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Original Research

Intra-rater reliability, measurement precision, and inter-test correlations of 1RM single-leg leg-press, knee-flexion, and knee-extension in uninjured adult agility-sport athletes: Considerations for right and left unilateral measurements in knee injury control

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ABSTRACT

Objectives: Knowledge of single-leg knee strength test reliability for the right and left limb is critical for between-limb clinical decision-making. Knowledge of between-test correlations is essential for understanding whether tests measure similar or different aspects of muscle strength. This study investigated the intra-rater, test-retest reliability and measurement precision of one repetition maximum (1RM) single-leg leg-press (LP), knee-flexion (KF), and knee-extension (KE) for both limbs, and inter-test correlations.
Design: Repeated measures;
Setting: University.
Participants: Six males, seven females (age 25.6 ± 5.5 yr; height 171.4 ± 8.4 cm; mass 71.8 ± 13.4 kg).
Main outcome measures: Normalised 1RM (percent body-mass (%BM)), intraclass correlation coefficient (ICC) (2,1), standard error of measurement (SEM; %BM), Pearson's correlation (r), coefficient of determination (r^2).
Results: Mean 1RM test-retest values were (right, left): LP, 214.2–218.5%BM, 213.5–215.4%BM; KF, 35.9–38.9%BM, 37.7–38.2%BM; KE, 43.3–44.6%BM, 36.2–39.3%BM. The ICCs/SEMs were (right, left): LP, 0.98/7.3%BM, 0.94/14.2%BM; KF, 0.75/4.9%BM, 0.95/1.9%BM; KE, 0.87/3.4%BM, 0.78/4.4%BM. Correlations were significant ($P < 0.01$), r/r^2 values were: LP-KF, 0.60/0.36; LP-KE, 0.59/0.35; KF-KE, 0.50/0.25.
Conclusions: Tests demonstrated good reliability and measurement precision, although ICCs and SEMs were different between limbs. Tests were correlated, but only one-third of the variance was shared between tests. Practitioners should be cognisant of between-limb differences in reliability and include all tests for knee clinical decision-making.

1. Introduction

Injury control refers to preventing or reducing the severity of injury (Avery, 1995) and includes the prevention, acute care, and rehabilitation phases of intervention (Rivara, 2003). In knee injury prevention, skeletal muscle shields noncontractile tissues (e.g. ligament) from excessive forces that cause injury (Clark et al., 2015), and those with sub-optimal quadriceps or hamstrings peak strength can sustain first-time traumatic and overuse knee injuries (Duvigneaud, Bernard, Stevens, Witvrouw, & Van Tiggelen, 2008; Myer et al., 2009; Van Tiggelen, Witvrouw, Coorevitsb, Croisierc, & Rogetd, 2004). In knee injury rehabilitation, skeletal muscle also shields injured or surgically-repaired non-contractile tissues from excessive forces (Clark et al., 2015), with short-term quadriceps peak strength being associated with medium-/long-term outcomes defined by patient self-report questionnaires (Eitzen, Holm, & Risberg, 2009; Logerstedt, Lynch, Axe, & Snyder-Mackler, 2013; Pietrosimone, Lepley, Ericksen, Gribble, & Levine, 2013). After rehabilitation, quadriceps peak strength is associated with patients' return-to-activity (RTA) rates (Lentz et al., 2012; Lepley & Palmieri-Smith, 2015; Schmitt, Paterno, & Hewett, 2012), while impaired

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quadriceps peak strength is associated with imaging signs (e.g. joint space narrowing) representative of knee post-trauma osteoarthritis (PTOA) (Hart, Turman, Diduch, Hart, & Miller, 2011; Tourville et al., 2014; Wang et al., 2015). In sports, superior quadriceps or hamstrings peak strength is associated with superior athletic performance (e.g. jumping) in uninjured (Newman, Tarpenning, & Marino, 2004; Wiklander & Lysholm, 1987) and ACL-injured (Holsgaard-Larsen, Jensen, & Aagaard, 2014; Ko, Yang, Ha, Choi, & Kim, 2012) athletes. Because knee muscle peak strength is important across the phases of knee injury control, is linked to knee PTOA, and is related to lower-limb athletic performance, measurement of knee muscle strength is critical in practitioners' routine practice.

