possible after ACL injury provides a more accurate estimate of pre-injury capacity [36].

4.1. Strength, limitations, and clinical recommendations

To ensure the findings from the current study were practicable, strength testing was performed with a commercially available dynamometer and equipment that should be readily accessible in a clinical setting. To improve the quality of the study, the GRRAS [39] and CHAMP [40] guidelines were followed, and the sample size was increased as recommended by COSMIN [38]. Average (mean) and absolute values are presented; averaging scores demonstrated smaller measurement error in healthy individuals and is therefore recommended for this population.

Clinical practice guidelines recommend isometric quadriceps strength testing at 60° knee flexion as soon as knee range of movement allows following ACL-reconstruction [9]. Quadriceps strength testing was not performed within 12-weeks of ACL-reconstruction and future studies should investigate the efficacy of earlier implementation. All ACL-reconstructions in the current study were performed using a hamstrings graft, therefore findings may not be generalisable to other graft types. In addition, 91.4% of ACL-reconstructed participants were male, which reflects a male-dominant caseload in this cohort but limits the inference to females. The highest force recorded with inline dynamometry was 1133 N (115.5 kg) in a healthy male participant, which should be taken into consideration when testing this population, to ensure the device has sufficient force capacity.

Isokinetic-ED measures torque through range, ensuring that peak torque angles are captured, whereas inline dynamometry can only be performed where peak torque is assumed to occur (i.e., approximately 60° knee flexion). Angle specific impairments identified with isokinetic-ED may provide a focus for rehabilitation, but peak torque values alone are used to quantify an individual's strength and inform criterion-based rehabilitation [14]. Peak torque values increase as angular velocity decreases, therefore isometric testing will produce higher values at peak torque angles than concentric isokinetic-ED [56]. Quadriceps strength was not measured at different angles in the current study, therefore higher peak tor-

que values may have been attainable at different knee positions. Pincivero et al. (2004) recorded highest peak torque values at 70° knee flexion using isometric-ED in healthy participants but did not test at 60° knee flexion [43]; these values are consistent with the mean absolute inline dynamometry scores for the same cohort in the current study, both for males (3.5 Nm/kg) and females (2.7 Nm/kg) and are considerably higher than those previously reported for inline dynamometry at 90° knee flexion [29,37].

Knee extensor rate of torque development (RTD) is considered an important metric following ACL-reconstruction [15,57] and can be assessed with isometric testing [58]. In the current study, the sampling rate for inline dynamometry was 75 Hz, which is appropriate for the assessment of peak torque but insufficient to accurately measure RTD, particularly early and maximum RTD [59]. Since completion of the study, the sampling rate for the device used has increased to 1000 Hz, therefore future studies should determine whether inline dynamometry produces reliable and valid measurements of RTD.

An interval of at least one week is recommended between measurement for intrarater reliability [46]; this timeframe was utilised for healthy participants, but the three maximal effort inline dynamometry scores were used for ACL-reconstructed participants, which were 30-seconds apart. This approach has been utilised previously [35] and was deemed appropriate for the current study as ACL-reconstructed patients may exhibit considerable changes in strength measurement over a one-week period due to the volatility of recovery rather than measurement error. For example, knee pain or effusion that develops between testing sessions can inhibit the quadriceps, while specific treatment techniques can disinhibit the quadriceps [60], both of which can cause measurement interference [47]. Consequently, there was not enough time between repetitions to remove and reapply the device, which could have impacted the results. However, intrarater reliability estimates for the ACL-reconstructed group are comparable with those of the healthy cohort, where the device was removed and reapplied one week later. Future studies should investigate the intrarater reliability following device removal and reapplication, and interrater reliability in ACL-reconstructed individuals.

5. Conclusion

Inline dynamometry, performed at 60° knee flexion, provides reliable measurements of quadriceps strength in healthy individuals. In participants who were at least 12-weeks post ACL-reconstruction using a hamstrings graft, inline dynamometry provides reliable measurements of quadriceps strength, with high concurrent validity. Inline dynamometry can be recommended as a practical means of measuring quadriceps strength, to inform clinical decision making, especially when gold-standard methods are inaccessible. Inline dynamometry can be performed with equipment that should be readily accessible in a clinical setting, is safe, and takes significantly less time than electromechanical dynamometry.

6. Open access policy

This study was approved by the NHS Health Research Authority, London - Bromley Research Ethics Committee (21/PR/0738).

Public trials registry and the registration number: ClinicalTrials.gov (NCT05109871).

