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Jump performance, lower limb function and inter-limb asymmetry: Seasonal variation in university team-sport athletes

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Abstract

Thirty-eight university basketball, hockey and netball athletes (age: 20.1 ± 1.4 yrs; height 1.8 ± 0.1 cm; body mass: 77.6 ± 12.7 m) completed bilateral and unilateral countermovement (CMJ) and horizontal jumps (HJ) across four seasonal time-points. Mixed-design ANOVAs assessed longitudinal sex- and sport-based differences in jump performance (normalised height/ distance), lower limb function (normalised CMJ power and impulse) and inter-limb asymmetry. Kappa coefficients (κ) assessed directional consistency in asymmetry scores. Males consistently outperformed females across all measures (all $p < 0.05$) and basketballers exhibited larger HJ distances and improved lower limb function than hockey and netball players (all $p < 0.05$). HJ performance and unilateral CMJ power improved significantly across the sample from preseason to competition (all $p < 0.05$), but improvements in CMJ performance and impulse were only observed in females and netballers. HJ derived inter-limb asymmetry decreased from preseason to competition (all $p < 0.05$), while CMJ derived asymmetries remained unchanged. Directional consistency in asymmetry was poor to substantial (κ = –0.20–0.80), with over 60% of athletes switching limb preferences across timepoints and up to 42% between tasks. These findings support the use of multidirectional jump testing for seasonal monitoring, although practitioners should consider both sport-specific and sex-specific factors when interpreting jump performance, function and asymmetry across a season.

Keywords

Basketball, gender, hockey, impulse, netball, power

Introduction

Jumping, both horizontally and vertically, is a fundamental movement in multidirectional team sports. The frequency and purpose of jumping, nonetheless, varies between sports and across positions.[1–3] In a 60-min netball match, for example, players were observed to perform approximately one jump per minute, however the goal shooter performed 36 fewer jumps than the wing attack.[2] Sport-specific jump performance is influenced by a combination of maximal strength, power output and technique efficiency which all contribute to increasing impulse prior to take-off, a key determinant of improved jump performance.[4–6] In practice, countermovement jump (CMJ) and horizontal jump (HJ) displacement are commonly used to assess an athlete's ability to maximise impulse prior to take-off. Although jump performance and strategy have been shown to vary independently by sex,[4,5,7,8] sport-specific demands,[9] and over the course of a season,[10–12] it remains unclear how the interaction between sex and sport-specific task-demands influences jump outcomes, lower limb neuromuscular function, and inter-limb asymmetry, or how these fluctuate across a season.

Jump displacement, typically quantified by vertical jump height or horizontal jump distance, is commonly used to indicate lower limb performance capabilities in both research and applied settings.[13–16] Jump performance is sensitive to neuromuscular adaptations and training effects, and has been used to quantify inter-limb asymmetry scores, making it a valuable measure for athlete monitoring.[15–17] Notably differences in jump performance have been observed between sexes, with males generally achieving greater displacement due to higher

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force and power production,[4,5,7,8] although normalising to anthropometrics may attenuate these differences.[6] These findings have led to jump displacement being utilised as a pseudo-measure for lower limb strength and power, particularly in the field where laboratory style rigour is impractical. Furthermore, performing the jump tests on force plates allows lower limb peak force, power and impulse to be determined, providing insight into movement strategies and technique. This approach has revealed sport-specific variations in force-time characteristics with higher performance outputs in sports displaying force-dominant strategies, which aim to maximise explosive force in shorter contact times, versus those with time-dominant strategies, characterised by longer contact times and lower forces.[9]

Inter-limb asymmetry, defined as the difference in function or output between limbs, has gained prominence in athlete monitoring due its association with injury risk and compromised performance.[13,1418–25] Asymmetries are commonly evaluated using CMJ and HJ tests with differences expected in limb dominance characteristics between unilateral and bilateral variations.[26] These measures are often used to inform return-to-play protocols, rehabilitation progress, and strength training interventions.[2127–30] However, the calculation and interpretation of asymmetry remains contested.[31] Arbitrary thresholds (e.g., 10–15%) are frequently applied to define 'meaningful' asymmetry, despite a lack of empirical support and the known influence of task, metric and individual variability.[31,32] Recent recommendations encourage the use of task-specific asymmetry indices that account for both magnitude and direction, and advocate for an individual approach to interpretation using sample-specific thresholds and individual variability to enhance practical relevance.[32,33]

Current findings suggest that the CMJ may be more sensitive than the HJ to seasonal changes in asymmetry,[11,12] although directionality is highly variable within individuals and may mask meaningful changes over time.[10,34] Furthermore, existing studies are typically limited to small, male-only cohorts within single sports, restricting the generalisability of findings. Only one known study has included both sexes across multiple sports.[12] Finally, most athlete monitoring protocols assess athletes once per mesocycle (e.g., pre-, mid-, end-season), which may not adequately capture intra-mesocycle fluctuations. Therefore, the purpose of this research study was to investigate seasonal variation in jump performance, lower limb function and inter-limb asymmetry in male and female athletes competing in different team sports.