Several methods are available for measuring knee muscle strength including isokinetic dynamometry, handheld dynamometry, manual muscle test (MMT), and the free-weight and lever-arm/cam/pulley resistance machine (hereafter, 'resistance machine') one repetition maximum (1RM). Isokinetic and handheld dynamometers generate a variety of clinically useful variables (e.g. peak torque, peak force, power) (Kannus, 1994; Mentiplay et al., 2015), but both types of dynamometer can be expensive and not easily accessible to practitioners. The MMT is a common method for assessing knee muscle strength and can be performed in any environment without any equipment (Clarkson & Gilewich, 1989), but has limited utility because of its subjective nature and poor reliability with higher levels of isometric muscle strength (e.g. Oxford Scale > Grade 3) (Dvir, 1997). A common free-weight test of muscle strength in injury prevention and sports performance research is the 1RM barbell back-squat (Newton et al., 2006), but this also has limited clinical utility because it is a bilateral task employing multiple joints and muscle groups and does not permit focused assessment of unilateral knee extensors or flexors. Resistance machines such as the leg press (LP) and knee extension (KE) are widely used to measure knee muscle strength in injury control and sports performance research (Clark, Gumbrell, Rana, Traole, & Morrissey, 2001; Neeter et al., 2006; Sinacore et al., 2017; Tagesson & Kvist, 2007). Compared to isokinetic and handheld dynamometry, resistance machines are widely available to athletes and practitioners in local communities (e.g. local health club). Compared to the MMT and 1RM barbell back-squat, resistance machine strength testing is quantitative and enables single-leg/single-muscle-group assessment, respectively. As such, practitioners in local communities should consider using resistance machines in their routine practice when the measurement of knee muscle strength is required.

For practitioners to confidently perform 1RM knee muscle strength tests with athletes in local communities using resistance machines, the reliability and measurement precision of the measurement procedure must be known. Reliability is the ability of a measurement procedure to generate consistent values (Portney & Watkins, 2009). Measurement precision is the ability of a measurement procedure to yield exact values (Portney & Watkins, 2009). Lack of reliability and measurement precision undermine the validity of raw data and compromise data analysis procedures and practitioners' decision-making (Batterham & George, 2003; Clark et al., 2016). Reliability and measurement precision of the 1RM single-leg LP and KE are reported for both uninjured and ACL-injured athletes (Clark et al., 2001; Neeter et al., 2006; Sinacore et al., 2017; Tagesson & Kvist, 2007; da Silva et al., 2013). Few authors, however, have reported reliability for the 1RM single-leg knee flexion (KF) (da Silva et al., 2013). No study has reported reliability and measurement precision for the 1RM single-leg LP, KE, and KF for the right and left limbs in the same category of uninjured or injured athletes (e.g. invasion games players). Knowledge of test reliability and measurement precision for both limbs is important in case reliability and measurement precision are different between limbs; 'good' reliability for one limb and 'poor' reliability for the other limb can result in flawed data analysis procedures (e.g. between-limb comparisons) because data for the former is valid whereas data for the latter is not.

Further to measurement reliability and precision considerations, the design of a muscle strength test battery (e.g. LP + KE + KF) should ensure correlations between tests are sufficiently weak so that each test offers unique data for decision-making processes (Clark & Mullally, 2018; Neeter et al., 2006). No author has reported correlations between different knee 1RM muscle strength tests and so it is unknown if the 1RM single-leg KE and KF are strongly related with the 1RM single-leg LP. If there are strong correlations between the 1RM single-leg LP, KE, and KF, this indicates two or more tests measure similar aspects of knee muscle strength, and not all tests are needed in a strength test battery. Eliminating unnecessary muscle strength tests from a test battery makes a test session safer for the athlete by reducing the number of test exposures and more time-efficient for both the practitioner and athlete by reducing session duration.

There were two purposes for this study. First, to establish the intra-rater, test-retest reliability and measurement precision of the 1RM single-leg LP, KF, and KE for right and left limbs in a cohort of uninjured, adult, recreational agility-sport athletes. It was hypothesised the 1RM single-leg LP, KF, and KE tests would demonstrate good reliability and measurement precision for both right and left limbs using the intraclass correlation coefficient (ICC) and standard error of measurement (SEM), respectively, as recommended by previous researchers (Atkinson & Nevill, 1998; Denegar & Ball, 1993). Second, to determine inter-test correlations between the 1RM single-leg LP, KF, and KE. It was hypothesised there would be significant positive correlations between the 1RM single-leg LP, KF, and KE. This study is original because no previous work has reported the reliability, measurement precision, and inter-test correlation for all the 1RM tests of interest for both limbs in the same category of athletes. This study's findings will be practically significant because they will highlight important considerations for the consistent administration and accurate interpretation of knee muscle strength tests in the prevention phase of the knee injury control process for adult, recreational agility-sport athletes. This paper includes reporting standards advised by Kottner et al. (Kottner et al., 2011).

2. Methods

2.1. Study design

Single cohort repeated measures for between-day (Day 1 (D1), Day 2 (D2)), intra-tester, test-retest reliability.

2.2. Sample size calculation

An *a priori* power analysis for ICC was performed (PASS 11, NCSS Statistical Software, Utah). Twelve participants were required to achieve 82% power and detect an ICC$\geq$0.90 with significance set at 0.05. To mitigate participant attrition or technical problems, two additional athletes could be recruited.

2.3. Ethical approval, participant recruitment, informed consent

University ethics approval was obtained. Participants were recruited from university staff/students/visitors and local sports teams/fitness centers using flyers on noticeboards and in e-newsletters. Informed consent and a physical activity readiness questionnaire were completed by all participants.

