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Reliability of lower limb strength assessment in female team sport athletes

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ABSTRACT

Background: Lower limb injury rates have increased dramatically in line with increased female sport participation levels. Muscle strength is a modifiable lower limb injury risk factor, guiding performance monitoring and rehabilitation.

Objectives: The aim of this study was to investigate the test-retest reliability of isokinetic and isometric lower limb peak torque to body mass of muscles acting on the hip, knee, and ankle in female team sport athletes. It was hypothesised the test-retest reliability would be good (intraclass correlation coefficients (ICC) ≥ 0.75).

Methods: Thirty-eight female athletes (Australian Rules Football = 18, netball = 12, soccer = 8) aged 16–35 years participated in this study. Participants performed isokinetic (60°/s and 120°/s) and isometric testing on a Biodex Isokinetic Dynamometer on three separate days.

Results: Poor to good reliability was demonstrated for all joint movements (ICC = 0.38–0.88) with small to moderate effect sizes (0.00–0.43) and typical errors (5.65–24.49).

Conclusion: Differences in peak torque to body mass were observed between sessions one and two and/or one and three, demonstrating a learning effect. Therefore, three testing sessions, and/or the inclusion of a familiarisation session, is recommended for future assessments in populations unfamiliar with dynamometry.

1. Introduction

Female participation rates across all levels of sport have increased over the past 40 years, possibly contributing to rising injury rates (Hecht & Arendt, 2014). Intervention programs that target modifiable risk factors such as neuromuscular function, have been shown to reduce knee injury risk (Brophy et al., 2010). Traditionally, the quadriceps and hamstrings have been the primary focus of knee injury risk research (Andrade et al., 2012). Previous studies have demonstrated that unilateral hamstring to quadricep strength ratio (agonist/antagonist ratio) (Andrade et al., 2012; Boden et al., 2000; Hewett et al., 2006; Hewett et al., 2004) and left to right limb asymmetry (Fousekis et al., 2010; Kabacinski et al., 2018; Knapik et al., 1991), were directly related to lower limb injury risk. Despite this focus, other studies have concluded that non-knee spanning muscles, (e.g. Soleus and hip internal and external rotators) can influence anterior cruciate ligament (ACL) loading and therefore ACL injury risk (Khayambashi et al., 2016; Malloy et al., 2016; Mokhtarzadeh et al., 2013). Thus, to understand the dynamic function of the entire lower limb, and lower limb injury risk and prevention strategies, reliability of the control and capacity of all lower limb joint muscle groups must be known.

Reliable assessment of muscular strength is crucial for athletes and practitioners as it supports and informs accurate monitoring and performance tracking strategies (Bird & Markwick, 2016; Suchomel et al., 2016), allowing confidence in comparing outcomes across and within population groups (Bahr & Holme, 2003). These strength assessments are commonly undertaken using machine isokinetic dynamometry (MID), the gold standard method for research and clinical environments (Chamorro et al., 2017; Martin et al., 2006). The MID is reported to produce mechanically reliable and valid measures of strength across a range of positions, torques, and velocities during isokinetic and isometric tests (intraclass correlation coefficient (ICC) > 0.99) (Drouin

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et al., 2004). Test-retest reliability of MID has been reported extensively within athletic male populations (ICC >0.88) (Dirnberger et al., 2012; Duarte et al., 2018; McCleary & Andersen, 1992), and male and female general populations (ICC >0.79) (Aydoğ et al., 2004; Claiborne et al., 2008; Meyer et al., 2013; Sole et al., 2007; Taskiran et al., 2013). However, little research has investigated the test-retest reliability of the MID for the female athletic population (Andrade et al., 2016; Eustace et al., 2019; Jenner et al., 2024; Manson et al., 2014). Further, prior studies of female athletes have only focused on specific sporting populations (e.g. soccer), and the quadricep and hamstring muscle groups (Jenner et al., 2024; Manson et al., 2014), without consideration to other muscle groups known to contribute to lower limb injuries (Khayambashi et al., 2016; Malloy et al., 2016; Mokhtarzadeh et al., 2013). Investigation of the test-retest reliability of muscle groups acting on the hip, knee and ankle across a range of team-based female sports (e.g. Australian Rules Football (ARF), netball and soccer) would aid future injury risk profiling, athlete monitoring and rehabilitation techniques.

The aim of this study was to investigate the test-retest reliability of isokinetic and isometric lower limb peak torque to body mass of muscles acting on the hip, knee, and ankle in female team sport athletes. It was hypothesised that the test-retest reliability of isokinetic and isometric lower limb peak torque to body mass would be good (ICC ≥0.75) (Manson et al., 2014), supporting future injury risk profiling, athlete monitoring, rehabilitation strategies and performance tracking (Chamorro et al., 2017; Martin et al., 2006).

2. Methods

2.1. Participants

Thirty-eight, female, team sport athletes (ARF = 18, netball = 12, soccer = 8) with a mean age (± standard deviation, SD) of 23.8 ± 4.1 yrs, height of 1.68 ± 0.08 m, and body mass of 67.7 ± 11.5 kg were recruited from South Australian sporting clubs (recreational to semi-professional). A priori power analysis (G*Power v3.1, Düsseldorf, Germany) indicated a sample size of 27 was required (effect size 0.3, $p < 0.05$, power 0.8) to determine moderate reliability of tests (ICC ≥0.5) (Meyer et al., 2013). Inclusion criteria for participants included: aged between 16 and 35 yrs; minimum of 1 yr playing experience in their respective sport; no current or previous ACL injury; no history of lower extremity surgery; no current musculoskeletal injuries, chronic pain, or systemic condition; and no concussion within the 14 days prior to testing. Additionally, participants were screened via Stage 1 of the Exercise and Sports Science Australia Exercise Pre-Screening form to confirm their health status (Exercise & Sports Science, 2019). This study was approved by a Human Research Ethics Committee (203007) with written informed consent obtained from all participants and/or a parent/legal guardian, when required.

2.2. Experimental design

This study followed a repeated-measures cohort design. All testing was conducted during the sporting pre-season period at a biomechanics laboratory. Participants completed maximal isokinetic and isometric lower limb strength testing over three sessions to assess test-retest reliability (Fig. 1). The same investigator conducted each session to ensure consistent sequence and set-up of tests. Each session was performed a minimum of 48 h apart (Aydog et al., 2004; Dirnberger et al., 2012), and participants were encouraged not to complete any strenuous physical activity for the immediate 24 h prior to each session.

2.3. Instrumentation

A Biodex Isokinetic Dynamometer (System 3 Pro Dynamometer, Biodex Medical Systems, NY, USA) was used to assess the isokinetic and isometric strength of the hip, knee, and ankle joint muscle groups.