Methods

Participants

A simulation-based *a priori* power analysis was conducted in MATLAB (R2025a, Mathworks Inc, Natick, MA) to estimate the minimum sample size required to detect a three-way interaction effect (sex×sport×time) in a $2 \times 3 \times 4$ mixed-design analysis of variance (ANOVA). Monte Carlo simulations (1000 iterations per sample size) assuming a medium effect size (Cohen's $f = 0.25$) and an alpha level of 0.05, indicated that a total sample size of 312 participants (i.e., 52 per sex×sport group) was required to achieve 80% statistical power. However, since it was not feasible to recruit a sufficiently large and varied sample to support a full three-way analysis, the effects of sex and sport were examined via two independent two-way analyses instead.

For each independent two-way analysis, an *a priori* power analysis was conducted using G*Power (Version 3.1, Düsseldorf, Germany) for a 2×4 (sex×time) and a 3×4 (sport×time) mixed-design ANOVA. To achieve 80% statistical power assuming a medium effect size (Cohen's $f = 0.25$), an alpha level of 0.05, a correlation among repeated measures of 0.5 and a nonsphericity correction of 1.0, a minimum of 24 participants would be required for a two-group comparison (12 per sex) and a minimum of 30 participants for the three-group comparison (10 per sport).

A total of 38 university team-sport athletes were therefore recruited, following a detailed health screening questionnaire to ensure eligibility, and provided written informed consent in accordance with the guidelines of Nottingham Trent University's Human Invasive Ethics Committee (ID: 1535801, version 1.0, dated: 19/07/2022). To be eligible, athletes were required to be aged between 18 and 35 years and actively competing in the British University and Colleges Sport (BUCS) League during the data collection season. They had to be healthy, with no lower limb musculoskeletal injuries in the six months prior to or during the study period, and free from any known illness or condition that could affect jumping performance. Athletes were also required to have participated in basketball, netball or hockey as their primary sport for a minimum of one year and routinely perform vertical and horizontal jump testing as part of their training and monitoring programme. These team sports were selected based on the primary reliance on lower limb function, as well as alignment in seasonal structure and availability for repeated testing. For athletes involved in multiple sports, their primary sport was identified as the one requiring the greatest weekly time commitment. Participants were instructed to report any injuries sustained during the study and to complete an injury report form. Those who became ineligible during the study were withdrawn and their data excluded from analysis. The final sample size was expanded to meet the minimum group power requirements across both independent groups (sex and sport) whilst also accounting for potential attrition (Table 1).

Data collection

Each participant attended Nottingham Trent University's Biomechanics Laboratory on four occasions, each lasting approximately two hours, during the 2022/2023 BUCS

Table 1. Participant characteristics and demographic frequencies for the study sample.

	Frequencies									Demographics		
		Sex		Sport			Level					
	All	M	F	B	H	N	L1	L2	L3	Age (years)	Height (m)	Mass (kg)
All	38	21	17	12	16	10	5	14	19	20.1 ± 1.4	1.78 ± 0.11	77.6 ± 12.7
Male				10	11	0	3	7	11	20.3 ± 1.2	1.84 ± 0.08	85.1 ± 9.4
Female				2	5	10	2	7	8	19.8 ± 1.5	1.71 ± 0.09	68.4 ± 9.8
Basketball		10	2				0	8	4	20.8 ± 1.4	1.87 ± 0.08	87.9 ± 10.1
Hockey		11	5				4	1	11	20.0 ± 1.3	1.74 ± 0.09	74.1 ± 12.5
Netball		0	10				1	5	4	19.5 ± 1.2	1.74 ± 0.07	71.0 ± 7.9

Note: body mass is the average value across all four timepoints. *Abbreviations: M = male; F = female; B = basketball; H = hockey; N = netball; L1 = international; L2 = national; L3 = university.*

season (1st August 2022 to 31st March 2023). Two testing sessions were conducted during two meso-cycles of the season: pre-season (1-August/September and 2-September/October) and competition (1-November/December and 2-February/March) with no testing during the off-season. Participants were scheduled to attend sessions at approximately the same time of day across all visits, and training data were collected using a self-reported training form to monitor team-level programming goals throughout the season.

At the start of each visit, participants' height and body mass were recorded using a stadiometer and calibrated scales, before completion of a standardised warm-up consisting of jogging, dynamic stretches (e.g., walking lunges, hamstring sweeps, side lunges), sprinting and acceleration-deceleration drills, followed by three familiarisation CMJ and HJ attempts. Upon completion of the warm-up, participants were reintroduced to the testing procedures and additional practice attempts were permitted for each jump prior to maximal effort testing.