2.4. Participants

Inclusion criteria were: male/female athletes aged 18–40 years and participating in Level I-II agility sports defined by the Noyes Sports Activity Rating Scale (SARS) (Noyes et al., 1989). Males and females were included because knee muscle strength testing is relevant to agility-sport athletes from both sexes. Level I and II agility sports (Noyes et al., 1989) were selected because our research group is primarily interested in invasion and court games players who participate in their sport at least once per week. Exclusion criteria were: current lower quadrant pain, time-loss lower quadrant injury within 12 months (i.e. injury requiring withdrawal from one or more practice/competition), any diagnosed knee ligament deficiency/meniscal lesion, any history of lower quadrant fracture that required immobilisation, and any history of lower quadrant surgery. Thirteen athletes participated (male n = 6; female n = 7; age 25.6 ± 5.5 years; height 171.4 ± 8.4 cm; mass 71.8 ± 13.4 kg; SARS 93.5 ± 8.0; football n = 7; rugby n = 2; netball n = 4).

2.5. Instrumentation

A general warm-up was performed on a Wattbike PRO exercise bike (Wattbike, Nottingham, UK). Tests employed CYBEX VR1 Leg Press and Dual Leg Extension-Leg Curl resistance machines (CYBEX, Cambridgeshire, UK). A universal goniometer (66fit, Lincolnshire, UK) was used to measure knee angles for 1RM tests. An adjustable ankle-weight cuff that could contain up to 11 individual 450 g metal bars (total = 4.95 kg (DKN UK, London, England, UK)) was used to add small incremental mass increases to machine weight-stacks for 1RM trials.

2.6. Procedures

All testing occurred in the university's training facility. A minimum of 72 h and maximum of seven days existed between days. For D2, the tester was masked to participants' D1 values. The tester possessed over five years' experience in sports medicine and conducted all measurements independently. Participants were instructed to avoid fatiguing exercise/sports for 48 h before testing. Participants completed a 5 min warm-up on the exercise bike at self-selected intensity sufficient to elicit light sweating. Test order progressed from multi-joint to single-joint tests: LP, KF, KE. Five minutes rest occurred between tests. Limb order was computer-randomised within tests for D1, the same order repeated for D2. Participants performed a specific warm-up/machine-familiarisation for each test at a set percentage of body-mass (Table 1). All 1RM test procedures (Table 1) were adapted from Kraemer and Fry (Kraemer et al., 1995). Strong verbal encouragement was provided for all trials, with trial failure defined as loss of strict technique/perceived cheating, inability to achieve the required range-of-motion (ROM), or perceived injury risk. Trials were terminated if participants reported any acute pain onset.

For the LP (Fig. 1), participants were sitting, knees and feet hip-width apart, knees at 90° flexion determined by goniometry, hands holding handles adjacent to the hips, lumbosacral spine in firm backrest contact. The non-test limb was removed from the foot-plate and actively held in approximately 90° hip and knee flexion. A calibration trial was performed with the warm-up percentage body-mass (%BM) to establish test range-of-motion (ROM): from the starting position of 90° knee flexion to the maximum possible knee extension (up to 0°) as limited by each participant's hamstring extensibility. Participants were instructed to maintain strict technique: push through the rearfoot (to discourage active plantar-flexion), maintain knee alignment with the ipsilateral hip and ankle, maintain lumbosacral spine backrest contact, and exhale during the concentric phase of the test. The 1RM was measured to the nearest 4.95 kg. Because the LP design required pushing the seat carriage and body up an inclined guide rail against gravity in addition to the selected weight-stack plates (Fig. 1), body-mass and the load moved were combined to represent the 1RM value used for data analyses.

For the KF (Fig. 2), participants were sitting, knees and feet hip-width apart, the lever-arm-pad level with the posterior ankle joint-line, in the maximum possible knee extension (up to 0°) as limited by each subject's hamstring extensibility, hands holding handles in front of the subject, lumbosacral spine in firm backrest contact. The non-test limb was removed from the lever-arm-pad and actively held in knee flexion away from the path of the lever-arm. A calibration trial was performed with the warm-up %BM to establish the test ROM: from the starting position of near/at 0° knee extension to 90° knee flexion. Participants were instructed to maintain strict technique: pull through the posterior ankle, maintain knee alignment with the ipsilateral hip and ankle, maintain lumbosacral spine backrest contact, and exhale during the concentric phase of the test. The 1RM was measured to the nearest 1.8 kg.

For the KE (Fig. 3), participants were in sitting, knees and feet hip-width apart, the lever-arm-pad as distal as possible on the tibia without being on the anterior ankle joint-line, knees at 90° flexion as determined by goniometry, hands holding handles adjacent to the hips, lumbosacral spine in firm backrest contact. The non-test limb was allowed to hang in a relaxed flexed position away from the path of the lever-arm. A calibration trial was performed with the warm-up %BM to establish the test ROM: this was from the starting position of 90° knee flexion to the maximum possible knee extension (up to 0°) as limited by each participant's hamstring extensibility. Participants were instructed to maintain strict technique: push through the distal tibia, maintain knee alignment with the ipsilateral hip and ankle, maintain lumbosacral spine backrest contact, and exhale during the concentric phase of the test. The 1RM was measured to the nearest 1.8 kg.