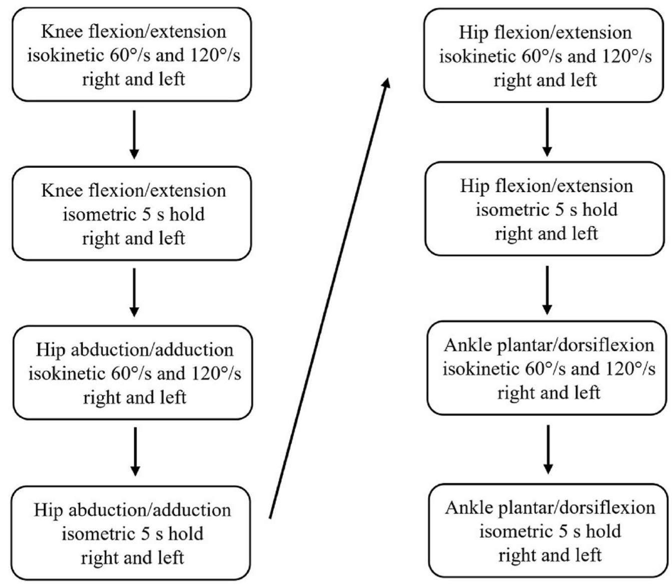

Fig. 1. Sequence of within session lower limb strength testing.

Previous mechanical reliability measures have been excellent (ICC >0.99) (Drouin et al., 2004). The machine was calibrated and set-up according to recommended software and hardware instructions (Biodex Medical Systems 1998a, 1998b). Muscle group actions were tested in the following order: knee flexion/extension; hip abduction/adduction; hip flexion/extension; and ankle plantarflexion/dorsiflexion (Fig. 1).

To assess knee flexion/extension strength, the participant was seated with the trunk and pelvis strapped to the dynamometer. The thigh of the testing limb was secured to avoid compensatory movements with the lower shank of the testing limb strapped against the dynamometer pad (Fig. 2A.). The calibration angle and start position of the test was 90° knee flexion with isometric tests completed at 20° knee flexion. Hip abduction/adduction, and hip flexion/extension strength, were assessed in standing positions with the thigh of the testing limb strapped against the dynamometer pad, as previously performed (Cahalan et al., 1989; Claiborne et al., 2008; Sugimoto et al., 2014a). For hip abduction/adduction, participants were positioned parallel to the dynamometer and instructed to hold onto it for stability whilst avoiding trunk or pelvis compensatory movements (Fig. 2B.). Hip flexion/extension were performed with the participant perpendicular to the dynamometer and instructed to hold onto the dynamometer and a rigid pole with the opposite hand (Fig. 2C.). The calibration angle and start position of both tests was 0° with isometric tests completed at 20° hip abduction and hip flexion. Ankle plantarflexion/dorsiflexion were performed with the participant seated and inclined (75°) in the dynamometer chair (Fig. 2D.). The thigh was supported with knee flexion at 30° to reduce contribution from other muscle groups where possible, and the ankle secured in the testing apparatus (Holmbäck et al., 1999). The trunk, pelvis, thighs, and ankle were strapped against the dynamometer to avoid compensatory movements. The calibration angle was 0° with start angle at maximal ankle plantarflexion with isometric tests completed at 20° ankle plantarflexion. All movements were cued and practiced with submaximal effort until participants were comfortable, prior to maximal testing.

Prior to test commencement the mass of the limb was measured by the MID (i.e. gravity correction) and the full range of motion (ROM) limits and calibration angle were set. The axis of rotation for the joint of interest was aligned with the mechanical axis of the MID using a consistent set-up procedure (Biodex Medical Systems 1998b).

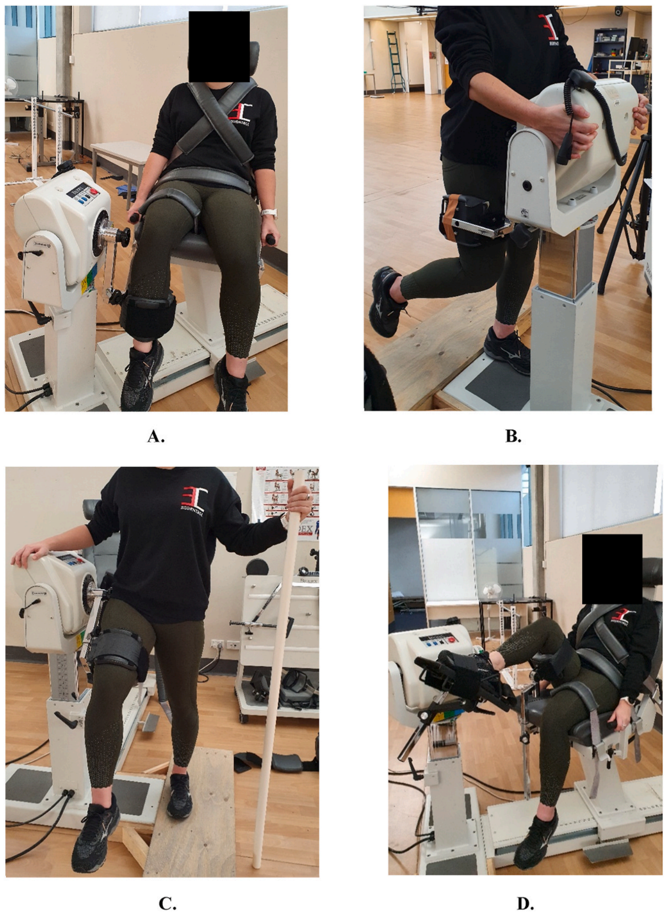

Fig. 2. Machine isokinetic dynamometry testing set-up positions. A. Knee flexion/extension, B. Hip abduction/adduction, C. Hip flexion/extension, D. Ankle plantarflexion/dorsiflexion.

2.4. Protocol

Upon arrival at the first testing session, the participant's height and mass were measured using a wall mounted stadiometer (SECA 216, Seca, NY, USA) and scales (TANITA DR-953 Inner Scan, Tanita, Tokyo, Japan), respectively. The dominant limb was determined by asking each participant which leg they would kick a ball with (Walsh et al., 2012). A dynamic warm-up was conducted prior to testing commencement, including 20 high knee skips, 10 leg swings (flexion/extension), 2 × 10 m runs at 50% of maximal speed, 2 × 10 m runs at 75% of maximal speed and 25 jumping jacks (modified from Manson et al. (2014)) prior to testing.

Isokinetic tests for each muscle group were conducted immediately before isometric tests to reduce fatigue effects and increase measurement efficiency (Fig. 1) (Thompson et al., 2018). Isokinetic testing included five repetitions per joint movement at angular velocities of 60°/s and 120°/s with 1 min rest between joints and velocities (Meyer et al., 2013). Isometric tests included three, maximal 5 s isometric contractions per limb with 30 s rest between repetitions. Participants were verbally encouraged consistently to perform at maximal effort for every repetition.