Three maximal effort CMJs, separated by 60 s of rest, were performed bilaterally first, followed by three unilateral efforts on each leg, beginning with the right. Kinetic data were collected using an embedded multiaxial dual force plate system (AMTI, Watertown, MA, USA), sampling at 1000 Hz. Participants were instructed to stand upright with hands on their hips and one foot centred on each force platform, then squat to a self-selected depth and rapidly explode upward to achieve maximal height, without excessive hip or knee flexion during flight or on landing. For unilateral tests, participants were instructed to flex the free knee to approximately 90° and to minimise swinging of the non-jumping limb to reduce its contribution to jump height, in a manner similar to the influence of arm swing.[35] To encourage maximal effort, participants were permitted to land on one or two feet regardless of the task. An attempt was considered successful if the hands remained on the hips, there was no excessive hip or knee flexion during the airborne phase, and landing was completed with extended hips, knees and ankles. Unsuccessful attempts were repeated following a 60-s rest period. Instructions were consistent across all four time points and standardised feedback was provided to ensure proper technique.

Upon completion of the CMJ attempts, three maximal effort HJs, separated by 60 s of rest, were performed bilaterally first, followed by three unilateral efforts on each leg, beginning with the right. Jump distance was measured using a tape measure as the perpendicular distance from the start line at take-off to the heel of the first landing foot. Participants were instructed to stand with their toes directly behind the start line and to jump as far forward as possible to achieve maximal horizontal distance. An attempt was considered successful if the first landing foot did not move upon contact with the ground and the hands remained on the hips throughout the jump. To minimise learning effects, additional attempts were completed if the jump distance improved by more than 10 cm between attempts.

Data processing

Kinetic data for each CMJ were exported unfiltered into a custom-made Excel spreadsheet for analysis.[36,37] Jump height, net impulse and peak power during the propulsive phase, were determined due to their association with performance.[38] Upon inspection of the pre-season CMJ force-time histories, the attempts across most participants lacked a clear body-weight phase suggesting the unweighting phase had begun prior to recording. To maintain consistency and validity across all four time points, jump height was calculated using the flight-time method, which has demonstrated highly validity and reliability.[39–41] Take-off and landing were defined as the instants when vertical ground reaction force (GRF) crossed a threshold equal to five times the standard deviation of the vertical force during the first 300 milliseconds of flight.[36,37,42] Jump height (CMJ) and jump distance (HJ) were both normalised to participant

Table 2. Inter-limb asymmetry thresholds (using sample-specific thresholds and individual CV values) and category frequencies.

	Countermovement Jump		Horizontal Jump	
	"Small to moderate"	"High to extreme"	"Small to moderate"	"High to extreme"
Preseason 1	11.11% (5)	17.58% (4)	7.47% (6)	13.52% (2)
Preseason 2	8.17% (6)	12.47% (6)	5.46% (9)	8.81% (4)
Competition 1	8.24% (5)	13.32% (6)	3.36% (6)	5.80% (6)
Competition 2	9.94% (8)	16.47% (3)	4.56% (8)	6.84% (5)

(n) = number of athletes whose asymmetry score exceeded their individual CV% and the specified threshold

height to account for anthropometric differences between individuals.

Net vertical impulse during the CMJ was derived by using jump height to calculate vertical centre of mass (COM) take-off velocity via the equations of constant acceleration, combined with each participant's body mass. Peak power was defined as the maximum power output during the propulsive phase normalised to body mass. Power output during the propulsive phase was calculated by multiplying the vertical GRF time history by the vertical COM velocity time history. The vertical COM velocity time history was obtained by integrating the net vertical acceleration (i.e., GRF minus body weight, divided by body mass) and scaled to align with the previously derived vertical COM take-off velocity. Peak power was defined as the maximum power output during the propulsive phase and was normalised to body mass.

Inter-limb asymmetries in jump performance (CMJ height and HJ distance) were quantified to detect both asymmetry magnitude and direction between right and left limbs (Equation 1).[31] The mean of the two best trials was used to compute an asymmetry index score (ASI) for unilateral jump tests at each timepoint.

$$ASI = \frac{(A - B)}{Max(A, B)} \times 100 \quad (1)$$

where ASI = asymmetry index score (%), A = right limb value, B = left limb value.

Statistical analysis

All statistical analyses were performed using SPSS v.29 (IBM Corporation, USA). To ensure consistency across participants and sessions, the two best bilateral and unilateral CMJ and HJ attempts (defined as those producing the greatest jump height or distance), were selected for analysis at each time point. Within-session reliability was assessed for these attempts using the coefficient of variation (CV) and two-way mixed effects intraclass correlation coefficients (ICC) for absolute agreement. All tests and groups demonstrated excellent ICC values (>0.90),[43] and acceptable CV values (<10%)[44,45] at each time point.