2.7. Statistical analyses

Raw data were normalised to %BM: (1RM (kg)÷BM (kg)) × 100. Normalised 1RM values were used for analyses. Normality of data was assessed using histogram inspection and Shapiro-Wilk tests. For the first study purpose, between-day, within-test, within-limb systematic error and learning effects were assessed with paired t-tests (Atkinson & Nevill, 1998) and Cohen's *d* (Portney & Watkins, 2009), with $d < 0.35$ considered small/negligible (Portney & Watkins, 2009). Relative reliability was assessed with the ICC (2,1) and 95% confidence intervals (Denegar & Ball, 1993; Portney & Watkins, 2009), an ICC>0.75 defined to represent good reliability (Portney & Watkins, 2009). Measurement precision (absolute reliability) was assessed with SEM (Atkinson & Nevill, 1998; Denegar & Ball, 1993), SEMs of ≤10%BM for the LP and ≤5%BM for the KF and KE considered good measurement precision. For the second study purpose, participants' D2 within-test between-limb difference was assessed with paired t-tests (Maulder & Cronin, 2005). Then, as in previous work (Maulder & Cronin, 2005; Neeter et al., 2006), participants' D2 right and left limb values were pooled within each test to yield 26 data points per test for inter-test correlation analyses. Correlations were assessed using Pearson's correlation (r) (Maulder & Cronin, 2005; Portney & Watkins, 2009). Correlations were defined moderate-to-strong (0.50–0.75) and strong-to-very strong (0.75–1.00) (Portney & Watkins, 2009). The proportion (%) of variance shared between tests was assessed with coefficient of determination (r^2) (Thomas, Nelson, & Silverman, 2011). An $r^2 \geq 0.60$ was used as a threshold for defining a high proportion of

Table 1
One repetition maximum test procedures.

Leg Press	Knee Flexion	Knee Extension
Warm-up set M & F, 1 × 10, ≈50%BM	Warm-up set M & F, 1 × 10, ≈10%BM	Warm-up set M & F, 1 × 10, ≈25%BM
120 s rest period (120RP)	120 s rest period (120RP)	120 s rest period (120RP)
Trial 1 M & F, 1 × 1, ≈100%BM	Trial 1 M & F, 1 × 1, ≈20%BM	Trial 1 M & F, 1 × 1, ≈30%BM
120RP	120RP	120RP
Incremental Load Increase (ILI) Increase load, M ≈ 30%BM, F ≈ 25%BM	Incremental Load Increase (ILI) Increase load, M ≈ 10%BM, F ≈ 5%BM	Incremental Load Increase (ILI) Increase load, M ≈ 20%BM, F ≈ 10%BM
120RP	120RP	120RP
Repeat ILI and 120RP until subject fails*	Repeat ILI and 120RP until subject fails*	Repeat ILI and 120RP until subject fails*
Load Adjustment Set load at that for last successful trial, then increase load in 4.95–9.90 kg increments (and repeat 120RP after each increment) until 1RM established	Load Adjustment Set load at that for last successful trial, then increase load in 0.90–1.80 kg increments (and repeat 120RP after each increment) until 1RM established	Load Adjustment Set load at that for last successful trial, then increase load in 1.80 kg increments (and repeat 120RP after each increment) until 1RM established

M = male; F = female; BM = body-mass; * = see text for definition of trial failure.

Fig. 1. Leg press one repetition maximum test Configuration.

Fig. 2. Knee flexion one repetition maximum test Configuration.

shared variance and that tests measured highly similar aspects of knee muscle strength (Clark & Mullally, 2018; Thomas et al., 2011). For all analyses alpha was set *a priori* at 0.05.

3. Results

No subject reported acute pain. There were no adverse events. Summary statistics are presented in Table 2. All data were normally distributed ($P > 0.05$). There were no between-day, within-test, within-limb significant differences and negligible learning effects for all tests ($P = 0.114$–0.745; $d = 0.03$–0.31).

The ICC (2,1) values and 95% confidence intervals, and SEM values, are reported in Table 3. All ICCs were good. The ICCs for the LP were consistently higher than for KF or KE. The ICCs for KF were very different between right and left limbs. The SEMs for the LP were very different between limbs with the SEM for the left limb being almost twice that of the right limb. The SEMs for KF and KE were consistently good at <5%BM, although the SEM for the KF right limb was more than twice that of the left limb.

There were no between-limb significant differences for any of the tests' D2 values ($P = 0.080$–0.616). Scatterplots are presented in Figs. 4–6. Outliers were apparent in the upper right quadrants of Figs. 4 and 6: all relevant datapoints were reviewed, verified, and then retained. Correlation between the LP and KF was: $r = 0.60$, $r^2 = 0.36$, $P < 0.01$. Correlation between the LP and KE was: $r = 0.59$, $r^2 = 0.35$, $P < 0.01$. Correlation between the KF and KE was: $r = 0.50$, $r^2 = 0.25$, $P < 0.01$. The three 1RM tests, therefore, shared ≤36% of the variance in knee muscle strength.