3. Data and statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics software version 25 (IBM Corp, NY, USA). Highest peak torque to body mass per limb from the best isokinetic and isometric repetitions were exported from the Biodex Isokinetic Dynamometer Software (Software, System 3 PRO, Rev N, version 3.30) for analysis. Mean and SD for testing sessions were calculated. All data was inspected through boxplots, identifying outliers in the dataset which were checked and corrected (if manual input error occurred). The Shapiro-Wilk goodness of fit test was used to check normality of the datasets. Repeated measures ANOVA and post-hoc, pairwise comparisons with a Bonferroni correction identified between session differences (e.g. 1 vs. 2, 1 vs. 3, 2 vs. 3) for all peak torque to body mass data. Test-retest reliability was assessed through $ICC_{3,1}$ where values < 0.50 were interpreted as poor, 0.50–0.75 as moderate, 0.75–0.90 as good and >0.90 as excellent (Portney & Watkins, 2009). Effect size (ES) (thresholds set as small = 0.2, moderate = 0.6, large = 1.2, very large = 2.0 and nearly perfect = 4.0) and typical error (TE) were calculated to represent magnitude of difference between sessions, and magnitude of error, respectively (Hopkins, 2015; Smith & Hopkins, 2011). TE was calculated by dividing the SD of the difference score by square root 2 (Hopkins, 2015). Mean and between-session (e.g. 1 vs. 2, 1 vs. 3, 2 vs. 3) ICC and TE are presented (Tables 1–3). The significance level was set at $p < 0.05$ for all analyses.

4. Results

All participants were unfamiliar with MID before participating in the study and completed the testing protocol successfully without pain or discomfort. Right limb dominance was reported by 90% of participants (34).

4.1. Isokinetic measurement at 60°/s

The mean isokinetic 60°/s lower limb strength assessments demonstrated moderate test-retest reliability for all movements (ICC = 0.64–0.74) besides right hip abduction, right and left hip adduction, left knee extension and left ankle plantarflexion (ICC = 0.79–0.85) which were good (Table 1). Peak torque to body mass for the right and left hip abduction and adduction were lower during session one compared with session three ($p < 0.05$). Left and right hip adduction were also lower during session one compared with session two ($p < 0.05$), and right hip adduction was lower during session two compared with session three ($p < 0.05$). Right and left ankle plantarflexion and dorsiflexion peak torque to body mass were lower during session one compared with session three, and session two compared with session 3 ($p < 0.05$). Lower peak torque to body mass was also observed during session one compared with session two for the right ankle plantarflexion and right and left dorsiflexion movements. All other movements showed similar peak torque to body mass values between sessions. Small to moderate ES (0.01–0.43) and TE (5.65–22.87) were observed for all movements (Table 1).

4.2. Isokinetic measurement at 120°/s

The mean isokinetic 120°/s lower limb strength assessments demonstrated moderate test-retest reliability for all movements (ICC = 0.57–0.75), besides left and right ankle dorsiflexion (ICC = 0.38–0.47) which were poor (Table 2). Peak torque to body mass for the right and left hip adduction were lower during session one compared with session three where right hip adduction was also lower during session one compared with session two ($p < 0.05$). Left and right ankle dorsiflexion and left plantarflexion were lower during session two compared with session three ($p < 0.05$). All other movements showed similar peak torque to body mass outcomes between sessions. Small ES (<0.16) and TE (7.78–24.49) were observed for all movements (Table 2).

4.3. Isometric measurement

Mean isometric lower limb strength assessments showed moderate test-retest reliability for all movements (ICC = 0.53–0.75), besides right hip flexion, right and left hip abduction and adduction, and left ankle

Table 1
Peak torque to body mass (N.m/kg) of hip, knee, and ankle muscle groups for the isokinetic 60°/s test.

Joint muscle group	Limb	Mean (SD)			ES	Sig.	$ICC_{3,1}$ (95%CI)			$ICC_{3,1}$ mean (95%CI)	TE (LL/UL)			TE mean (LL/UL)
		Sn. 1	Sn. 2	Sn. 3			Sn. 2-1	Sn. 3-1	Sn. 3-2		Sn. 2-1	Sn. 3-1	Sn. 3-2	
HF	Right	125.5 (26.5)	131.2 (27.5)	133.6 (22.6)	0.08	0.07	0.78 (0.61–0.88)	0.63 (0.40–0.79)	0.70 (0.50–0.83)	0.71 (0.58–0.83)	12.97 (10.58–16.79)	15.15 (12.35–19.60)	13.96 (11.38–18.06)	14.06 (12.29–16.63)
	Left	119.6 (24.5)	127.2 (29.3)	129.5 (27.1)	0.09	0.05	0.70 (0.49–0.83)	0.55 (0.28–0.73)	0.71 (0.51–0.84)	0.64 (0.48–0.78)	15.09 (12.30–19.52)	17.63 (14.37–22.81)	15.36 (12.53–19.88)	16.07 (14.05–19.01)
HE	Right	193.1 (34.9)	197.9 (35.8)	197.2 (37.8)	0.01	0.50	0.72 (0.52–0.84)	0.66 (0.44–0.81)	0.78 (0.62–0.88)	0.72 (0.58–0.83)	19.02 (15.51–24.61)	21.42 (17.46–27.71)	17.42 (14.20–22.54)	19.36 (16.92–22.90)
	Left	200.6 (39.6)	207.9 (45.3)	209.0 (43.7)	0.03	0.22	0.68 (0.46–0.82)	0.71 (0.51–0.84)	0.78 (0.62–0.88)	0.72 (0.58–0.83)	24.45 (19.93–31.63)	22.82 (18.60–29.52)	21.22 (17.30–27.46)	22.87 (19.99–27.05)
HAB	Right	101.1[b] (27.0)	107.0 (26.3)	109.9 (23.2)	0.15	**0.00**	0.84 (0.72–0.92)	0.76 (0.59–0.87)	0.88 (0.78–0.94)	0.83 (0.74–0.90)	10.77 (8.78–13.93)	12.45 (10.15–16.11)	8.83 (7.20–11.42)	10.78 (9.43–12.76)
	Left	102.4[b] (24.4)	109.2 (23.9)	110.1 (22.9)	0.12	**0.00**	0.68 (0.47–0.82)	0.60 (0.34–0.77)	0.77 (0.59–0.87)	0.71 (0.58–0.82)	12.44 (10.14–16.09)	13.09 (10.67–16.94)	11.39 (9.29–14.74)	12.33 (10.76–14.54)
HAD	Right	96.2[a],[b] (32.3)	112.0[b] (34.0)	118.9 (36.3)	0.43	**0.00**	0.85 (0.72–0.92)	0.82 (0.69–0.90)	0.89 (0.80–0.94)	0.85 (0.76–0.91)	13.28 (10.83–17.19)	14.74 (12.01–19.07)	12.06 (9.83–15.60)	13.41 (11.72–15.86)
	Left	98.3[a],[b] (35.1)	112.2 (35.9)	117.0 (36.8)	0.25	**0.00**	0.80 (0.64–0.89)	0.75 (0.57–0.86)	0.83 (0.69–0.91)	0.79 (0.68–0.87)	16.42 (13.39–21.25)	18.36 (14.97–23.76)	16.80 (14.69–19.88)	12.33 (10.76–14.54)
KF	Right	123.3 (19.9)	126.5 (23.2)	127.2 (25.8)	0.02	0.40	0.68 (0.47–0.82)	0.56 (0.29–0.74)	0.77 (0.60–0.87)	0.65 (0.50–0.78)	12.38 (10.09–16.01)	15.50 (12.64–20.06)	11.97 (9.76–15.49)	13.38 (11.70–15.83)
	Left	120.5 (21.4)	120.6 (22.5)	122.7 (24.5)	0.01	0.68	0.77 (0.61–0.88)	0.64 (0.41–0.80)	0.74 (0.55–0.85)	0.71 (0.57–0.82)	10.64 (8.67–13.76)	13.93 (11.35–18.02)	12.26 (10.00–15.87)	12.35 (10.80–14.61)
KE	Right	240.2 (38.9)	229.1 (38.6)	230.9 (36.7)	0.08	0.05	0.65 (0.41–0.80)	0.67 (0.45–0.81)	0.89 (0.80–0.94)	0.74 (0.61–0.84)	23.41 (19.09–30.29)	22.09 (18.01–28.57)	12.84 (10.47–16.61)	20.01 (17.49–23.67)
	Left	228.1 (36.7)	222.5 (38.3)	227.2 (36.1)	0.03	0.27	0.81 (0.66–0.90)	0.82 (0.69–0.90)	0.82 (0.68–0.90)	0.82 (0.72–0.89)	16.70 (13.62–21.61)	15.60 (12.72–20.18)	16.01 (13.06–20.72)	16.11 (14.09–19.06)
AP	Right	92.6[a],[b] (31.0)	106.5[b] (33.2)	117.4 (29.1)	0.36	**0.00**	0.72 (0.53–0.85)	0.68 (0.47–0.82)	0.75 (0.57–0.86)	0.72 (0.58–0.83)	17.21 (14.03–22.27)	17.23 (14.05–22.30)	15.95 (13.01–20.64)	16.81 (14.70–19.89)
	Left	101.0[b] (35.0)	107.6[b] (31.1)	115.4 (34.1)	0.17	**0.00**	0.74 (0.56–0.86)	0.75 (0.56–0.86)	0.85 (0.74–0.92)	0.79 (0.67–0.87)	17.06 (13.91–22.07)	17.74 (14.46–22.95)	12.74 (10.38–16.48)	16.00 (13.99–18.93)
AD	Right	35.7[a],[b] (10.5)	38.9[b] (10.7)	44.0 (8.9)	0.35	**0.00**	0.79 (0.63–0.88)	0.58 (0.32–0.76)	0.71 (0.50–0.84)	0.70 (0.56–0.82)	4.98 (4.06–6.44)	6.43 (5.24–8.32)	5.44 (4.44–7.04)	5.65 (4.94–6.68)
	Left	37.0[a],[b] (9.6)	40.2[b] (10.6)	45.2 (7.3)	0.34	**0.00**	0.77 (0.59–0.87)	0.46 (0.17–0.68)	0.63 (0.39–0.79)	0.64 (0.49–0.78)	4.97 (4.05–6.43)	6.28 (5.12–8.13)	5.65 (4.60–7.31)	5.66 (4.95–6.70)