Normality of each jump performance and asymmetry variable was assessed using boxplots and Shapiro-Wilk tests, which indicated violations of the assumption of normality ($p < 0.05$) across both performance and asymmetry metrics. To address this, all data were subsequently log transformed prior to analysis. Asymmetry data were transformed using $log_{10}(|x| + 1)$ to account for the presence of negative values in the dataset.

A two-way (2 × 4) mixed design ANOVA, with an alpha significance level of 0.05, was conducted to examine differences in log transformed jump performance and asymmetry metrics between sexes across timepoints. A second two-way (3 × 4) mixed design ANOVA was performed using the same approach to assess differences between sports across timepoints. The magnitude of change for group-level comparisons was calculated using a corrected effect size (Hedges, *g)* in accordance with recommendations for small and unequal sample sizes.[45] Effect sizes were interpreted as trivial ($g < 0.2$), small ($0.2 \le g < 0.5$), medium ($0.5 \le g < 0.8$), and large ($g \ge 0.8$).

Interpretation of ASI values was conducted relative to each participant's test CV at the corresponding time point, based on the rationale that asymmetries exceeding an individual's within-session variability may be considered meaningful.[33] Sample-specific thresholds (Table 2) were used to categorise asymmetry scores: "small to moderate" asymmetries were defined as scores greater than the population mean plus the smallest worthwhile change (SWC; 0.2 × between-subject SD), while "high to extreme" asymmetries were defined as scores exceeding the population mean plus one standard deviation (1.0 × between-subject SD). Cohen's kappa coefficients were calculated to assess consistency in asymmetry direction (i.e., consistency in preference for the right or left limb) between timepoints and jump tests which goes undetected when using absolute asymmetry scores in traditional statistical analyses. The strength of agreement was characterised as follows: poor (≤ 0); slight (0.01–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), perfect (0.81–1.00).

Results

Jump performance

Significant interactions in bilateral CMJ height were observed for both sex and sport over time ($p < 0.02$), with

Table 3. Group means and standard deviations for normalised height and inter-limb asymmetry scores (absolute values) in the bilateral and unilateral countermovement jump at four timepoints throughout the season.

	Preseason 1	Preseason 2	Competition 1	Competition 2
Bilateral (m)				
× All	***0.19 ± 0.04***	***0.19 ± 0.04***	***0.19 ± 0.03***	*0.19 ± 0.04*
**** Male***	^{F} ***0.21 ± 0.04***	^{F} ***0.20 ± 0.04***	^{F} ***0.20 ± 0.04***	^{F} ***0.21 ± 0.04***
**** Female***	^{M} ***0.16 ± 0.02*** ^{C1}	^{M} ***0.17 ± 0.02*** ^{C1}	^{M} ***0.17 ± 0.02*** ^{P1,P2}	^{M} ***0.17 ± 0.02***
Basketball	0.20 ± 0.05	0.20 ± 0.05	0.20 ± 0.04	0.20 ± 0.05
Hockey	0.19 ± 0.03	0.19 ± 0.03	0.19 ± 0.03	0.19 ± 0.04
Netball	***0.16 ± 0.03*** ^{C1,C2}	***0.17 ± 0.02*** ^{C1,C2}	***0.18 ± 0.02*** ^{P1,P2}	***0.18 ± 0.02*** ^{P1,P2}
Unilateral: Right (m)				
All	0.10 ± 0.02	0.10 ± 0.02	0.10 ± 0.02	0.10 ± 0.02
**** Male***	^{F} ***0.11 ± 0.02***	^{F} ***0.11 ± 0.02***	^{F} ***0.11 ± 0.02***	^{F} ***0.11 ± 0.02***
**** Female***	^{M} ***0.09 ± 0.02***	^{M} ***0.09 ± 0.02***	^{M} ***0.09 ± 0.01***	^{M} ***0.09 ± 0.02***
Basketball	0.11 ± 0.02	0.11 ± 0.02	0.11 ± 0.02	0.11 ± 0.03
Hockey	0.10 ± 0.02	0.10 ± 0.02	0.10 ± 0.02	0.10 ± 0.02
Netball	0.09 ± 0.02	0.09 ± 0.02	0.09 ± 0.01	0.09 ± 0.02
Unilateral: Left (m)				
All	0.10 ± 0.03	0.10 ± 0.02	0.10 ± 0.02	0.10 ± 0.02
**** Male***	^{F} ***0.11 ± 0.03***	^{F} ***0.11 ± 0.02***	^{F} ***0.11 ± 0.02***	^{F} ***0.11 ± 0.03***
**** Female***	^{M} ***0.09 ± 0.02***	^{M} ***0.09 ± 0.02***	^{M} ***0.09 ± 0.01***	^{M} ***0.09 ± 0.02***
Basketball	0.11 ± 0.03	0.11 ± 0.03	0.11 ± 0.03	0.10 ± 0.03
Hockey	0.10 ± 0.02	0.10 ± 0.02	0.10 ± 0.02	0.10 ± 0.02
Netball	0.09 ± 0.03	0.09 ± 0.01	0.09 ± 0.02	0.09 ± 0.02
Unilateral: ASI (%)				
All	9.5 ± 8.1	7.1 ± 5.4	7.0 ± 6.4	8.3 ± 8.2
Male	9.8 ± 9.3	5.9 ± 4.1	7.4 ± 7.3	8.1 ± 7.9
Female	9.1 ± 6.7	8.6 ± 6.4	6.4 ± 5.2	8.6 ± 8.7
Basketball	10.7 ± 10.6	6.9 ± 3.0	9.8 ± 8.2	11.8 ± 11.8
Hockey	8.3 ± 6.3	5.3 ± 4.6	5.0 ± 4.1	8.2 ± 5.7
Netball	9.9 ± 7.9	10.2 ± 7.5	6.7 ± 6.2	4.3 ± 3.8

