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Effect of 6-week single leg countermovement jump training on force time metrics in elite female youth footballers

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ABSTRACT
Female football participation has grown exponentially. Unfortunately, females exhibit greater injury risk than male athletes, and experience increased mechanical stress during adolescence. Force plates provide accurate and reliable force-time characteristics enabling profiling of injury risk and benchmarking using a variety of jump and isometric tasks. The purpose of this study was to determine whether test-retest reliability and force-time characteristics of SLCMJ, bilateral countermovement jump (CMJ), countermovement rebound jump (CMJ-R) and isometric mid-thigh pull (IMTP) change with six weeks of SLCMJ training. Twenty-eight elite youth female footballers (13.7 ± 1.1 years, 53.27 ± 8.82 kg, 162.20 ± 5.37 cm) completed six weeks of SLCMJ as part of a routine strength and plyometric training program. SLCMJ training did not influence test-retest reliability and resulted in favourable adaptations indicated through small to large changes in force-time characteristics for SLCMJ. Significant ($p < 0.05$) yet trivial to small favourable changes were observed for the CMJ and CMJ-R, with small increases observed for IMTP. The results of this study demonstrate that six weeks of SLCMJ training does not influence phase-specific test-rest reliability (i.e. braking and propulsion) and causes weekly fluctuations in force-time characteristics leading to improvements in SLCMJ, CMJ, CMJ-R and IMTP. Practitioners can use such information to inform training design and monitor athlete performance.

KEYWORDS
Unilateral; vertical jump; adolescent; girls' soccer; force plates

Introduction

Participation in female football is growing exponentially with organised football estimated at approximately 16.6 million globally, increasing 24% from 2019 to 2023. Additionally, girls' youth competitions have grown from 1,717 in 2019 to 4,743 in 2023 (FIFA, 2023). This has led to greater exposure for training and competition and increased physical demands during match-play (Harkness-Armstrong et al., 2022). Football is an intermittent sport, involving high intensity bouts interspersed with periods of low intensity activity (Stølen et al., 2015). International female football players cover approximately 9–11 km during a match (Hewitt et al., 2014). High intensity running and sprinting distances during matches vary, due to the different locomotive thresholds used (high intensity running = 3.33–6.39 $m \cdot s^{-1}$, 395–2563 m, and sprinting 5–6.94 $m \cdot s^{-1}$, 119–777 m) (Vescovi et al., 2021). Other high intensity actions include jumping, accelerating, decelerating, cutting and changes of direction, which are often related to scoring opportunities (Lockie et al., 2018). These movements often include unilateral components which place a high demand on the musculoskeletal system (Hovey et al., 2021; Taylor et al., 2016), including greater knee moments (Taylor et al., 2016) and ground reaction forces (DiStefano et al., 2016). Further, injuries such anterior cruciate ligament rupture (ACL) are more likely to occur during unilateral tasks such as decelerations, landing manoeuvres and changes of direction (Grassi et al., 2017; Krosshaug et al., 2007; Shimokochi & Shultz, 2008). This highlights the importance of lower limb strength, power, reactive strength, motor control or a combination of these qualities to tolerate increasing loading.

Unfortunately, female athletes exhibit greater risk of non-bone related injuries i.e., soft tissue, such as ACL injuries, than male athletes which is attributed to several risk factors (López-Valenciano et al., 2021; Patel et al., 2021; Robles-Palazón et al., 2022). Strength is a modifiable risk factor that is strongly associated with injury risk (Ryman Augustsson et al., 2017; Suchomel et al., 2016), in particular, adolescent team sport athletes with higher vertical jumping asymmetries and lower jump performance are associated with increased injury risk (Fort-Vanmeerhaeghe et al., 2022). Thomas et al. (2017) reported lower relative strength during isometric and dynamics tasks in female football players compared to males and other team sports. Meanwhile, Jones et al. (2017) demonstrated better change of direction performance in eccentrically stronger athletes compared to weaker athletes. Interestingly, no sex-differences in rapid force generation have been reported between strength matched male and female athletes demonstrating the importance of strength development (Comfort et al., 2024), collectively highlighting the importance of combined resistance, ballistic and plyometric training to improve

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such modifiable factors (i.e., interlimb asymmetries and relative strength) to better prepare female athletes for the high intensity actions that occur during matches and are associated with greater injury risk (Bettariga et al., 2024; Comfort et al., 2024; Nimphius, 2019; Roso-Moliner et al., 2024).