AD = ankle dorsiflexion; AP = ankle plantarflexion; CI = confidence interval; ES = effect size; ICC = intraclass correlation coefficient; HAB = hip abduction; HAD = hip adduction; HE = hip extension; HF = hip flexion; KE = knee extension; KF = knee flexion; LL = lower limit; SD = standard deviation; Sig = significance; Sn = session; TE = typical error; UL = upper limit.

[a] < 0.05 vs. Sn. 2.

[b] < 0.05 vs. Sn. 3.

Table 2
Peak torque to body mass (N.m/kg) of hip, knee, and ankle muscle groups for the isokinetic 120°/s test.

Joint muscle group	Limb	Mean (SD)			ES	Sig.	$ICC_{3,1}$ (95%CI)			$ICC_{3,1}$ mean (95%CI)	TE (LL/UL)			TE mean (LL/UL)
		Sn. 1	Sn. 2	Sn. 3			Sn. 2-1	Sn. 3-1	Sn. 3-2		Sn. 2-1	Sn. 3-1	Sn. 3-2	
HF	Right	128.4 (26.3)	128.3 (27.7)	126.0 (26.3)	0.00	0.72	0.71 (0.51–0.84)	0.62 (0.38–0.78)	0.83 (0.69–0.91)	0.72 (0.58–0.83)	14.76 (12.03–19.10)	16.43 (13.40–21.26)	11.48 (9.36–14.86)	14.37 (12.57–17.00)
	Left	120.4 (22.8)	119.9 (26.1)	127.4 (26.8)	0.07	0.05	0.71 (0.50–0.84)	0.68 (0.46–0.82)	0.80 (0.65–0.89)	0.72 (0.58–0.83)	13.54 (11.04–17.52)	14.36 (11.70–18.57)	12.08 (9.85–15.63)	13.36 (11.68–15.80)
HE	Right	180.3 (29.2)	188.1 (35.9)	190.0 (42.0)	0.04	0.16	0.60 (0.36–0.77)	0.41 (0.11–0.64)	0.78 (0.61–0.88)	0.57 (0.40–0.72)	20.88 (17.02–27.01)	27.98 (22.81–36.20)	18.82 (15.34–24.35)	22.90 (20.02–27.09)
	Left	188.9 (34.6)	194.9 (42.8)	197.3 (52.1)	0.03	0.31	0.65 (0.42–0.80)	0.66 (0.44–0.81)	0.76 (0.58–0.87)	0.67 (0.51–0.79)	23.33 (19.02–30.19)	26.10 (21.28–33.77)	23.95 (19.52–30.98)	24.49 (21.41–28.97)
HAB	Right	105.4 (26.4)	104.5 (24.1)	103.3 (26.8)	0.00	0.80	0.54 (0.27–0.73)	0.55 (0.28–0.74)	0.80 (0.65–0.89)	0.63 (0.47–0.77)	17.32 (14.12–22.41)	18.11 (14.76–23.43)	11.63 (9.48–15.05)	15.95 (13.95–18.87)
	Left	104.7 (26.5)	103.0 (26.2)	102.7 (29.4)	0.00	0.77	0.63 (0.39–0.79)	0.64 (0.40–0.79)	0.86 (0.74–0.92)	0.71 (0.56–0.82)	16.30 (13.29–21.08)	17.11 (13.95–22.13)	10.82 (8.82–14.00)	15.01 (13.12–17.75)
HAD	Right	97.3[a],[b] (36.7)	110.1 (34.9)	112.6 (36.6)	0.16	**0.00**	0.70 (0.49–0.83)	0.69 (0.47–0.82)	0.85 (0.73–0.92)	0.75 (0.62–0.85)	20.03 (16.33–25.92)	20.90 (17.04–27.04)	14.23 (11.60–18.41)	18.62 (16.28–22.03)
	Left	94.6[b] (37.4)	105.0 (37.0)	107.1 (37.0)	0.10	**0.01**	0.71 (0.51–0.84)	0.68 (0.46–0.82)	0.82 (0.69–0.90)	0.74 (0.61–0.84)	20.34 (16.59–26.32)	21.35 (17.41–27.62)	15.88 (12.95–20.55)	19.34 (16.91–22.88)
KF	Right	112.5 (18.2)	109.5 (20.4)	112.8 (22.6)	0.02	0.40	0.68 (0.47–0.82)	0.59 (0.34–0.77)	0.73 (0.54–0.85)	0.65 (0.50–0.78)	11.03 (9.00–14.28)	13.26 (10.81–17.15)	11.30 (9.21–14.62)	11.90 (10.41–14.08)
	Left	109.1 (21.8)	106.8 (19.5)	107.5 (19.5)	0.00	0.74	0.72 (0.52–0.84)	0.51 (0.23–0.71)	0.65 (0.42–0.80)	0.63 (0.47–0.77)	11.20 (9.14–14.50)	15.34 (12.50–19.84)	12.32 (10.05–15.94)	13.07 (11.43–15.47)
KE	Right	190.5 (28.3)	187.6 (28.5)	188.4 (29.6)	0.01	0.66	0.72 (0.53–0.85)	0.63 (0.40–0.79)	0.83 (0.70–0.91)	0.73 (0.59–0.83)	15.25 (12.43–19.73)	17.78 (14.49–23.00)	12.23 (9.97–15.82)	15.25 (13.34–18.05)
	Left	185.8 (29.7)	185.2 (29.4)	185.3 (29.4)	0.00	0.98	0.75 (0.58–0.86)	0.68 (0.46–0.82)	0.82 (0.69–0.90)	0.75 (0.63–0.85)	14.91 (12.15–19.29)	16.96 (13.83–21.95)	12.64 (10.30–16.35)	14.94 (13.06–17.68)
AP	Right	96.8 (34.7)	98.6 (31.0)	107.0 (32.6)	0.08	0.08	0.74 (0.56–0.86)	0.67 (0.45–0.82)	0.74 (0.55–0.85)	0.72 (0.59–0.83)	17.01 (13.87–22.01)	19.58 (15.96–25.33)	16.64 (13.57–21.53)	17.79 (15.56–21.05)
	Left	102.3 (31.0)	98.6[b] (26.5)	110.2 (29.9)	0.10	**0.01**	0.71 (0.51–0.84)	0.61 (0.36–0.78)	0.67 (0.45–0.82)	0.67 (0.52–0.80)	15.73 (12.83–20.36)	19.31 (15.74–24.98)	16.42 (13.39–21.25)	17.22 (15.06–20.38)
AD	Right	37.2 (12.2)	37.4[b] (10.3)	41.8 (10.1)	0.09	**0.02**	0.47 (0.18–0.68)	0.31 (0.00–0.57)	0.56 (0.29–0.74)	0.47 (0.29–0.65)	8.30 (6.76–10.73)	9.31 (7.59–12.05)	6.89 (5.61–8.91)	8.23 (7.19–9.73)
	Left	38.6 (10.0)	39.0[b] (10.1)	43.4 (9.1)	0.10	**0.01**	0.57 (0.31–0.75)	0.12 (−0.20-0.42)	0.39 (0.09–0.63)	0.38 (0.20–0.57)	6.66 (5.43–8.61)	8.96 (7.31–11.59)	7.55 (6.16–9.77)	7.78 (6.80–9.20)