Note:

- ***Bold italics*** indicate significance at $p < 0.05$, ***bold italics with underlining*** indicate significance at $p < 0.01$.
- An '×' preceding time (All) headings represents a significant interaction of time×sex or time×sport.
- An '*' preceding time (All), sex and sport row headings represents significant main effects of time, sex or sport.
- M and F represent significant sex differences between males and females, respectively.
- B, H, and N represent significant sport differences between basketball, hockey and netball, respectively.
- P1, P2, C1, and C2 represent significant time differences between preseason-1, preseason-2, competition-1 and competition 2, respectively.
- *Abbreviations: ASI = asymmetry index score.*

females ($p < 0.05$, $g = 0.31$ to 0.46) and netballers ($p < 0.05$, $g = 0.35$ to 0.66) showing a significant increase during the competition phase compared to preseason but males, basketballers and hockey players showing no changes (Table 3). No significant differences were observed for unilateral CMJ height (Table 3) but normalised HJ distances increased over the season for all participants ($p < 0.01$), with greater unilateral and bilateral distances during the competition phase compared to preseason ($p < 0.05$, $g = -0.61$ to 0.47; Table 4).

Males demonstrated greater normalised jump displacements than females ($p < 0.01$) across all CMJ and HJ variations for all time points (CMJ: $p < 0.05$, $g = 0.87$ to 1.61; HJ: $p < 0.05$, $g = 0.79$ to 2.28). On average, normalised CMJ height was 2–4 cm higher in males than in females (Table 3), while normalised HJ distance was 10–12 cm greater in males across jump variations (Table 4).

Significant differences were observed between sports for normalised HJ distance ($p = 0.05$), with netballers exhibiting shorter distances compared to basketball (bilateral: $p < 0.05$, $g = 0.85$ to 1.04; right: $p < 0.05$, $g = 1.60$ to 1.75; left: $p < 0.05$, $g = 1.48$ to 1.57) and hockey (bilateral: $p < 0.01$, $g = 1.39$ to 1.60; right: $p < 0.05$, $g = 0.90$ to 1.29; and left: $p < 0.05$, $g = 0.63$ to 1.18) players at all timepoints (Table 4). No significant differences were found between sports for bilateral or unilateral CMJ jump height (Table 3).

Lower limb function

Significant interactions in both bilateral and unilateral CMJ impulse were observed between sexes over time ($p < 0.02$;

Table 4. Group means and standard deviations for normalised distance and inter-limb asymmetry scores (absolute values) in the bilateral and unilateral horizontal jump at four timepoints throughout the season.