Fig. 3. Knee extension one repetition maximum test Configuration.

Table 2
Summary statistics ($n = 13$; mean ± SD).

	1RM Leg Press	1RM Knee Flexion	1RM Knee Extension
Right side			
D1 (%BM)	214.2 ± 52.0	35.9 ± 11.1	44.6 ± 11.0
D2 (%BM)	218.5 ± 55.5	38.9 ± 7.9	43.3 ± 8.4
D1-D2 diff. (%BM)	4.3 ± 11.3	3.0 ± 7.0	1.3 ± 5.1
Left side			
D1 (%BM)	213.5 ± 58.0	37.7 ± 8.3	36.2 ± 9.9
D2 (%BM)	215.4 ± 62.5	38.2 ± 9.5	39.3 ± 9.4B
D1-D2 diff. (%BM)	1.9 ± 20.9	0.5 ± 2.8	3.1 ± 6.5

SD = standard deviation; 1RM = one repetition maximum; D1 = day 1; D2 = day 2; %BM = percentage of body-mass; diff. = absolute difference.

Table 3
Reliability statistics ($n = 13$).

	1RM Leg Press	1RM Knee Flexion	1RM Knee Extension
Right side			
ICC (2,1)	0.98*	0.75*	0.87*
ICC (2,1) 95% CI	0.93–0.99	0.33–0.91	0.62–0.96
SEM (%BM)	7.3	4.9	3.4
Left side			
ICC (2,1)	0.94*	0.95*	0.78*
ICC (2,1) 95% CI	0.82–0.98	0.84–0.98	0.41–0.93
SEM (%BM)	14.2	1.9	4.4

1RM = one repetition maximum; ICC = intraclass correlation coefficient; CI = confidence interval;
SEM = standard error of measurement; %BM = percentage of body-mass; * = $P < 0.01$.

4. Discussion

The first purpose of this study was to establish the intra-rater, test-retest reliability and measurement precision of the 1RM single-leg LP, KF, and KE for right and left limbs in uninjured, adult, recreational agility-sport athletes. It was hypothesised the 1RM tests would demonstrate good reliability and measurement precision for both right and left limbs. Findings demonstrate all tests possess good reliability defined by ICCs>0.75, but ICCs can be quite different between limbs for some tests (Table 3). Findings also demonstrate tests possess good measurement precision, but SEMs can also be quite different between limbs (Table 3). The second purpose of this study was to determine correlations between the 1RM single-leg LP, KF, and KE. It was hypothesised there would be significant positive correlations between the 1RM single-leg LP, KF, and KE. Findings demonstrate there are significant positive correlations between tests, but the shared variance between tests is low.

A direct comparison of the %BM values from this study to previous literature is not possible because no work has reported single-leg 1RM normalised values for both limbs for the LP, KF, and KE in an uninjured mixed-sex cohort. The alternative is to compare the present normalised data to non-normalised data reported by others. An issue with such comparisons is some works fail to specify which limb was tested (Worrell, Borchert, Erner, Fritz, & Leerar, 1993), whilst others use different types of resistance machine or recruited single-sex cohorts. For the LP, Clark et al. (Clark et al., 2001) report a single-leg mean 1RM of 129.3 kg for an uninjured mixed-sex cohort with a mean body-mass of 65.6 kg tested using a Technogym resistance machine, and Worrell et al. (Worrell et al., 1993) report a single-leg mean 1RM value of approximately 140.0 kg for an uninjured mixed-sex group with a mean body-mass of 68.2 kg tested using a Paramount resistance machine. Crude calculation reveals both studies report a single-leg LP 1RM of approximately 200%BM. For KF, da Silva et al. (da Silva et al., 2013) report a single-leg mean 1RM of 16.1 kg for a male uninjured cohort with a mean body-mass of 75.3 kg tested using an unspecified resistance machine. Crude calculation demonstrates the study reports a single-leg KF 1RM of approximately 21%BM. For KE, Clark et al. (Clark et al., 2001) also report a single-leg mean 1RM of 40.4 kg tested using a Universal resistance machine, and Wilkinson et al. (Wilkinson, Tarnopolsky, Grant, Correia, & Phillips, 2006) report a single-leg mean 1RM of 47.0 kg for an uninjured male sample with a mean body-mass of 75.6 kg tested using a Nautilus resistance machine. Crude calculation illustrates both studies report a single-leg KE 1RM of approximately 60%BM. The present LP normalised mean values (Table 2) appear similar to data reported by others. The present KF and KE normalised mean values (Table 2) do not. Inconsistencies in data and findings between studies can be a reflection of differences in the samples' physical capabilities as well as the different mechanics of different make of resistance machine (Folland & Morris, 2008; Nunn & Mayhew, 1988). Practitioners should be mindful of the potential for such differences when comparing values between studies.

Systematic error and learning effects alter repeated measurement values relative to a measurement's true value, and both should be considered when evaluating measurement procedure properties (Atkinson & Nevill, 1998; Denegar & Ball, 1993; Portney & Watkins, 2009). Results of this study demonstrate no between-day significant differences and small/negligible learning effects for the three tests. Based on such findings, the 1RM procedures employed in this study (Table 1) were successful at mitigating sources of systematic error and learning effects.