However, the structural and neuromuscular changes occurring during adolescence leads to an increased mechanical stress, particularly in youth female football players (Emmonds et al., 2018). Researchers have highlighted the importance of including unilateral actions such as SLCMJ into female youth football training programs (Roso-Moliner et al., 2024), however combined strength and plyometric training interventions typically complete twice per week and over six weeks leads to improvements in physical performance (Ramirez-Campillo et al., 2018; Sánchez et al., 2020; Zhang et al., 2023) with unilateral training demonstrating superior improvements in performance (Bogdanis et al., 2019; Drouzas et al., 2020; Liao et al., 2022; Stern et al., 2020). Advanced physical qualities in youth female footballers are associated with superior linear speed and change of direction performance (Emmonds et al., 2019; Lockie et al., 2018; Roso-Moliner et al., 2024). These are often associated with actions relating to propulsion (Mero, 1988; Roso-Moliner et al., 2024). Results from Emmonds et al. (2018) highlighted increases in jump height and isometric mid-thigh pull (IMTP) absolute peak force (gross), but no change in relative peak force, suggesting that changes in performance are likely due to growth and maturation. A limitation of these studies is the use of contact mats or photocell devices which only provide information relating to the outcome of the jump (i.e., jump height, estimated from flight time) rather than the strategy adopted (e.g., time to take-off, countermovement depth). Additionally, jump height is calculated using the flight time using such methods, which is less advantageous and prone to greater error than determining jump height from the velocity of the centre of mass at take-off (Attia et al., 2017; Eythorsdottir et al., 2024; McMahon et al., 2016; Xu et al., 2023b).

Force plates have become increasingly popular in football (Weldon et al., 2021) and enable detailed analysis on task performance including six phases of CMJ tasks (McMahon et al., 2018). Such information enables practitioners to profile athletic performance and injury risk (Andersson et al., 2008; Bromley et al., 2021). The most common test used in football is the bilateral countermovement jump (CMJ) (Guthrie et al., 2023). The single leg CMJ (SLCMJ) has demonstrated acceptable within-session (Bishop et al., 2021), test-retest reliability (Fahey et al., 2024), and sensitivity to detect changes in neuromuscular performance (Bromley et al., 2021; Hart et al., 2019; Mitchell et al., 2021). Fu et al. (2022) highlighted meaningful interlimb differences in force-time characteristics for SLCMJ in university female footballers with non-dominant limb greater than dominant limb across numerous metrics. However, the terminology used to describe the phases of the CMJ do not relate to the correct biomechanical principles (Hahn, 2023). Specifically, the unweighting and braking phases are referred to the downward or eccentric phase, and propulsive phase is referred to the upward or concentric phase. This may mislead practitioners compromising validity compared to gold standard (McMahon et al., 2018; Merrigan et al., 2022).

Test-retest reliability has been reported in female youth footballers (Fahey et al., 2024), however the effect of weekly SLCMJ familiarisation in addition to regular in-season strength and conditioning training on force-time characteristics are unknown. Considering the increased injury risk and importance placed on strength and plyometric training in female football players, the purpose of this study was to (i) identify whether the inclusion of SLCMJ familiarisation in addition to regular in-season strength and conditioning training would influence the test-retest reliability of SLCMJ, (ii) assess whether SLCMJ force-time change following six weeks of training, and (iii) determine whether the underpinning bilateral physical qualities (i.e., CMJ, countermovement rebound jump (CMJ-R) and isometric mid-thigh pull (IMTP)) change following six weeks of training and if the reliability changes in elite youth female footballers. It was hypothesised that inclusion of SLCMJ training would not impact test-retest reliability within a week of testing, but force-time characteristics would change over the study duration due to adaptations to training.

Methods

Experimental design

An observational study design was used to monitor changes in test-retest reliability and force-time metrics in elite female youth footballers. An *a priori* sample size estimation was calculated based on two methods: reliability and mean difference. Reliability estimate used an expected intraclass coefficient correlation (ICC) of 0.91 (Mokkink et al., 2023), with lower bound 95% confidence interval (ICC-95) of 0.81 and minimum statistical power of 0.80 with three repeated measures, resulting in a minimum sample size of 29 participants. Mean difference estimate used an effect size of 0.712 (Sánchez et al., 2020), minimum statistical power of 0.80 and alpha probability of 0.05, resulting in a minimum sample size of 18 participants, using Jamovi 2.3.28. The higher sample size ($n = 29$) was used as a more robust requirement. SLCMJ was measured twice per week, separated by 48-hours during a six-week period as part of routine monitoring during a combined strength and plyometric training program (Figure 1, Table 1). Participants also completed three football session per week (Table 2). Test-retest reliability conducted across two sessions within 48-hours at the start, mid and end of the study for SLCMJ. Test-retest reliability was conducted start and end of the study for CMJ, CMJ-R and IMTP. This was because only 30-minutes was allocated for strength training before the participants field-based session. Prescription of the six-weeks strength and plyometric training were focused on technical competency with the addition on load once sufficient technique had been observed. Parental assent was obtained prior to the study which was approved by a local University institutional review board (ID. 13428) and conformed with the Declaration of Helsinki.

Participants

Thirty-two highly trained-to-elite youth female footballers (tiers 3–4, McKay et al., 2021), registered at an FA Tier One Plus Accredited Regional Talent Centre volunteered for the

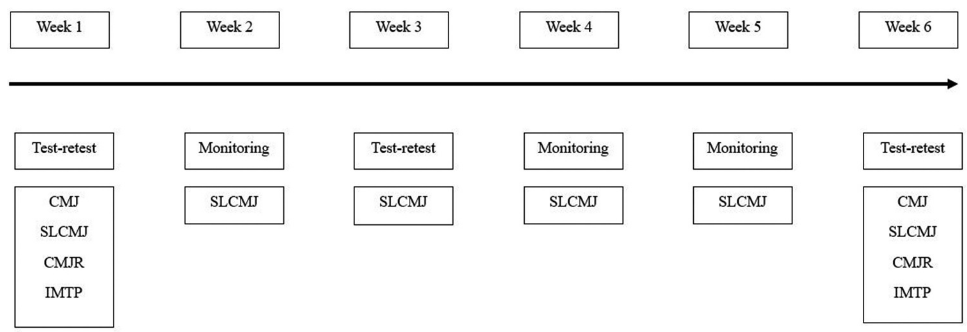

Figure 1. Testing schematic. CMJ = countermovement jump, SLCMJ = single leg countermovement jump, CMJ-R = countermovement rebound jump, IMTP = isometric mid-thigh pull.