	Preseason 1	Preseason 2	Competition 1	Competition 2
Bilateral (m)				
*** All**	***0.96 ± 0.12*** $^{C1, C2}$	***0.98 ± 0.13*** $^{C1, C2}$	***1.00 ± 0.12*** ^{P1,P2}	***1.01 ± 0.12*** ^{P1,P2}
*** Male**	^{F} ***1.01 ± 0.12***	^{F} ***1.04 ± 0.13***	^{F} ***1.05 ± 0.12***	^{F} ***1.06 ± 0.12***
*** Female**	^{M} ***0.91 ± 0.09***	^{M} ***0.91 ± 0.09***	^{M} ***0.95 ± 0.08***	^{M} ***0.94 ± 0.09***
*** Basketball**	^{N} ***1.00 ± 0.14***	^{N} ***1.00 ± 0.16***	^{N} ***1.03 ± 0.14***	^{N} ***1.03 ± 0.15***
*** Hockey**	^{N} ***1.00 ± 0.09***	^{N} ***1.03 ± 0.10***	^{N} ***1.04 ± 0.08***	^{N} ***1.05 ± 0.09***
*** Netball**	$^{B, H}$ ***0.87 ± 0.09***	$^{B, H}$ ***0.88 ± 0.08***	$^{B, H}$ ***0.91 ± 0.09***	$^{B, H}$ ***0.91 ± 0.09***
Unilateral: Right (m)				
*** All**	***0.83 ± 0.12*** ^{P2,C1,C2}	***0.86 ± 0.10*** ^{P1,C1}	***0.89 ± 0.11*** ^{P1,P2}	***0.87 ± 0.11*** ^{P1}
*** Male**	^{F} ***0.87 ± 0.12***	^{F} ***0.89 ± 0.10***	^{F} ***0.94 ± 0.10***	^{F} ***0.91 ± 0.11***
*** Female**	^{M} ***0.78 ± 0.10***	^{M} ***0.81 ± 0.09***	^{M} ***0.82 ± 0.07***	^{M} ***0.82 ± 0.08***
*** Basketball**	0.85 ± 0.14	0.88 ± 0.12	^{N} ***0.93 ± 0.12***	^{N} ***0.90 ± 0.13***
*** Hockey**	^{N} ***0.87 ± 0.08***	0.87 ± 0.08	^{N} ***0.90 ± 0.08***	^{N} ***0.90 ± 0.07***
*** Netball**	^{H} ***0.76 ± 0.11***	0.80 ± 0.10	^{B,H} ***0.81 ± 0.09***	^{B,H} ***0.79 ± 0.08***
Unilateral: Left (m)				
*** All**	***0.83 ± 0.14*** ^{C1,C2}	***0.84 ± 0.12*** ^{C1,C2}	***0.89 ± 0.10*** ^{P1,P2}	***0.87 ± 0.10*** ^{P1,P2}
*** Male**	^{F} ***0.87 ± 0.15***	^{F} ***0.90 ± 0.11***	^{F} ***0.94 ± 0.10***	^{F} ***0.91 ± 0.09***
*** Female**	^{M} ***0.78 ± 0.10***	^{M} ***0.78 ± 0.10***	^{M} ***0.82 ± 0.07***	^{M} ***0.82 ± 0.09***
*** Basketball**	0.83 ± 0.19	^{N} ***0.88 ± 0.14***	^{N} ***0.92 ± 0.13***	0.88 ± 0.13
*** Hockey**	0.86 ± 0.10	^{N} ***0.87 ± 0.08***	^{N} ***0.91 ± 0.06***	^{N} ***0.90 ± 0.08***
*** Netball**	0.76 ± 0.11	$^{B, H}$ ***0.76 ± 0.10***	$^{B, H}$ ***0.81 ± 0.09***	^{H} ***0.80 ± 0.07***
Unilateral: ASI (%)				
*** All**	***6.0 ± 7.6*** ^{C1}	***4.6 ± 4.2*** ^{C1}	***3.1 ± 2.7*** ^{P1,P2}	4.0 ± 2.9
Male	6.5 ± 9.6	3.5 ± 2.3	3.0 ± 2.7	3.9 ± 2.7
Female	5.3 ± 4.0	6.0 ± 5.5	3.3 ± 2.7	4.2 ± 3.1
Basketball	8.4 ± 12.4	3.8 ± 3.6	3.6 ± 3.2	4.8 ± 3.4
Hockey	4.5 ± 3.2	3.8 ± 2.8	3.1 ± 2.4	4.0 ± 2.7
Netball	5.4 ± 4.1	7.0 ± 5.9	2.6 ± 2.7	3.0 ± 2.3

Note:

- ***Bold italics*** indicate significance at $p < 0.05$, ***bold italics with underlining*** indicate significance at $p < 0.01$.
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- P1, P2, C1, and C2 represent significant time differences between preseason-1, preseason-2, competition-1 and competition 2, respectively.
- *Abbreviations: ASI = asymmetry index score.*

Table 5). Impulse in females increased significantly from preseason to the competition phase ($p < 0.05$, $g = 0.15$ to 0.55), whereas impulse in males only increased during the competition phase ($p < 0.05$, $g = 0.18$ to 0.23). No significant differences were observed in CMJ impulse between sports over the season (Table 5).

Significant differences were observed in unilateral CMJ peak power for all participants across the season ($p < 0.05$) with greater values ($p < 0.05$, $g = 0.16$ to 0.24) observed during the competition phase compared to preseason (Table 6). No significant differences were observed in CMJ peak power over the season.