CRediT authorship contribution statement

Richard Norris: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Scot Morrison:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Alan Price:** Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. **Sian Pulford:** Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Erik Meira:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Seth O'Neill:** Conceptualization, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Huw Williams:** Investigation, Writing – original draft, Writing – review & editing. **Thomas W. Maddox:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Paul Carter:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Rachel A. Oldershaw:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Medical Research Council (MRC) and Versus Arthritis as part of the Medical Research Council Versus Arthritis Centre for Integrated Research into Musculoskeletal Ageing (CIMA) [MR/P020941/1]. The MRC Versus Arthritis Centre for Integrated Research into Musculoskeletal Ageing is a collaboration between the Universities of Liverpool, Sheffield and Newcastle.

This work was supported by Kinvent, through provision of the KForce Link and KForce Pro iOS application for the duration of the study. Kinvent was not involved in the design or execution of the study and did not contribute to the manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.knee.2023.12.006.

References

[1] Moses B, Orchard J. Systematic review: annual incidence of ACL injury and surgery in various populations. Res Sports Med 2012;20(3–4):157–79.
[2] Saueressig T, Braun T, Steglich N, Diemer F, Zebisch J, Herbst M, et al. Primary surgery versus primary rehabilitation for treating anterior cruciate ligament injuries: a living systematic review and meta-analysis. Br J Sports Med 2022;56(21):1241–51.
[3] Beard DJ, Davies L, Cook JA, Stokes J, Leal J, Fletcher H, et al. Rehabilitation versus surgical reconstruction for non-acute anterior cruciate ligament injury (ACL SNNAP): a pragmatic randomised controlled trial. Lancet 2022;400(10352):605–15.
[4] Abram SGF, Price AJ, Judge A, Beard DJ. Anterior cruciate ligament (ACL) reconstruction and meniscal repair rates have both increased in the past 20 years in England: hospital statistics from 1997 to 2017. Br J Sports Med 2020;54(5):286–91.
[5] Mall NA, Chalmers PN, Moric M, Tanaka MJ, Cole BJ, Bach BR, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. Am J Sports Med 2014;42(10):2363–70.
[6] Herzog MM, Marshall SW, Lund JL, Pate V, Mack CD, Spang JT. Trends in incidence of ACL reconstruction and concomitant procedures among commercially insured individuals in the United States, 2002–2014. Sports Health 2018;10(6):523–31.
[7] van Melick N, van Cingel RE, Brooijmans F, Neeter C, van Tienen T, Hullegie W, et al. Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. Br J Sports Med 2016;50(24):1506–15.
[8] Filbay SR, Grindem H. Evidence-based recommendations for the management of anterior cruciate ligament (ACL) rupture. Best Pract Res Clin Rheumatol 2019;33(1):33–47.
[9] Brinlee AW, Dickenson SB, Hunter-Giordano A, Snyder-Mackler L. ACL reconstruction rehabilitation: clinical data, biologic healing, and criterion-based milestones to inform a return-to-sport guideline. Sports Health 2021:19417381211056873.
[10] Rambaud AJM, Ardern CL, Thoreux P, Regnaux JP, Edouard P. Criteria for return to running after anterior cruciate ligament reconstruction: a scoping review. Br J Sports Med 2018;52(22):1437–44.
[11] Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med 2016;50(13):804–8.
[12] Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. 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(15):946–51.
[13] Maestroni L, Turner A, Papadopoulos K, Cohen D, Sideris V, Graham-Smith P, et al. Comparison of strength and power characteristics before ACL rupture and at the end of rehabilitation before return to sport in professional soccer players. Sports Health 2023:19417381231171566.