Table 1. Strength and plyometric training program.

Exercise	Sets	Reps	Intensity range
Box Jump	3	4	30-60 cm
Broad Jump	3	4	Bodyweight
Pogo Jumps	3	10	Bodyweight
Split Squat	3	6 each limb	0 – 25 kg
Banded assisted pull up	3	8	Bodyweight
Press Up	3	10	Bodyweight
Squat	3	6	20-60 kg
Romanian deadlift	3	6	20-50 kg
Lateral lunge	3	6 each limb	5-20 kg
Single leg calf raises	3	8	0-15 kg

*Strength and plyometric program was completed twice per week separated by 48-hours.

Table 2. Field training program.

Monday	Wednesday	Thursday	Saturday
Technical training	Technical training	Futsal	Match
120 (minutes)	120 (minutes)	(60-minutes)	
Warm up	Warm up	Skills	
Passing	Passing	SSG's	
1v1 training	1v1 training		
Tactical	Tactical		
SSG's	SSG's		

study (13.6 ± 1.0 years, 53.65 ± 8.66 kg, 162.36 ± 5.30 cm). All participants had two years or more training experience consisting of two strength and conditioning sessions, three technical training sessions and one competitive match each week and were injury free. Two players sustained injuries during the first week of the study during technical training and were excluded, with a further two participants excluded due to not completing the final testing session ($n = 28$, 13.7 ± 1.1 years, 53.27 ± 8.82 kg, 162.20 ± 5.37 cm). Testing was conducted during the competitive season (October – December 2023).

Procedures

All testing was carried out at the Regional Talent Centre gymnasium (Figure 2) and was integrated in the participants allocated strength session, delivered by qualified and accredited strength and conditioning staff. A familiarisation session was completed prior to the testing allowing the participants to experience the different test requirements and verbal instructions. All participants had previous experience of CMJ, SLCMJ and CMJ-R within their training programs (Fahey et al., 2024). On arrival participants completed a standardized RAMP warm up including 5-minutes low level cycling, dynamic stretches and movements including squats, lunges, hops, and submaximal jumps. To reduce order effects, tests were completed in a randomised order. Tests were conducted using on a dual sensor portable force plate sampling at 1000 hz (Hawkin Dynamics Inc., Maine, USA). Foam surrounds placed around the force plates for participant safety during all jump tests.

IMTP was conducted by two accredited strength and conditioning professionals, in accordance with the recommendations of Comfort et al. (2019) ensuring that the posture reflected the start of the second pull phase of a clean; 125–145° knee angle and 140–150° hip angle. Weightlifting straps were used to eliminate grip strength as a limiting factor. Participants were required to remain as still as possible for at least 1-second to allow calculation of system mass. Strong verbal encouragement included 'push' with consistent instruction to as 'push as hard and as fast as possible for 3–5 seconds'. An additional trial was included in a difference of > 250 N was achieved between tests.

Figure 2. Isometric mid-thigh pull test setup.

CMJ, and CMJ-R were completed with arms akimbo. SLCMJ was completed with arms akimbo twice per week as part of routine combined strength and plyometric training program. Participants were required to stand centrally on each force plate (centrally on one plate for SLCMJ). For SLCMJ, dominant limb (DL) and non-dominant limb (NDL) were assigned based on kicking preference (Dos'Santos et al., 2021). Participants were instructed to 'jump as high and as fast as possible', contextualized to the phase of the jump, for example, 'jump as fast' refers to performing the countermovement, propulsive and rebound phases as quickly as possible. Any trials that involved hands coming off the hips, a slow countermovement, tucking of the knee and/or ankle, and/or use of contralateral limb was excluded from data analysis with a new trial performed. CMJ-R was performed with the same instruction as the CMJ but with the added instruction to rebound as high and as fast as possible upon landing from the initial CMJ portion of the task.

Data analysis

Vertical ground reaction force was low pass filtered at 50 hz in accordance with recommendations (Harry et al., 2022). All jump metrics were calculated automatically by the force plate software, in accordance with McMahon et al. (2018) which has been validated against a gold standard (Merrigan et al., 2022, 2024) and are defined in supplementary Table S1 (supplementary material, Table S1). The start of the jumps was identified when force reduced to > 5 standard deviations of the force during the one second weighting period. Relative metrics were calculated by dividing the absolute scores by body mass. The IMTP force-time data were analysed using an onset threshold of an increase in force > 3 standard deviations of the force during the one second period of quiet standing (as per manufacturer proprietary software settings), with the highest force achieved identified as the peak force, with system mass subtracted from this value to ensure that only net peak force was reported. Although five standard deviations are recommended for the onset of movement identification, these settings are fixed by the manufacturer setting but supported by Guppy et al. (2024).