Males demonstrated greater impulse ($p < 0.001$, $g = 1.98$ to 2.59) and peak power (all $p < 0.001$, $g = 1.14$ to 1.64) compared to females for bilateral and unilateral CMJs across all timepoints. Significant differences were also observed between sports for impulse ($p < 0.01$) and peak power ($p < 0.05$) for all CMJ variations, with basketballers exhibiting greater impulse and peak power than hockey (impulse: $p < 0.05$, $g = 0.85$ to 1.26; power: $p < 0.05$, $g = 0.91$ to 0.95) and netball (impulse: $p < 0.05$, $g = 1.87$ to 2.72; power: $p < 0.05$, $g = 1.10$ to 1.43) players (Tables 5–6).

Lower limb asymmetry

Significant differences were observed in HJ ASI over time ($p < 0.05$), with declining asymmetry scores for all participants ($p < 0.05$, g −0.61 to −0.39) from preseason to the start of competition (Table 4). No other significant differences in asymmetry were observed between sexes or sports, or across the season (Tables 3–6).

Table 5. Group means and standard deviations for impulse and inter-limb asymmetry scores (absolute values) in the bilateral and unilateral countermovement jump at four timepoints throughout the season.

	Preseason 1	Preseason 2	Competition 1	Competition 2
Bilateral (N.s)				
x All	***201 ± 46.6***	***199 ± 45.1***	***200 ± 40.9***	***204 ± 45.8***
* ***Male***	$^{\underline{F}}$ ***232 ± 30.3***	$^{\underline{F}}$ ***230 ± 30.5***	$^{\underline{F}}$ ***227 ± 27.9*** ^{C2}	$^{\underline{F}}$ ***233 ± 33.3*** ^{C1}
* ***Female***	$^{\underline{M}}$ ***163 ± 32.1*** ^{C2}	$^{\underline{M}}$ ***161 ± 26.2*** $^{\underline{C1,C2}}$	$^{\underline{M}}$ ***167 ± 28.4*** $^{\underline{P2},C2}$	$^{\underline{M}}$ ***168 ± 30.4*** $^{P1,\underline{P2}}$
* ***Basketball***	$^{H,\underline{N}}$ ***237 ± 37.2***	$^{\underline{H,N}}$ ***238 ± 35.7***	$^{\underline{H,N}}$ ***235 ± 28.9***	$^{H,\underline{N}}$ ***240 ± 37.1***
* ***Hockey***	^{B} ***190 ± 47.6***	$^{\underline{B}}$ ***189 ± 43.8***	$^{\underline{B}}$ ***190 ± 41.1***	^{B} ***193 ± 48.5***
* ***Netball***	$^{\underline{B}}$ ***174 ± 26.5***	$^{\underline{B}}$ ***168 ± 19.5***	$^{\underline{B}}$ ***175 ± 22.7***	$^{\underline{B}}$ ***178 ± 18.5***
Unilateral: Right (N.s)				
x ***All***	***144 ± 33.2***	***143 ± 32.3***	***147 ± 28.6***	***147 ± 34.1***
* ***Male***	$^{\underline{F}}$ ***168 ± 19.7***	$^{\underline{F}}$ ***166 ± 21.3***	$^{\underline{F}}$ ***166 ± 21.5***	$^{\underline{F}}$ ***169 ± 23.4***
* ***Female***	$^{\underline{M}}$ ***114 ± 18.5*** $^{\underline{C1}}$	$^{\underline{M}}$ ***115 ± 18.1*** $^{\underline{C1}}$	$^{\underline{M}}$ ***125 ± 18.2*** $^{\underline{P1,P2},C2}$	$^{\underline{M}}$ ***119 ± 21.8*** ^{C1}
* ***Basketball***	$^{H,\underline{N}}$ ***172 ± 23.2***	$^{\underline{H,N}}$ ***171 ± 25.3***	$^{\underline{H,N}}$ ***173 ± 21.2***	^{H,N} ***174 ± 24.9***
* ***Hockey***	^{B} ***138 ± 34.3***	^{B} ***138 ± 31.2***	$^{\underline{B}}$ ***141 ± 26.3***	^{B} ***139 ± 36.7***
* ***Netball***	$^{\underline{B}}$ ***119 ± 12.2***	$^{\underline{B}}$ ***120 ± 13.6***	$^{\underline{B}}$ ***127 ± 15.1***	^{B} ***126 ± 12.2***
Unilateral: Left (N.s)				
x ***All***	***142 ± 33.5***	***144 ± 33.5***	***144 ± 29.9*** ^{P2}	***147 ± 33.0*** ^{P1}
* ***Male***	$^{\underline{F}}$ ***166 ± 21.8***	$^{\underline{F}}$ ***167 ± 22.0***	$^{\underline{F}}$ ***164 ± 22.9*** ^{P2}	$^{\underline{F}}$ ***169 ± 23.2*** ^{P1}
* ***Female***	$^{\underline{M}}$ ***114 ± 20.7*** $^{\underline{C1},C2}$	$^{\underline{M}}$ ***115 ± 19.2*** $\underline{C1}$	$^{\underline{M}}$ ***120 ± 17.5*** $^{\underline{P1,P2}}$	$^{\underline{M}}$ ***119 ± 18.9*** ^{P1}
* ***Basketball***	$^{H,\underline{N}}$ ***169 ± 24.6***	$^{\underline{H,N}}$ ***174 ± 26.2***	$^{\underline{H,N}}$ ***170 ± 23.4***	$^{H,\underline{N}}$ ***170 ± 27.7***
* ***Hockey***	^{B} ***137 ± 34.7***	$^{\underline{B}}$ ***136 ± 31.5***	$^{\underline{B}}$ ***137 ± 29.0***	^{B} ***141 ± 36.5***
* ***Netball***	$^{\underline{B}}$ ***119 ± 15.4***	$^{\underline{B}}$ ***120 ± 13.3***	$^{\underline{B}}$ ***125 ± 13.5***	$^{\underline{B}}$ ***127 ± 11.0***
Unilateral: ASI (%)				
All	5.0 ± 4.5	3.8 ± 3.0	4.2 ± 5.1	4.4 ± 4.5
Male	5.1 ± 5.1	3.1 ± 2.4	3.9 ± 3.9	4.2 ± 4.4
Female	4.8 ± 3.8	4.5 ± 3.6	4.7 ± 6.3	4.6 ± 4.7
Basketball	6.0 ± 5.9	3.5 ± 1.5	5.1 ± 4.5	6.3 ± 6.6
Hockey	4.3 ± 3.4	2.9 ± 2.7	4.1 ± 6.4	4.3 ± 3.0
Netball	5.0 ± 4.4	5.4 ± 4.2	3.4 ± 3.3	2.2 ± 1.9