AD = ankle dorsiflexion; AP = ankle plantarflexion; CI = confidence interval; ES = effect size; ICC = intraclass correlation coefficient; HAB = hip abduction; HAD = hip adduction; HE = hip extension; HF = hip flexion; KE = knee extension; KF = knee flexion; LL = lower limit; SD = standard deviation; Sig = significance; Sn = session; TE = typical error; UL = upper limit.

[a] < 0.05 vs. Sn. 2.

[b] < 0.05 vs. Sn. 3.

Table 3
Peak torque to body mass (N.m/kg) of hip, knee and ankle muscle groups for the isometric test.

Joint muscle group	Limb	Mean (SD)			ES	Sig.	$ICC_{3,1}$ (95%CI)			$ICC_{3,1}$ mean (95%CI)	TE (LL/UL)			TE mean (LL/UL)
		Sn. 1	Sn. 2	Sn. 3			Sn. 2-1	Sn. 3-1	Sn. 3-2		Sn. 2-1	Sn. 3-1	Sn. 3-2	
HF	Right	117.5 (25.1)	122.1 (26.9)	123.3 (27.0)	0.05	0.11	0.73 (0.54–0.85)	0.72 (0.52–0.84)	0.89 (0.81–0.94)	0.78 (0.66–0.87)	13.67 (11.14–17.68)	14.09 (11.49–18.23)	8.99 (7.33–11.63)	12.47 (10.90–14.75)
	Left	110.2 (28.1)	112.1 (26.5)	115.3 (32.8)	0.02	0.39	0.60 (0.35–0.77)	0.56 (0.30–0.74)	0.85 (0.72–0.92)	0.67 (0.51–0.79)	17.43 (14.21–22.55)	20.51 (16.72–26.53)	11.95 (9.74–15.45)	17.00 (14.86–20.11)
HE	Right	110.9 (22.5)	116.5 (28.5)	117.0 (27.5)	0.06	0.08	0.75 (0.56–0.86)	0.69 (0.47–0.82)	0.85 (0.72–0.92)	0.75 (0.62–0.85)	13.20 (10.76–17.08)	14.31 (11.67–18.51)	11.22 (9.15–14.51)	12.97 (11.34–15.35)
	Left	112.0 (29.2)	113.5 (25.9)	117.2 (28.5)	0.03	0.30	0.71 (0.51–0.84)	0.73 (0.54–0.85)	0.74 (0.56–0.86)	0.74 (0.61–0.84)	15.04 (12.26–19.46)	15.16 (12.36–19.61)	14.03 (11.44–18.15)	14.75 (12.90–17.45)
HAB	Right	100.6 (25.0)	98.8 (24.7)	100.0 (23.2)	0.00	0.71	0.82 (0.67–0.90)	0.70 (0.50–0.83)	0.89 (0.81–0.94)	0.81 (0.70–0.89)	10.88 (8.87–14.08)	13.41 (10.93–17.35)	7.99 (6.51–10.33)	10.99 (9.60–13.00)
	Left	94.9 (26.1)	90.9 (24.2)	94.0 (24.1)	0.05	0.13	0.87 (0.77–0.93)	0.87 (0.76–0.93)	0.90 (0.81–0.94)	0.88 (0.81–0.93)	9.22 (7.52–11.93)	9.40 (7.66–12.16)	7.98 (6.51–10.33)	8.89 (7.77–10.52)
HAD	Right	124.9 (30.7)	121.2 (27.3)	126.7 (31.1)	0.05	0.14	0.87 (0.76–0.93)	0.82 (0.68–0.90)	0.83 (0.70–0.91)	0.84 (0.75–0.91)	10.77 (8.78–13.94)	13.41 (10.93–17.34)	12.21 (9.95–15.80)	12.18 (10.65–14.41)
	Left	133.4 (29.2)	133.7 (27.6)	130.8 (31.1)	0.01	0.55	0.85 (0.73–0.92)	0.80 (0.65–0.89)	0.81 (0.67–0.90)	0.82 (0.72–0.89)	11.33 (9.23–14.65)	13.69 (11.16–17.71)	13.03 (10.63–16.86)	12.72 (11.12–15.05)
KF	Right	143.8 (26.6)	137.4 (26.8)	136.4 (27.7)	0.05	0.12	0.64 (0.41–0.80)	0.52 (0.24–0.72)	0.72 (0.53–0.85)	0.63 (0.46–0.77)	16.22 (13.23–20.99)	19.04 (15.52–24.63)	14.58 (11.89–18.86)	16.72 (14.61–19.78)
	Left	136.6 (32.9)	131.6 (28.8)	131.7 (29.7)	0.02	0.45	0.53 (0.25–0.72)	0.54 (0.27–0.73)	0.72 (0.53–0.85)	0.61 (0.44–0.75)	21.54 (17.56–27.87)	21.52 (17.54–27.84)	15.69 (12.80–20.30)	19.78 (17.29–23.40)
KE	Right	81.0 (26.6)	77.4 (20.4)	83.7 (23.3)	0.03	0.26	0.51 (0.23–0.71)	0.32 (0.00–0.58)	0.75 (0.57–0.86)	0.54 (0.37–0.70)	16.76 (13.67–20.77)	20.77 (16.93–26.87)	11.09 (9.04–14.35)	16.69 (14.59–19.74)
	Left	88.9 (28.3)	91.0 (31.1)	86.2 (26.8)	0.01	0.60	0.46 (0.17–0.68)	0.38 (0.07–0.62)	0.58 (0.33–0.76)	0.47 (0.29–0.65)	22.03 (17.96–28.51)	21.85 (17.81–28.27)	18.99 (15.48–24.57)	21.00 (18.36–24.85)
AP	Right	125.1 (40.8)	124.9[a] (38.6)	138.6 (47.9)	0.11	**0.01**	0.71 (0.51–0.84)	0.65 (0.42–0.80)	0.85 (0.73–0.92)	0.73 (0.60–0.84)	21.63 (17.63–27.98)	26.78 (21.83–34.65)	17.27 (14.08–22.35)	22.24 (19.44–26.31)
	Left	118.1[a] (41.3)	122.3 (48.2)	132.6 (48.8)	0.11	**0.01**	0.78 (0.62–0.88)	0.76 (0.58–0.87)	0.85 (0.73–0.92)	0.79 (0.68–0.88)	21.49 (17.52–27.80)	22.60 (18.42–29.23)	19.05 (15.53–24.64)	21.10 (18.45–24.96)
AD	Right	54.8[a] (12.0)	53.9[a] (11.8)	61.2 (11.3)	0.19	**0.00**	0.70 (0.49–0.83)	0.37 (0.06–0.61)	0.50 (0.21–0.70)	0.53 (0.35–0.69)	6.65 (5.42–8.60)	9.31 (7.59–12.05)	8.31 (6.78–10.75)	8.16 (7.14–9.66)
	Left	53.8 (11.8)	53.4[a] (11.9)	59.2 (10.5)	0.13	**0.00**	0.71 (0.50–0.84)	0.26 (−0.06-0.53)	0.41 (0.11–0.64)	0.48 (0.30–0.65)	6.51 (5.30–8.42)	9.65 (7.87–12.48)	8.68 (7.07–11.22)	8.38 (7.33–9.91)