Statistical analyses

A two-way mixed effect, absolute agreement ICC (model 3,1) was used to assess relative reliability (Koo & Li, 2016). ICC values were interpreted based on the lower bound 95% confidence interval (ICC-95) as: poor < 0.50, moderate 0.50–0.74, good 0.75–0.89 and excellent > 0.90, based on recommendations from Koo and Li (2016). Absolute reliability was interpreted from the upper 95% confidence interval for the CV (CV + 95) interpreted as: ≥15%, 10–15%, 5–10% and ≤ 5% were considered to represent poor, moderate, good and excellent absolute reliability, respectively. Standard error of measurement (SEM) was calculated by multiplying the ICC by the square root of 1 minus the pooled standard deviation (between participant standard deviation of sessions 1 and 2 combined). Minimal detectable change (MDC) was calculated by multiplying the square root of SEM^2 by 1.96. This was also expressed as a percentage by dividing MDC by the pooled mean (average of session 1 and 2 combined) and multiplying by 100.

A repeated measures analysis of variance (RM ANOVA) with Bonferroni post-hoc analysis and Hedge's g effect sizes (g) were used to determine between week differences in SLCMJ using JASP statistical software. An alpha level was set at $p < 0.05$, and ES were interpreted as 0.00–0.19 = trivial, 0.20–0.59 = small, 0.60–1.19 = moderate, 1.20–1.99 = large and ≥ 2.00 = very large. Data were bootstrapped to 1000 samples and are presented using marginal means ± standard error (SE).

Results

Test-retest reliability

DL SLCMJ had poor to excellent absolute reliability for pre-intervention (CV + 95 ≤ 16.32) and post-intervention (CV + 95 ≤ 17.24), with poor to good reliability for mid-intervention (CV + 95 ≤ 15.10). Relative reliability was moderate to excellent for pre-intervention (ICC-95 ≥ 0.536) and post-intervention (ICC-95 ≥ 0.812), with moderate to good reliability for mid-intervention (ICC-95 ≥ 0.679) (supplementary Table S2).

NDL SLCMJ had moderate to excellent absolute reliability for pre-intervention (CV + 95 ≤ 14.29), poor to excellent for reliability mid-intervention (CV + 95 ≤ 17.09) and post-intervention (CV + 95 ≤ 17.32). Relative reliability was moderate to excellent for pre-intervention (ICC-95 ≥ 0.684), mid-intervention (ICC-95 ≥ 0.684) and post-intervention (ICC-95 ≥ 0.730) (supplementary Table S2).

CMJ had moderate to excellent absolute reliability for pre-intervention (CV + 95 ≤ 11.38), and post-intervention (CV + 95 ≤ 10.60). Relative reliability was poor to excellent for pre-intervention (ICC-95 ≥ 0.354), and moderate to excellent for post intervention (ICC-95 ≥ 0.657) (supplementary Table S2).

The countermovement portion of the CMJ-R had moderate to excellent absolute reliability for pre-intervention (CV + 95 ≤ 14.70), and post-intervention (CV + 95 ≤ 13.50). Relative reliability was moderate to excellent for pre-intervention (ICC-95 ≥ 0.664), and poor to excellent for post intervention (ICC-95 ≥ 0.489). The rebound portion of the CMJ-R had poor to excellent absolute reliability for pre-intervention (CV + 95 ≤ 36.48), and poor to good for post-intervention (CV + 95 ≤ 43.37). Relative reliability was poor to excellent for pre- and post-intervention (ICC-95 ≥ 0.473) (supplementary Table S2).

IMTP had good to excellent absolute reliability for pre-intervention (CV + 95 ≤ 8.65), and post-intervention (CV + 95 ≤ 9.43). Relative reliability was moderate to good for pre-intervention (ICC-95 ≥ 0.598), and moderate to excellent for post intervention (ICC-95 ≥ 0.487) (supplementary Table S2).

Unilateral task between week differences

Small to large changes were observed across the training intervention DL SLCMJ ($p < 0.001$–0.345, $\eta p^2 = 0.042$–0.188) and NDL SLCMJ ($p = 0.005$–0.807, $\eta p^2 = 0.019$–0.119) (Figure 3 and Table 3). Post-hoc analyses revealed meaningful changes for NDL system weight (week 1 vs. 6, $p < 0.05$, g = 0.04), DL countermovement depth (week 1 vs. 6, $p < 0.05$, g = 0.34) (Figure 3 and