A direct comparison of the ICCs and SEMs from this study to previous literature is also limited because no other author has reported such statistics for single-leg normalised 1RM values for both limbs for the same tests or category of athletes and because different ICC models yield different ICC and SEM values (Denegar & Ball, 1993). The alternative is to compare the present findings to studies that fail to specify whether intra- or inter-tester reliability was reported, do not state which limb was tested, or do not report which model ICC was used. For the LP, Clark et al. (Clark et al., 2001) report a single-leg ICC = 0.94 for an uninjured mixed-sex cohort, and Neeter et al. (Neeter et al., 2006) report a single-leg ICC = 0.94 also for an uninjured mixed-sex group. For KF, da Silva et al. (da Silva et al., 2013) report a single-leg ICC≥0.75 for an uninjured

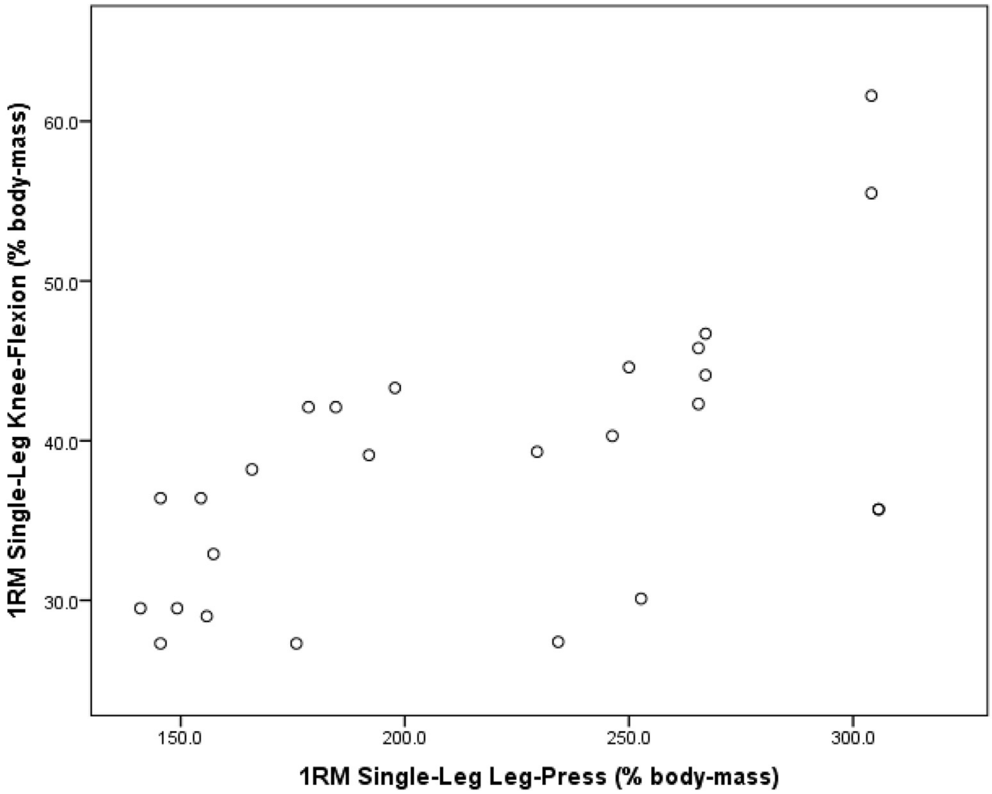

Fig. 4. Scatterplot for one repetition maximum (1RM) single-leg leg-press and single-leg knee-flexion.