AD = ankle dorsiflexion; AP = ankle plantarflexion; CI = confidence interval; ES = effect size; ICC = intraclass correlation coefficient; HAB = hip abduction; HAD = hip adduction; HE = hip extension; HF = hip flexion; KE = knee extension; KF = knee flexion; LL = lower limit; SD = standard deviation; Sig = significance; Sn = session; TE = typical error; UL = upper limit.

[a] < 0.05 vs. Sn. 3.

plantarflexion (ICC = 0.78–0.88) which were good, and left knee flexion and left ankle dorsiflexion (ICC = 0.47–0.48) which were poor (Table 3). Right and left ankle dorsiflexion were lower during session two compared with session three with right ankle dorsiflexion also lower during session one compared with session three ($p < 0.05$). Right ankle plantarflexion was lower during session two compared with session three ($p < 0.05$), and left ankle plantarflexion was lower during session one compared with session three ($p < 0.05$). All other movements showed similar peak torque to body mass outcomes between sessions. Small ES (<0.19) and TE (8.16–22.24) were observed for all movements (Table 3).

5. Discussion

The purpose of this study was to investigate the test-retest reliability of isokinetic and isometric lower limb muscle strength in female team sport athletes. Poor to good test-retest reliability was observed for all joint movements across both isokinetic and isometric tests (ICC = 0.38–0.88). It was hypothesised that good test-retest reliability would be observed for all joint movements (ICC ≥0.75) which was not observed in the current study. Majority of peak torque to body mass differences were observed between sessions one and two and/or one and three with peak torque to body mass commonly lower in session one across all joint movements. This may be due to a learning effect, indicating that where possible, three testing sessions is recommended for future dynamometry assessments, or the addition of a familiarisation session in populations unfamiliar with dynamometry testing. These results provide practitioners with confidence in collecting reliable data, which can inform injury risk assessments, rehabilitation screenings or return to sport tests. To the authors knowledge, this study is the first to develop normative peak torque to body mass outcomes of the hip, knee, and ankle isokinetic and isometric muscle strength measures for female team sport athletes. This normative data will inform sporting industry staff and athletes about strength profiles to help with athlete rehabilitation and preparation for greater team sport success.

Inconsistencies in testing set-up protocols contribute to peak torque to body mass and test-retest reliability outcomes, creating doubt in delivering or interpreting dynamometry assessments. For example, ankle plantarflexion/dorsiflexion can be performed using different protocols, such as seated, supine or prone positions (Jenner et al., 2024). The ankle joint is difficult to isolate due to the posterior shank muscles crossing the knee joint (Fleming et al., 2001; Gonosova et al., 2018a; Gonçalves et al., 2017). Through supporting the knee joint at 30° of flexion, contribution from other muscle groups was reduced where possible. At 60°/s, both ankle plantarflexion and dorsiflexion demonstrated moderate to good reliability. However, at 120°/s and for the isometric test, ankle dorsiflexion showed poor to moderate reliability compared with ankle plantarflexion, demonstrating moderate to good reliability outcomes. Therefore, further analysis may be needed to determine the most effective and reliable position to assess dynamometry of the ankle joint movement across different positions and test types. The hip joint has also been tested in various positions, for example Manson et al. (2014) followed a prone position for hip flexion/extension, whereas other studies have followed standing, side-lying, seated or supine positions, each producing different reliability outcomes (Castro et al., 2020). Although it is more challenging to control and isolate hip muscles in a standing position, the current study followed a standing position and achieved moderate to good reliability. Therefore, this testing position is recommended as it isolates the hip joint and replicates specific movements of athletic populations. Consistency in the use of set-up protocols is important for future MID assessments, to allow for direct comparison between populations or athletes and the collection of reliable information specific to athletic populations.