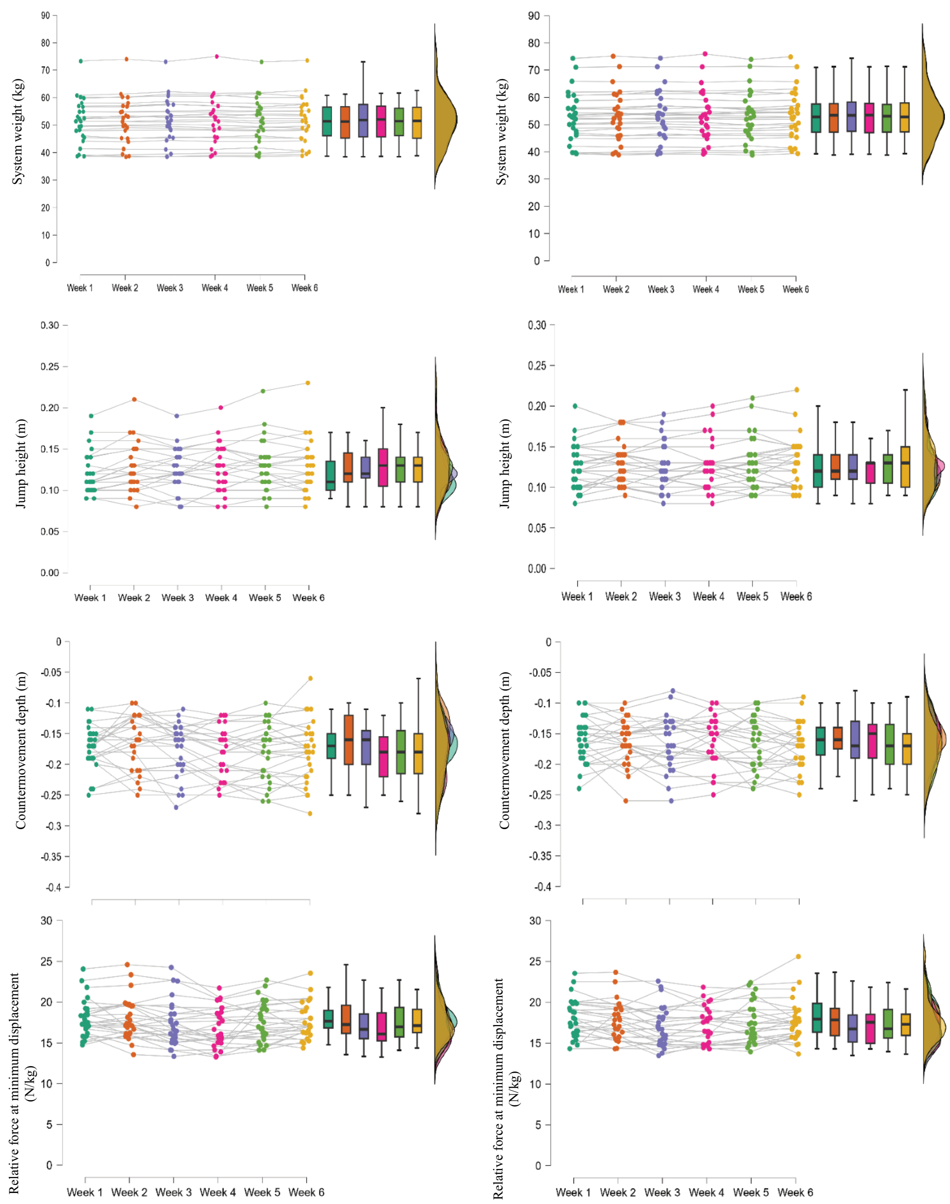

Figure 3. Weekly changes in DL SLCMJ (left) and NDL SLCMJ (right) for system weight, jump height, countermovement depth and relative force at minimum displacement.

Table 3. Weekly SL CMJ marginal means ± standard error for dominant and non-dominant limb.

	Dominant limb							Non-dominant limb						
Metric	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	P (η_p^2)	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	P (η_p^2)
Outcome														
Jump height (m)	0.12 ± 0.00	0.13 ± 0.01	0.13 ± 0.00	0.13 ± 0.01	0.13 ± 0.01	0.13 ± 0.01	<0.001 (0.148)	0.12 ± 0.01	0.13 ± 0.01	0.13 ± 0.01	0.13 ± 0.01	0.13 ± 0.01	0.13 ± 0.01	0.014 (0.103)
Take-off velocity ($m{\cdot}s^{-1}$)	1.52 ± 0.03	1.57 ± 0.03	1.55 ± 0.03	1.56 ± 0.03	1.58 ± 0.03	1.58 ± 0.04	0.001 (0.139)	1.54 ± 0.03	1.56 ± 0.03	1.55 ± 0.03	1.57 ± 0.03	1.57 ± 0.03	1.59 ± 0.04	0.008 (0.091)
Jump momentum (Kg. $m{\cdot}s^{-1}$)	80.17 ± 3.14	82.64 ± 3.26	82.18 ± 3.20	82.61 ± 3.33	83.23 ± 3.42	83.33 ± 3.36	0.003 (0.156)	81.81 ± 3.08	83.41 ± 3.09	83.04 ± 3.28	83.87 ± 3.28	83.84 ± 3.09	84.75 ± 3.10	0.006 (0.117)
Strategy														
Countermovement depth (m)	−0.17 ± 0.01	−0.16 ± 0.01	−0.18 ± 0.01	−0.18 ± 0.01	−0.18 ± 0.01	−0.18 ± 0.01	0.026 (0.092)	−0.16 ± 0.01	−0.16 ± 0.01	−0.16 ± 0.01	−0.16 ± 0.01	−0.17 ± 0.01	−0.17 ± 0.01	0.340 (0.042)
Braking phase (ms)	0.16 ± 0.01	0.16 ± 0.01	0.17 ± 0.01	0.19 ± 0.01	0.17 ± 0.01	0.16 ± 0.01	<0.001 (0.156)	0.16 ± 0.01	0.16 ± 0.01	0.18 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.049 (0.081)
Propulsive phase (ms)	0.29 ± 0.01	0.28 ± 0.01	0.30 ± 0.01	0.31 ± 0.01	0.30 ± 0.01	0.30 ± 0.01	<0.001 (0.170)	0.28 ± 0.01	0.28 ± 0.01	0.29 ± 0.01	0.28 ± 0.01	0.29 ± 0.01	0.28 ± 0.01	0.807 (0.019)
Kinetics														
Relative average braking force (N/kg)	1.58 ± 0.03	1.57 ± 0.03	1.54 ± 0.04	1.51 ± 0.03	1.55 ± 0.03	1.58 ± 0.03	0.003 (0.126)	15.44 ± 0.25	14.75 ± 0.63	14.84 ± 0.30	14.97 ± 0.25	15.06 ± 0.31	15.26 ± 0.31	0.021 (0.096)
Relative average propulsive force (N/kg)	1.56 ± 0.03	1.59 ± 0.03	1.57 ± 0.03	1.54 ± 0.03	1.57 ± 0.03	1.57 ± 0.03	0.010 (0.109)	15.55 ± 0.26	15.64 ± 0.252	15.45 ± 0.295	15.62 ± 0.285	15.64 ± 0.338	15.77 ± 0.337	0.652 (0.025)
Relative force at minimum displacement (N/kg)	1.84 ± 0.04	1.83 ± 0.05	1.77 ± 0.05	1.72 ± 0.04	1.79 ± 0.04	1.80 ± 0.04	<0.001 (0.170)	18.11 ± 0.54	17.80 ± 0.45	17.09 ± 0.47	17.22 ± 0.42	17.50 ± 0.48	17.66 ± 0.26	0.008 (0.112)