[14] O'Malley E, Richter C, King E, Strike S, Moran K, Franklyn-Miller A, et al. Countermovement jump and isokinetic dynamometry as measures of rehabilitation status after anterior cruciate ligament reconstruction. J Athl Train 2018;53(7):687–95.
[15] Gokeler A, Dingenen B, Hewett TE. Rehabilitation and return to sport testing after anterior cruciate ligament reconstruction: where are we in 2022? Arthrosc Sports Med Rehabil 2022;4(1):e77–82.
[16] Bishop C, Read P, Chavda S, Turner A. Asymmetries of the lower limb: the calculation conundrum in strength training and conditioning. Strength & Conditioning Journal 2016;38(6):27–32.
[17] Herrington L, Ghulam H, Comfort P. Quadriceps strength and functional performance after anterior cruciate ligament reconstruction in professional soccer players at time of return to sport. J Strength Cond Res 2018.
[18] Barfod KW, Feller JA, Hartwig T, Devitt BM, Webster KE. Knee extensor strength and hop test performance following anterior cruciate ligament reconstruction. Knee 2019;26(1):149–54.
[19] Nagai T, Schilaty ND, Laskowski ER, Hewett TE. Hop tests can result in higher limb symmetry index values than isokinetic strength and leg press tests in patients following ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 2019.
[20] Kuenze C, Hertel J, Saliba S, Diduch DR, Weltman A, Hart JM. Clinical thresholds for quadriceps assessment after anterior cruciate ligament reconstruction. J Sport Rehabil 2015;24(1):36–46.
[21] Pietrosimone B, Lepley AS, Harkey MS, Luc-Harkey BA, Blackburn JT, Gribble PA, et al. Quadriceps strength predicts self-reported function post-ACL reconstruction. Med Sci Sports Exerc 2016;48(9):1671–7.
[22] Ithurburn MP, Altenburger AR, Thomas S, Hewett TE, Paterno MV, Schmitt LC. Young athletes after ACL reconstruction with quadriceps strength asymmetry at the time of return-to-sport demonstrate decreased knee function 1 year later. Knee Surg Sports Traumatol Arthrosc 2018;26(2):426–33.
[23] Øiestad BE, Juhl CB, Culvenor AG, Berg B, Thorlund JB. Knee extensor muscle weakness is a risk factor for the development of knee osteoarthritis: an updated systematic review and meta-analysis including 46 819 men and women. Br J Sports Med 2021.
[24] Sinacore JA, Evans AM, Lynch BN, Joreitz RE, Irrgang JJ, Lynch AD. Diagnostic accuracy of handheld dynamometry and 1-repetition-maximum tests for identifying meaningful quadriceps strength asymmetries. J Orthop Sports Phys Ther 2017;47(2):97–107.
[25] Welsch MA, Williams PA, Pollock ML, Graves JE, Foster DN, Fulton MN. Quantification of full-range-of-motion unilateral and bilateral knee flexion and extension torque ratios. Arch Phys Med Rehabil 1998;79(8):971–8.
[26] Krishnan C, Williams GN. Effect of knee joint angle on side-to-side strength ratios. J Strength Cond Res 2014;28(10):2981–7.
[27] Chamorro C, Armijo-Olivo S, De la Fuente C, Fuentes J, Javier CL. Absolute reliability and concurrent validity of hand held dynamometry and isokinetic dynamometry in the hip, knee and ankle joint: systematic review and meta-analysis. Open Med (Wars) 2017;12:359–75.
[28] Whiteley R, Jacobsen P, Prior S, Skazalski C, Otten R, Johnson A. Correlation of isokinetic and novel hand-held dynamometry measures of knee flexion and extension strength testing. J Sci Med Sport 2012;15(5):444–50.
[29] Toonstra J, Mattacola CG. Test-retest reliability and validity of isometric knee-flexion and -extension measurement using 3 methods of assessing muscle strength. J Sport Rehabil 2013;22(1).
[30] Reinking MF, Bockrath-Pugliese K, Worrell T, Kegerreis RL, Miller-Sayers K, Farr J. Assessment of quadriceps muscle performance by hand-held, isometric, and isokinetic dynamometry in patients with knee dysfunction. J Orthop Sports Phys Ther 1996;24(3):154–9.
[31] Bohannon RW, Bubela DJ, Wang YC, Magasi SR, Gershon RC. Adequacy of belt-stabilized testing of knee extension strength. J Strength Cond Res 2011;25(7):1963–7.