Differences in peak torque to body mass were consistently seen between sessions, particularly for the isokinetic 60°/s test. Session one peak torque to body mass was often lower than sessions two and/or three, potentially indicating a learning effect for this group of participants. Prior studies have also observed a learning effect when examining dynamometry for knee flexion/extension, and ankle inversion/eversion assessments (Aydoğ et al., 2004; Larsson et al., 2003). Knee flexion/extension was one of two joint movements showing no differences between the three sessions. This is consistent with previous research for the isokinetic knee flexion/extension assessment (Tsiros et al., 2011). The robustness of this test may be due to the ability to isolate the knee joint more effectively than the hip or ankle joints with minimal compensatory methods possible. The protocol for knee flexion/extension has been reviewed extensively in previous literature and used consistently in current research methods with its moderate to excellent reliability evident across different populations (Andrade et al., 2012; Boden et al., 2000; Fousekis et al., 2010; Hewett et al., 2004; Jenner et al., 2024; Sole et al., 2007). Differences in peak torque to body mass were also seen between limbs for all tests where limb dominance may contribute to these outcomes. The right hip flexion and knee flexion showed higher peak torque to body mass outcomes compared with the left for all test types, where 90% of participants reported right limb dominance. Only the left hip extension showed greater outcomes than the right with all other tests demonstrating inconsistent differences between limbs.

The current study included three testing sessions to ensure that any learning effect was accommodated, and an accurate representation of peak torque to body mass and reliability outcomes could be observed. Nonetheless, our results demonstrated a change between sessions one and two, and sessions one and three, suggesting that the optimal number of testing sessions is yet to be determined. Where possible, three testing sessions is suggested, and/or the addition of a familiarisation session prior to testing, until further research is conducted. However, it is important to note that the participants were unfamiliar with MID testing before completing this study, therefore these recommendations are based on this population and may be different in populations who are familiar with MID testing.

This is the first study to develop normative peak torque to body mass outcomes of the hip, knee, and ankle isokinetic and isometric muscle strength measures for female team sport athletes. These results provide practitioners with normative data for the female team sport athlete population, which can inform injury risk assessments, rehabilitation screenings or return to sport tests, assisting with preparation for greater team sport success. This study was limited by no maximum standardized time between testing sessions (only minimum), inconsistencies regarding range of motion each participant reached, and inconsistencies regarding isolation of the joint muscle group and use of compensatory movements.

6. Conclusion

Poor to good test-retest reliability was observed for the muscles acting on the hip, knee and ankle joints for the female team sport athlete population. A learning effect was observed with three testing sessions and/or the addition of a familiarisation session recommended for all future dynamometry assessments in populations unfamiliar with dynamometry testing. Understanding the reliability of these hip, knee and ankle joint muscle group assessments and their respective sport specific protocols will give practitioners the confidence in utilising this information for athlete monitoring practices. Additionally, the normative peak torque to body mass data will assist in reference values for rehabilitation, return to sport protocols and benchmarks for this female athlete population.

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Ethics approval

This study was conducted according to the guidelines of the Declaration of Helsinki and approved by the University Ethics Committee approved on September 16, 2020.

Consent to participate

Informed consent was obtained from all participants and/or a parent/legal guardian, when required, involved in the study.

Consent to publish

Participants signed informed consent regarding publication of their data and images in Fig. 2.

Data availability statement

Not applicable.

Ethical approval

This study was approved by the Human Research Ethics Committee with written informed consent obtained from all participants and/or a parent/legal guardian.

CRediT authorship contribution statement

Brooke Jenner: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carmel Nottle:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Julie L. Walters:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Steven W. Saunders:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Anthony S. Leicht:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Robert G. Crowther:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

References

Andrade, M., De Lira, C., Koffes, F., Mascarin, N., Benedito-Silva, A., & Da Silva, A. (2012). Isokinetic hamstrings-to-quadriceps peak torque ratio: The influence of sport modality, gender, and angular velocity. *Journal of Sports Sciences, 30*(6), 547–553.

Andrade, M., Mascarin, N., Benedito-Silva, A., Minozzo, F., Vancini, R., & De Lira, C. (2016). Assessment of isokinetic peak torque reliability of the hip flexor, extensor, adductors and, abductors muscles in female soccer players from 16 to 25 years old. *The Journal of Sports Medicine and Physical Fitness, 56*(7), 843–848.

Aydoğ, E., Aydoğ, S., Çakci, A., & Doral, M. (2004). Reliability of isokinetic ankle inversion- and eversion-strength measurement in neutral foot position, using the biodex dynamometer. *Knee Surgery, Sports Traumatology, Arthroscopy, 12*(5), 478–481.

Bahr, R., & Holme, I. (2003). Risk factors for sports injuries — a methodological approach. *British Journal of Sports Medicine, 37*(5), 384–392.

Biodex Medical Systems. (1998a). *Biodex System 3 software manual, Biodex medical Systems*. New York: Inc.

Biodex Medical Systems. (1998b). *System 3 Pro application/operation manual*. New York: Biodex Medical Systems, Inc.

Bird, S., & Markwick, W. (2016). Musculoskeletal screening and functional testing: Considerations for basketball athletes. *International Journal of Sports Physical Therapy, 11*(5), 784–802.

Boden, B., Dean, S., Feagin, J., & Garrett, W. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics, 23*(6), 573–578.

Brophy, R., Silvers, H., & Mandelbaum, B. (2010). Anterior cruciate ligament injuries: Etiology and prevention. *Sports Medicine and Arthroscopy Review, 18*(1), 2–11.

Cahalan, T., Johnson, M., Liu, S., & Chao, E. (1989). Quantitative measurements of hip strength in different age groups. *Clinical Orthopaedics and Related Research*, (246), 136–145.

Castro, M., Ruschel, C., Santos, G., Ferreira, T., Pierri, C., & Roesler, H. (2020). Isokinetic hip muscle strength: A systematic review of normative data. *Sports Biomechanics, 19*(1), 26–54.

Chamorro, C., Armijo-Olivo, S., De la Fuente, C., Fuentes, J., & Javier, C. L. (2017). 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 Medicine, 12*(1), 359–375.

Claiborne, T., Timmons, M., & Pincivero, D. (2008). Test–retest reliability of cardinal plane isokinetic hip torque and EMG. *Journal of Electromyography and Kinesiology, 19*(5), 345–352.

Dirnberger, J., Kosters, A., & Muller, E. (2012). Concentric and eccentric isokinetic knee extension: A reproducibility study using the IsoMed 2000-dynamometer. *Isokinetics and Exercise Science, 20*(1), 31–35.

Drouin, J., Valovich-mcLeod, T., Shultz, S., Gansneder, B., & Perrin, D. (2004). Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *European Journal of Applied Physiology, 91*(1), 22–29.

Duarte, J., Valente-dos-Santos, J., Coelho-e-Silva, M., Couto, P., Costa, D., Martinho, D., Seabra, A., Cyrino, E., Conde, J., Rosado, J., & Gonçalves, R. (2018). Reproducibility of isokinetic strength assessment of knee muscle actions in adult athletes: Torques and antagonist-agonist ratios derived at the same angle position. *PLoS One, 13*(8), 1–12.

Eustace, S., Page, R., & Greig, M. (2019). Isokinetic strength differences between elite senior and youth female soccer players identifies training requirements. *Physical Therapy in Sport, 39*, 45–51.