N.B. all metrics were significantly different across the 6-week intervention. P-and η_p^2 values relate to the repeated measures ANOVA.

Table 2) and mRSI (week 1 vs. 6, $p < 0.19$, g = 0.04). Trivial to small, non-meaningful changes were observed across all other weeks (g = 0.05–0.46, supplementary Table S3).

Bilateral task between week differences

Trivial to small changes from pre- to post-intervention for CMJ (g = 0.01–0.26), countermovement portion of the CMJ-R (g = 0.04–0.26) and rebound portion of the CMJ-R (g = 0.01–0.26) (supplementary table 4). Moderate changes were observed pre- to post intervention for IMTP (g ≥ 0.60) (supplementary Table 4).

Discussion

The purpose of this study was to assess whether six weeks of weekly SLCMJ jump training would influence test-retest reliability, and force time characteristics in CMJ, SLCMJ CMJ-R and IMTP in elite female footballers. The main findings were that inclusion of weekly SLCMJ training did not influence test-retest reliability and resulted in favourable adaptations indicated through small to large changes in force time metrics (jump height, take-off velocity, jump momentum, time to take-off, countermovement depth, braking phase duration, propulsive phase duration, relative average braking force, relative average propulsive force, and relative average force at minimum displacement) for SLCMJ. Force-time characteristics were also improved in CMJ, CMJ-R and IMTP to trivial to small magnitudes. These findings support our original hypotheses for reliability and force-time characteristics. The results of this study provide important information to practitioners highlighting that six weeks of familiarisation did not influence reliability of SLCMJ metrics and metrics that demonstrate poor test-retest reliability would offer minimal insight when assessing SLCMJ performance in elite female youth footballers. Practitioners should consider metrics with good to excellent test-retest reliability when monitoring athletic performance. Further, practitioners could include weekly SLCMJ as part of training to improve force-time characteristics and unilateral vertical jump performance including jump height, jump momentum (and thereby relative propulsive net impulse).