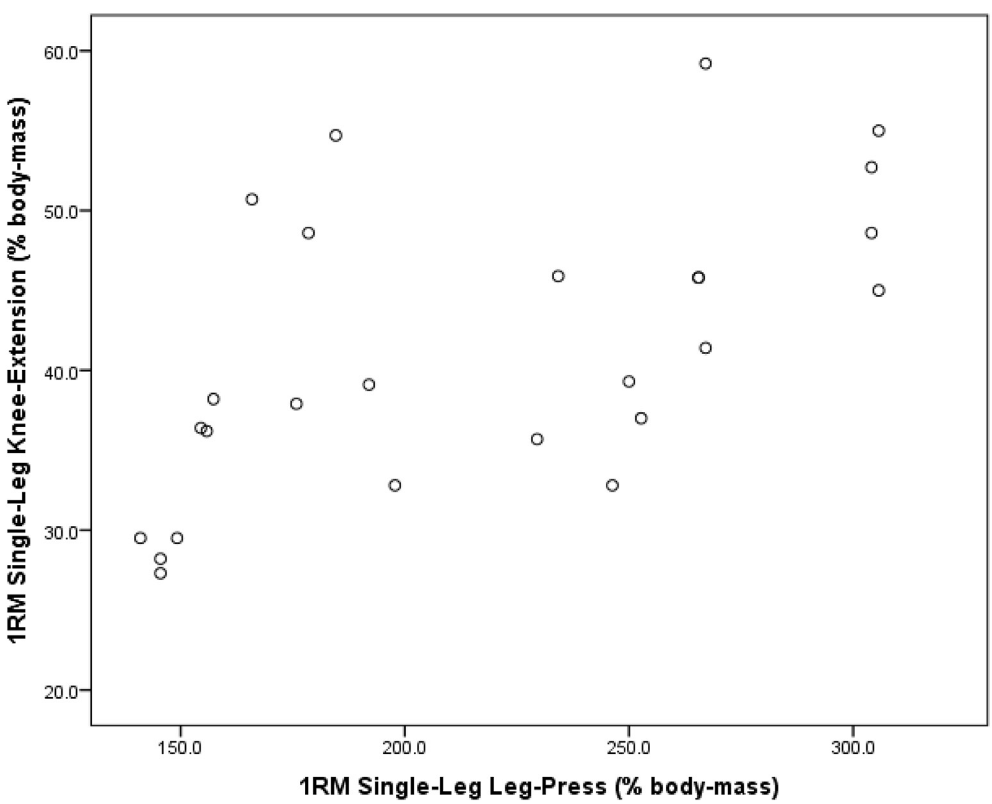

Fig. 5. Scatterplot for one repetition maximum (1RM) single-leg leg-press and single-leg knee-extension.

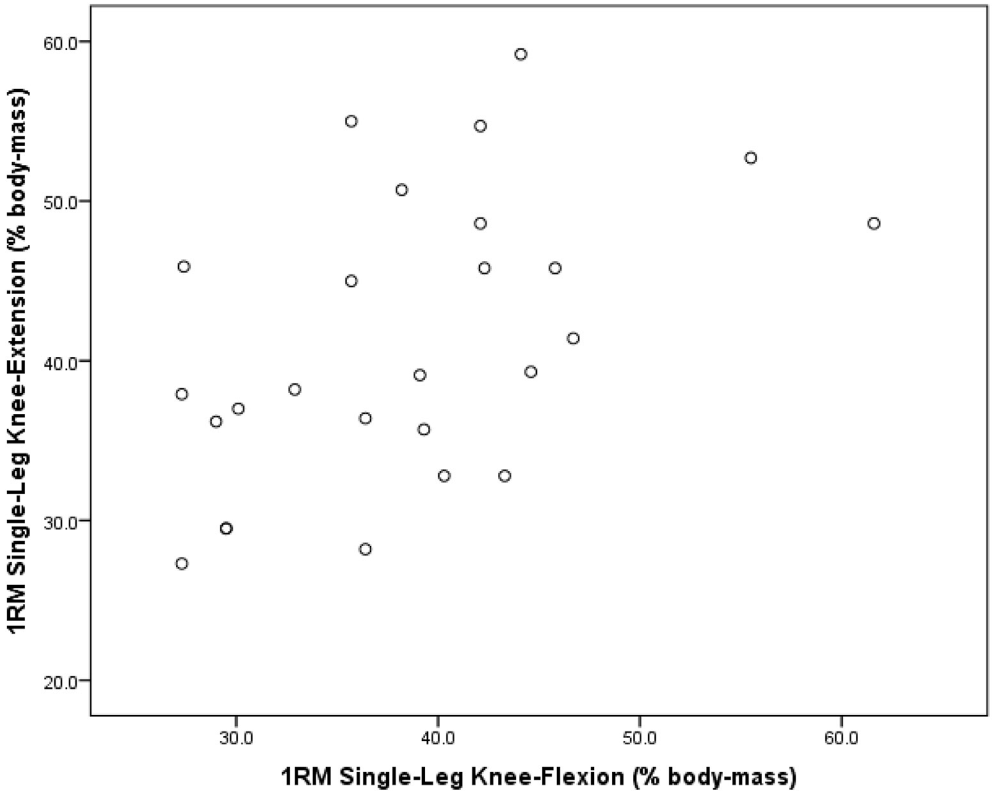

Fig. 6. Scatterplot for one repetition maximum (1RM) single-leg knee-flexion and single-leg knee-extension.

male sample. For KE, Clark et al. (Clark et al., 2001) report a single-leg ICC = 0.85 for an uninjured mixed-sex cohort, and Tagesson and Kvist (Tagesson & Kvist, 2007) report a single-leg ICC = 0.90 also for an uninjured mixed-sex group. The present ICC values (Table 3) are consistent with the ICCs reported by other works. Also as for other works just cited, single-leg ICCs are higher for multi-joint, multi-muscle-group versus single-joint, single-muscle-group 1RM tests (Table 3). Overall, the present 1RM measurement procedures are accepted as yielding good or greater than good intra-tester, test-retest reliability defined by a minimum threshold ICC>0.75 (Portney & Watkins, 2009). For the LP, KF, and KE, no other study has reported single-leg SEMs in %BM form. This study operationally defined SEMs of ≤10%BM for the LP and ≤5%BM for the KF and KE as representing good measurement precision. The majority of SEMs for this study (Table 3) fulfil the present criteria for good measurement precision.