Exercise and Sports Science Australia. (2019). *Adult pre-exercise screening system (APSS), 2* pp. 1–4). Exercise and Sports Science Australia. viewed 13 July 2021 https://www.essa.org.au/Public/ABOUT_ESSA/Pre-Exercise_Screening_Systems.aspx.

Fleming, B., Renstrom, P., Ohlen, G., Johnson, R., Peura, G., Beynnon, B., & Badger, G. (2001). The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *Journal of Orthopaedic Research, 19*(6), 1178–1184.

Fousekis, K., Tsepis, E., & Vagenas, G. (2010). Lower limb strength in professional soccer players: Profile, asymmetry, and training age. *Journal of Sports Science and Medicine, 9*(3), 364–373.

Gonçalves, G., Sendín, F., Da Silva Serrão, P., Selistre, L., Petrella, M., Carvalho, C., & Mattiello, S. (2017). Ankle strength impairments associated with knee osteoarthritis. *Clinical Biomechanics, 46*, 33–39.

Gonosova, Z., Linduska, P., Bizovska, L., & Svoboda, Z. (2018). Reliability of ankle–foot complex isokinetic strength assessment using the isomed 2000 dynamometer. *Medicina, 54*(3), 1–11.

Hecht, S., & Arendt, E. (2014). Training the female athlete. In M. Mountjoy (Ed.), *Handbook of sports medicine and science: The female athlete* (pp. 1–8). Hoboken, NJ, USA: John Wiley & Sons, Inc. Hoboken, NJ, USA.

Hewett, T., Ford, K., & Myer, G. (2006). Anterior cruciate ligament injuries in female athletes. Part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. *The American Journal of Sports Medicine, 34*(3), 490–498.

Hewett, T., Myer, G., & Ford, K. (2004). Decrease in neuromuscular control about the knee with maturation in female athletes. *The Journal of Bone and Joint Surgery, 86A*(8), 1601–1608.

Holmbäck, A., Porter, M., Downham, D., & Lexell, J. (1999). Reliability of isokinetic ankle dorsiflexor strength measurements in healthy young men and women. *Scandinavian Journal of Medicine & Science in Sports, 21*(4), 229–239.

Hopkins, W. (2015). Spreadsheets for analysis of validity and reliability. *Sportscience, 19*. viewed 24 October 2020 https://sportsci.org/2015/ValidRely.htm.

Jenner, B., Nottle, C., Walters, J., Saunders, S., Leicht, A., Palmer, B., & Crowther, R. (2024). The use of dynamometry for lower limb strength assessment in female team sport athletes: A scoping review. *Journal of Science in Sport and Exercise*, 1–15.

Kabacinski, J., Murawa, M., Mackala, K., & Dworak, L. (2018). Knee strength ratios in competitive female athletes. *PLoS One, 13*(1), 1–12.

Khayambashi, K., Ghoddosi, N., Straub, R., & Powers, C. (2016). Hip muscle strength predicts noncontact anterior cruciate ligament injury in male and female athletes a prospective study. *The American Journal of Sports Medicine, 44*(2), 355–361.

Knapik, J., Bauman, C., Jones, B., Harris, J., & Vaughan, L. (1991). Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *The American Journal of Sports Medicine, 19*(1), 76–81.

Larsson, B., Karlsson, S., Eriksson, M., & Gerdle, B. (2003). Test–retest reliability of EMG and peak torque during repetitive maximum concentric knee extensions. *Journal of Electromyography and Kinesiology, 13*(3), 281–287.

Malloy, P., Morgan, A., Meinerz, C., Geiser, C., & Kipp, K. (2016). Hip external rotator strength is associated with better dynamic control of the lower extremity during landing tasks. *The Journal of Strength & Conditioning Research, 30*(1), 282–291.

Manson, S., Brughelli, M., & Harris, N. (2014). Physiological characteristics of international female soccer players. *The Journal of Strength & Conditioning Research, 28*(2), 308–318.

Martin, H., Yule, V., Syddall, H., Dennison, E., Cooper, C., & Aihie, S. A. (2006). Is hand-held dynamometry useful for the measurement of quadriceps strength in older people? A comparison with the gold standard biodex dynamometry. *Gerontology, 52*(3), 154–159.

McCleary, R., & Andersen, J. (1992). Test-retest reliability of reciprocal isokinetic knee extension and flexion peak torque measurements. *Journal of Athletic Training, 27*(4), 362–365.

Meyer, C., Corten, K., Wesseling, M., Peers, K., Simon, J., Jonkers, I., & Desloovere, K. (2013). Test-retest reliability of innovated strength tests for hip muscles. *PLoS One, 8*(11), 1–8.

Mokhtarzadeh, H., Yeow, C., Hong Goh, J., Oetomo, D., Malekipour, F., & Lee, P. (2013). Contributions of the soleus and gastrocnemius muscles to the anterior cruciate ligament loading during single-leg landing. *Journal of Biomechanics, 46*(11), 1913–1920.

Portney, L., & Watkins, M. (2009). *Foundations of clinical research: Applications to practice* (3rd ed.). Upper Saddle River, New Jersey: Pearson/Prentice Hall.

Smith, T., & Hopkins, W. (2011). Variability and predictability of finals times of elite rowers. *Medicine & Science in Sports & Exercise, 43*(11), 2155–2160.

Sole, G., Hamrén, J., Milosavljevic, S., Nicholson, H., & Sullivan, J. (2007). Test-retest reliability of isokinetic knee extension and flexion. *Archives of Physical Medicine and Rehabilitation, 88*(5), 626–631.

Suchomel, T., Nimphius, S., & Stone, M. (2016). The importance of muscular strength in athletic performance. *Sports Medicine, 46*(10), 1419–1449.

Sugimoto, D., Mattacola, C., Mullineaux, D., Palmer, T., & Hewett, T. (2014). Comparison of isokinetic hip abduction and adduction peak torques and ratio between sexes. *Clinical Journal of Sport Medicine, 24*(5), 422–428.

Taskiran, O., Gzdugan, V., Sepici, V., & Meray, J. (2013). Test-retest and inter-rater reliability of isokinetic ankle dorsiflexor and plantar flexor strength measurement in healthy adults. *Turkish Journal of Physical Medicine and Rehabilitation, 59*(1), 32–35.

Thompson, B., Cazier, C., Bressel, E., & Dolny, D. (2018). A lower extremity strength-based profile of NCAA division I women's basketball and gymnastics athletes: Implications for knee joint injury risk assessment. *Journal of Sports Sciences, 36*(15), 1749–1756.

Tsiros, M., Grimshaw, P., Shield, A., & Buckley, J. (2011). Test-retest reliability of the biodex system 4 isokinetic dynamometer for knee strength assessment in paediatric populations. *Journal Of Allied Health, 40*(3), 115–119.

Walsh, M., Boling, M., McGrath, M., Blackburn, T., & Padua, D. (2012). Lower extremity muscle activation and knee flexion during a jump-landing task. *Journal of Athletic Training, 47*(4), 406–413.