Given the increased utilization of force plates in football, it is important that practitioners select reliable metrics based on typical error and calculation of appropriate minimal detectable change thresholds for monitoring and benchmarking (Swinton et al., 2022; Swinton & Murphy, 2022). Bishop et al. (2021) reported moderate to excellent within-session reliability for SLCMJ, based off the point estimate statistic (i.e., ICC). This study is the first to assess test-retest reliability specific to elite female youth footballers across an in-season training cycle which included weekly SLCMJ prescription and provides similar findings to previous findings in elite female youth footballers (Fahey et al., 2024) based of the lower bound 95% CI for the ICC and upper bound 95% CI for the CV%. This approach provides a stricter criterion for reliability, enabling practitioners to envision the worst case-scenario for reliability. Franceschi et al. (2023) reported test-retest reliability for CMJ in elite youth male footballers using the same criterion as the present study, highlighting good to excellent absolute reliability and moderate to excellent relative reliability. In comparison to our findings, similar SLCMJ relative reliability was observed with jump height (ICC-95 = 0.85–0.91) and mRSI (ICC-95 = 0.80–-0.83), with greater relative reliability for force at minimum displacement (ICC-95 = 0.85–0.88). Absolute reliability was reported as a point estimate rather than upper bound confidence intervals (Fraceshi et al., 2023) thus making comparisons difficult. Further the metric terminology reported by Franceshi et al. (2023) are different to the current study and relate to muscle actions (i.e., eccentric, concentric) rather than the correct biomechanical principles (i.e., braking and propulsion). For the countermovement portion of the CMJ-R, similar findings were observed in comparison to Xu et al. (2023a) for jump height (ICC-95 = 0.90 vs 0.93, CV + 95 = 6.63 vs 6.09) and time to take-off (ICC-95 = 0.66 vs 0.64, CV + 95 = 11.58 vs 10.83%) whereas mRSI relative reliability was greater at baseline (ICC-95 = 0.79 vs 0.67) yet absolute reliability was lower (CV + 95 = 11.58 vs 10.83%). Rebound jump height demonstrated poor reliability in the CMJ-R compared to Xu et al. (2023a) (ICC-95 = 0.54 vs 0.87); however, this improved following six weeks (ICC-95 = 0.80). Grgic et al. (2022) reported good-excellent reliability based on point estimate ICC and CV. The results of the present study demonstrate good absolute reliability for gross, net and relative peak force (CV < 10%) whereas relative reliability ranged from moderate too good for gross peak force (ICC-95 = 0.86), net peak force (ICC-95 = 0.74) and relative peak force (ICC-95 = 0.60). It should be noted that all metrics demonstrated good relative reliability following six weeks (ICC-95 > 0.75). A limitation of the previous studies is that these were not assessed longitudinally whereas the present study monitored in-season changes in reliability. Based on these findings, practitioners can identify reliable metrics for benchmarking (i.e., jump height, jump momentum, average braking and propulsive force and duration, mRSI and relative braking and propulsive net impulse) and monitoring purposes (i.e., jump height, jump momentum, average braking and propulsive force, relative braking and propulsive net impulse) with confidence in the reliability. Future researchers may wish to establish this in specific populations such as wider age categories and longer durations (i.e., multiple seasons).

Regarding outcome metrics, moderate to large main effects were observed for jump height, take-off velocity and jump momentum in DL and NDL SLCMJ ($p < 0.05$, $\eta p^2 \geq 0.09$). However, pairwise comparisons revealed non-meaningful changes in both limbs. It should be noted that changes in jump height exceeded the MDC for DL and NDL (MDC = 0.04 m, 0.00 m, respectively), however as the 95% CI crossed zero, changes in scores are deemed not significant or meaningful. The lack of meaningful pairwise comparisons may be due to the intervention duration, with programs ≥ eight weeks demonstrating large effect on jump height compared to moderate effects for programs < eight weeks, or twelve session (Ramirez-Campillo et al., 2020). Compliance rate ranged from 75–100% (9–12 session) which may further explain these findings. Fu et al. (2023) reported greater SLCMJ jump heights in female footballers using force plates (DL = 16.92 ± 4.02 cm, NDL = 17.47 ± 3.61 cm) whilst Emmonds et al. (2018) reported increased power output with age in elite female youth footballers because of increased body mass and bilateral CMJ jump height. However data from the current study is not directly comparable to those previously reported for several methodological differences, for example recruitment of older athletes and inclusion of arm swing (Fu et al., 2023) and the use of photocell devices (Emmonds et al., 2018) as these do not measure instantaneous velocity demonstrating poor accuracy and artificially inflate power scores in comparison to the impulse-momentum method when using force plates (Attia et al., 2017; Linthorne, 2001, 2021; McMahon et al., 2016; Xu et al., 2023b). Jump momentum (take-off velocity × system mass) increased following the training intervention which was likely explained by trivial increases in take-off velocity. Jump momentum can provide information for monitoring as changes in body mass may influence jump strategy and outcome metrics (McMahon et al., 2018; Owen et al., 2023; Spencer et al., 2023). Considering the increased mechanical stress caused by increases in body mass during adolescence (Emmonds et al., 2018), future research may wish to consider changes in jump momentum when monitoring and benchmarking athletic performance in youth athletes.

Regarding strategy metrics, small to large main effects were observed for countermovement depth, braking phase and propulsive phase durations in DL and NDL SLCMJ ($p < 0.001–0.807$, $\eta p^2 \geq 0.042$). Pairwise comparisons revealed no meaningful changes in both limbs for each metric as the 95 CI's crossed zero. These changes may further explain changes in outcome metrics (i.e., take-off velocity) as participants increased their countermovement depth, braking and propulsive phase durations, and therefore impulse. Previous findings highlight the influence of countermovement depth on CMJ performance, strategy and kinetics (Jidovtseff et al., 2014; Kirby et al., 2011; Pérez-Castilla et al., 2021). The increase exposure of SLCMJ and combined strength training may explain the changes in displacement and temporal metrics due to improved stability (Liao et al., 2022). As with the outcome metrics fluctuations beyond the MDC were observed during the training cycle (countermovement depth and braking phase duration in both limbs), but these were deemed non-meaningful. Such changes may be useful for monitoring practices but are insufficient to identify changes to establish benchmarking (Swinton et al., 2022).