[32] Bohannon RW, Kindig J, Sabo G, Duni AE, Cram P. Isometric knee extension force measured using a handheld dynamometer with and without belt-stabilization. Physiother Theory Pract 2012;28(7):562–8.
[33] Stark T, Walker B, Phillips JK, Fejer R, Beck R. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. PM R 2011;3(5):472–9.
[34] Urhausen AP, Berg B, Øiestad BE, Whittaker JL, Culvenor AG, Crossley KM, et al. Measurement properties for muscle strength tests following anterior cruciate ligament and/or meniscus injury: What tests to use and where do we need to go? A systematic review with meta-analyses for the OPTIKNEE consensus. Br J Sports Med 2022.
[35] Almeida GPL, Albano TR, Melo AKP. Hand-held dynamometer identifies asymmetries in torque of the quadriceps muscle after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 2019;27(8):2494–501.
[36] 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(5):334–8.
[37] Suzuki T. Reliability of measurements of knee extensor muscle strength using a pull-type hand-held dynamometer. J Phys Ther Sci 2015;27(3):967–71.
[38] Terwee CB, Mokkink LB, Knol DL, Ostelo RW, Bouter LM, de Vet HC. Rating the methodological quality in systematic reviews of studies on measurement properties: a scoring system for the COSMIN checklist. Qual Life Res 2012;21(4):651–7.
[39] Kottner J, Audigé L, Brorson S, Donner A, Gajewski BJ, Hróbjartsson A, et al. Guidelines for Reporting Reliability and Agreement Studies (GRRAS) were proposed. J Clin Epidemiol 2011;64(1):96–106.
[40] Mansournia MA, Collins GS, Nielsen RO, Nazemipour M, Jewell NP, Altman DG, et al. A CHecklist for statistical Assessment of Medical Papers (the CHAMP statement): explanation and elaboration. Br J Sports Med 2021;55(18):1009–17.
[41] van Melick N, Meddeler BM, Hoogeboom TJ, Nijhuis-van der Sanden MWG, van Cingel REH. How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. PLoS One. 2017;12(12):e0189876.
[42] Arampatzis A, Karamanidis K, De Monte G, Stafilidis S, Morey-Klapsing G, Brüggemann GP. Differences between measured and resultant joint moments during voluntary and artificially elicited isometric knee extension contractions. Clin Biomech (Bristol, Avon) 2004;19(3):277–83.
[43] Pincivero DM, Salfetnikov Y, Campy RM, Coelho AJ. Angle- and gender-specific quadriceps femoris muscle recruitment and knee extensor torque. J Biomech 2004;37(11):1689–97.
[44] Grindstaff TL, Palimenio MR, Franco M, Anderson D, Bagwell JJ, Katsavelis D. Optimizing between-session reliability for quadriceps peak torque and rate of torque development measures. J Strength Cond Res 2019;33(7):1840–7.
[45] Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J Chiropr Med 2016;15(2):155–63.
[46] Terwee CB, Bot SD, de Boer MR, van der Windt DA, Knol DL, Dekker J, et al. Quality criteria were proposed for measurement properties of health status questionnaires. J Clin Epidemiol 2007;60(1):34–42.
[47] De Vet HC, Terwee CB, Mokkink LB, Knol DL. Measurement in medicine: a practical guide. Cambridge University Press; 2011.
[48] Ho KM. Using linear regression to assess dose-dependent bias on a Bland-Altman plot. J Emerg Crit Care Med 2018;2(2):68.
[49] Greenberg EM, Greenberg ET, Albaugh J, Storey E, Ganley TJ. Rehabilitation practice patterns following anterior cruciate ligament reconstruction: a survey of physical therapists. J Orthop Sports Phys Ther 2018;48(10):801–11.
[50] Ebert JR, Webster KE, Edwards PK, Joss BK, D'Alessandro P, Janes G, et al. Current perspectives of the Australian knee society on rehabilitation and return to sport after anterior cruciate ligament reconstruction. J Sport Rehabil 2020;29(7):970–5.
[51] Hansen EM, McCartney CN, Sweeney RS, Palimenio MR, Grindstaff TL. Hand-held dynamometer positioning impacts discomfort during quadriceps strength testing: a validity and reliability study. Int J Sports Phys Ther 2015;10(1):62–8.
[52] Escamilla RF, Macleod TD, Wilk KE, Paulos L, Andrews JR. Anterior cruciate ligament strain and tensile forces for weight-bearing and non-weight-bearing exercises: a guide to exercise selection. J Orthop Sports Phys Ther 2012;42(3):208–20.
[53] Perriman A, Leahy E, Semciw AI. The effect of open- versus closed-kinetic-chain exercises on anterior tibial laxity, strength, and function following anterior cruciate ligament reconstruction: a systematic review and meta-analysis. J Orthop Sports Phys Ther 2018;48(7):552–66.
[54] Englander ZA, Garrett WE, Spritzer CE, DeFrate LE. In vivo attachment site to attachment site length and strain of the ACL and its bundles during the full gait cycle measured by MRI and high-speed biplanar radiography. J Biomech 2020;98:109443.
[55] Forelli F, Barbar W, Kersante G, Vandebrouck A, Duffiet P, Ratte L, et al. Evaluation of muscle strength and graft laxity with early open kinetic chain exercise after ACL reconstruction: a cohort study. Orthop J Sports Med. 2023;11(6):23259671231177594.
[56] van Melick N, van der Weegen W, van der Horst N. Quadriceps and hamstrings strength reference values for athletes with and without anterior cruciate ligament reconstruction who play popular pivoting sports, including soccer, basketball, and handball: a scoping review. J Orthop Sports Phys Ther 2022;52(3):142–55.
[57] Maestroni L, Read P, Turner A, Korakakis V, Papadopoulos K. Strength, rate of force development, power and reactive strength in adult male athletic populations post anterior cruciate ligament reconstruction - A systematic review and meta-analysis. Phys Ther Sport 2021;47:91–104.
[58] Lesnak J, Anderson D, Farmer B, Katsavelis D, Grindstaff TL. Validity of hand-held dynamometry in measuring quadriceps strength and rate of torque development. Int J Sports Phys Ther 2019;14(2):180–7.
[59] Thompson BJ. Influence of signal filtering and sample rate on isometric torque - time parameters using a traditional isokinetic dynamometer. J Biomech 2019;83:235–42.
[60] Pietrosimone B, Lepley AS, Kuenze C, Harkey MS, Hart JM, Blackburn JT, et al. Arthrogenic muscle inhibition following anterior cruciate ligament injury. J Sport Rehabil 2022:1–13.