It is not clear why the ICCs for KF and the SEMs for the LP and KF were very different between limbs (Table 3). Such findings represent differences in the magnitude of measurement variance (variability) within each limb (Denegar & Ball, 1993; Portney & Watkins, 2009). The exclusion criteria for this study should have mitigated acute pain and previous injury/surgery as sources of increased variability. Participants were instructed not to perform any fatiguing exercise/sports for 48 h before testing. The same tester followed the same standardised measurement procedures for both limbs for all tests. The tester consistently verbally encouraged all participants to be fully engaged for all trials for both limbs across all tests. There is no statistically significant effect of limb dominance on lower-limb motor performance (McGrath et al., 2016). Although sources of tester error and within-subject acute variance were considered and mitigated, it appears there can still be substantial differences in between-limb reliability and measurement precision for the same 1RM test.

Interpretation of the magnitude and relevance of a correlation coefficient can change with changes in study context and sample size and the coefficient of determination is useful for indicating the proportion (%) of variance in one variable that is accounted for by another variable (Portney & Watkins, 2009; Thomas et al., 2011). Correlation and the coefficient of determination can be used to examine whether one test captures similar or different aspects of lower-limb motor performance compared to another test (Clark & Mullally, 2018; Maulder & Cronin, 2005). Although all between-test correlations in this study were statistically significant and positive, magnitudes were moderate. Consequently, coefficients of determination revealed that one 1RM test only accounted for approximately one-third of the variance at most in another 1RM test. Each 1RM test, therefore, captures unique information about knee muscle strength. For example, even though the LP and KE both involve the quadriceps, the different 1RM tests still appear to capture different information about muscle strength during the maximum-effort knee extension that occurs within both tests.

Potential technical limitations include not measuring the length of the KF-KE resistance machine lever arm to adjust raw data to an estimated anisometric torque (da Silva et al., 2013). Such adjustment was not performed because it is not typically done in real-world practice, because such KF and KE correction/normalisation procedures are not possible for the LP, and because data normalisation procedures to %BM are likely more meaningful to athletes than anisometric torque values. Potential data analysis limitations include not performing dominant-nondominant comparisons. Such comparisons were not performed because dominance changes according to the nature of the task (e.g. load-bearing versus skill) and because knee strength tests with uninjured participants consistently fail to demonstrate a significantly stronger side of the body (McGrath et al., 2016; Spry et al., 1993). This study can only be generalised to contexts that use the same make of resistance machine because different makes of resistance machine have different designs and mechanics (e.g. lever-arm/cam/pulley), resulting in different muscle strength values for the same individual (Folland & Morris, 2008; Nunn & Mayhew, 1988). However, there is a consistently significant positive correlation between muscle strength values on one strength testing device and muscle strength values on another strength testing device for the same joint motion (e.g. KE) performed by the same individual (da Silva et al., 2013; Jameson, Knight, Ingersoll, & Edwards, 1997; Verdijk, van Loon, Meijer, & Savelberg, 2009) - if athletes are ‘strong’ on one machine, they are likely to be ‘strong’ on another machine. The critical issue, therefore, is that serial measurements of an athlete's knee muscle strength must occur on the same resistance machine to have the potential to reliably, accurately, and validly assess changes in muscle strength across time. As such, if they wish, practitioners may choose to cautiously employ the 1RM strength testing procedures from this study with other makes of LP, KF, and KE machine as long as they then continue using the same machine for future knee muscle strength tests with the same athlete. Future research should determine the reliability and measurement precision for the 1RM single-leg LP, KF, and KE using other makes of resistance machine. Future research should also determine the reliability and measurement precision of, and the correlations between, the 1RM single-leg LP, KF, and KE in injured adult recreational agility-sport athletes engaging in the rehabilitation phase of knee injury control. Both suggestions for future research will elucidate whether the nature of the findings in this study are consistent between different makes of resistance machine across two of the phases of knee injury control.

5. Conclusion

Knee 1RM tests possess different levels of reliability and measurement precision between limbs. Such findings present implications for unilateral measurements in knee injury control because the reliability and measurement precision of a 1RM test for one limb should not be extrapolated to the opposite limb. Subsequently, repeated measurements and change scores within one limb will need to be interpreted differently to that of the opposite limb. Practitioners' should be aware of such differences for the consistent administration and accurate interpretation of knee 1RM tests for both limbs. Different knee 1RM tests capture different information about knee muscle strength, even if tests employ the same muscle groups. All three 1RM tests should, therefore, be included in a knee muscle strength test battery applied for thorough assessment and reasoning processes in the prevention phase of knee injury control. This study highlights important considerations for the consistent administration and accurate interpretation of knee muscle strength measurements for uninjured, adult, recreational agility-sport athletes and helps inform practitioners about how a battery of knee muscle strength tests can be constructed for such athletes in the local community using resistance machines.

Declaration of interest

None.

Conflicts of interest

None declared.

Ethical statement

This study received institutional ethics approval and all participants gave informed consent to participate.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2019.09.003.

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