Regarding kinetic metrics, small to large main effects were observed for relative force at minimum displacement, relative average braking force and relative average propulsive force in DL and NDL SLCMJ ($p < 0.001–0.652$, $\eta p^2 \geq 0.025$). Pairwise comparisons revealed no meaningful changes in both limbs for each metric as the 95 CI's crossed zero. For both limbs, as participants increased their countermovement depth which resulted in application of force to a greater mass over a longer duration, they were able to increase their impulse. The increased impulse, where greater force is applied to a greater mass, possibly over a longer duration (i.e., greater countermovement depth) enables greater acceleration, take-off velocity (and momentum), and thus jump height (Linthorne, 2001). This may be the result of combined strength and plyometric training which has demonstrated improvements in jump performance (Bogdanis et al., 2019, Drouzas et al., 2020; Liao et al., 2022; Sánchez et al., 2020; Stern et al., 2020; Zhang et al., 2023). Weekly fluctuations greater than the MDC were observed for NDL but not DL, which may be explained by changes in system weight greater than the MDC, reflecting a less stable weighing phase during the SL CMJ. Acute changes in body mass and jump strategy may help to explain the increases in jump height, take-off velocity, and jump momentum.

For the bilateral tasks, CMJ mRSI increased due to a small increase in jump height and reduction in time to take-off. Interestingly, participants increased their countermovement depth but performed faster braking and propulsive phases, meaning participants applied greater braking and propulsive forces to increase their impulse. Increased impulse may have a translated benefit from SLCMJ training as slower muscle contraction and movement velocities, meaning an increased duration of force application, are observed in unilateral jumps compared to bilateral (Bobbert et al., 2006). Similar findings have been demonstrated following 10 weeks of training (Cormie et al., 2009; Hoffman et al., 2022). This would highlight a favourable adaptation to training as participants were able to reduce their time to take-off whilst achieving small increases kinetic and outcome measures.

Trivial to small changes were observed for CMJ-R mRSI, CMJ height, time to take-off within the CMJ phase and RSI, ground contact time (GCT) and rebound jump height within the rebound phase. Participants had small reductions in rebound depth, relative average braking force and force at minimum displacement, demonstrating a stiffer braking strategy was adopted. However, trivial increases were observed for rebound relative propulsive force. These results may be explained by the limited exposure to such training during the training cycle. It should be acknowledged that jump height was lower in the CMJ portion of the CMJ-R when compared CMJ alone, with rebound jump height being similar to CMJ jump height. These findings are similar to Xu et al. (2023a) and Talpey et al. (2022) and highlights that players did not perform the CMJ portion of the CMJ-R maximally, potentially due to a lack of familiarity, or an adopted strategy to try and perform the rebound task faster. Further, ground contact time was >250 ms, demonstrating an ineffective use of the stretch shortening cycle. Despite this, ground contact times in the present study are shorter than those reported in male NCAA American footballers (Talpey et al., 2022) and sport science students (Xu et al., 2023a). Future researchers may wish to consider the effect of weekly CMJ-R training in this population and the effect of alternative criteria (e.g., ground contact time <250 ms) to determine acceptable trials (Ünver et al., 2024).

Moderate increases in peak force (gross, net, and relative) for IMTP highlight a positive training response. These improvements could be an effect of weekly SLCMJ training which has demonstrated improved performance in bilateral tasks (Bogdanis et al., 2019). Higher forces are generated during SLCMJ compared to bilateral CMJ because of slower contraction and movement velocity (Bobbert et al., 2006). The slower contract velocities during SLCMJ which are closer to their optimum, resulting in greater impulse (Bobbert et al., 2006). Emmonds et al. (2018) reported increases in relative peak force in U14 players (+1.7 N/kg) from pre- to mid-season but decreases from mid to post season, attributing these findings to large increases in body mass because of maturation. Absolute peak force has also been shown to increase with age and maturation (Emmonds et al., 2018), however relative strength did not change. This highlights a potential problem for strength and conditioning coaches working with youth female footballers who should aim to develop effective training programs to ensure relative strength increases during maturation and enables athletes to cope with increasing mechanical stress.

A limitation of the current study is that the information covers narrow age range of elite youth footballers (U13-U14). Future research should consider monitoring changes in force time characteristics over a longer duration (e.g., months and consecutive seasons). Further information spanning a wider range of youth footballers would be more insightful, with a goal to provide normative benchmarks across a range of performance tests.

This is the first study to monitor weekly changes in SLCMJ in female footballers using force plates providing evidence of the utility of the SLCMJ during in-season training. The key findings highlight that weekly SLCMJ has did not influence test-retest reliability within youth athletes and practitioners working with youth female footballers can effectively monitor metrics such as jump height, jump momentum, relative average braking and propulsive force, relative net propulsive impulse force during in-season training with greater confidence. Weekly changes in SLCMJ appear to be trivial to small in magnitude whereby participants increase their jump momentum (and thereby relative propulsive net impulse) by achieving greater displacement and applying force over a longer duration. Practitioner can implement SLCMJ training in-season to achieve favourable changes in SLCMJ performance and are recommended to conduct component analysis of impulse to effectively identify the mechanisms responsible for changes in jump height. Trivial to small changes in CMJ, CMJ-R and IMTP performance are likely explained by an adapted movement strategy and improved strength from combined strength and SLCMJ training. Practitioners may use this information to select reliable metrics for profiling (ICC) and monitoring (CV) SLCMJ performance during in-season strength training to support athletic development of elite female youth footballers and reduce injury risk.

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