Note:

- ***Bold italics*** indicate significance at $p < 0.05$, ***bold italics with underlining*** indicate significance at $p < 0.01$.
- An 'x' preceding time (All) headings represents a significant interaction of time×sex or time×sport.
- An '*' preceding time (All), sex and sport row headings represents significant main effects of time, sex or sport.
- M and F represent significant sex differences between males and females, respectively.
- B, H, and N represent significant sport differences between basketball, hockey and netball, respectively.
- P1, P2, C1, and C2 represent significant time differences between preseason-1, preseason-2, competition-1 and competition 2, respectively.
- *Abbreviations: ASI = asymmetry index score.*

Low levels of agreement (κ < 0.20) in asymmetry direction were observed between timepoints for both CMJ height and HJ distance (Table 7), with 25 (65.8%) participants switching limb preference in the CMJ over the course of testing and 23 (60.5%) participants doing so in the HJ (Figures 1–2). Females were observed to switch more than males, while basketballers had the most consistent limb preference across time points (Table 7). Similarly, low levels of agreement (κ < 0.20) were observed between tests at each of the four time points (Table 8). Within each testing session, 13 (34.2%), 15 (39.5%), 16 (42.1%) and 11 (28.9%) participants changed limb preference for the CMJ versus HJ in preseason-1, preseason-2, competition-1 and competition-2, respectively. Females were the most consistent within each testing timepoint and hockey players were the least (Table 8).

Discussion

This study aimed to investigate seasonal variation in jump performance, lower limb function and inter-limb asymmetry in male and female athletes across different team sports. Although the original design intended to explore three-way interactions (sex×sport×time), the required sample size made this unfeasible. Instead, a sample was recruited to investigate seasonal changes in performance, lower limb function and inter-limb asymmetry between sexes (sex×time) and sports (sport×time). While seasonal improvements in CMJ performance were confined to females and netballers for a single task

Table 6. Group means and standard deviations for normalised power and inter-limb asymmetry scores (absolute values) in the bilateral and unilateral countermovement jump at four timepoints throughout the season.

	Preseason 1	Preseason 2	Competition 1	Competition 2
Bilateral (W.kg^{-1})				
All	52.7 ± 9.2	52.1 ± 8.7	52.5 ± 7.4	53.6 ± 8.4
$\underline{*}$ ***Male***	$^{\underline{F}}$ ***56.6 ± 8.4***	$^{\underline{F}}$ ***56.8 ± 9.0***	$^{\underline{F}}$ ***56.6 ± 7.1***	$^{\underline{F}}$ ***58.1 ± 8.5***
$\underline{*}$ ***Female***	$^{\underline{M}}$ ***47.8 ± 7.9***	$^{\underline{M}}$ ***46.3 ± 3.0***	$^{\underline{M}}$ ***47.4 ± 3.5***	$^{\underline{M}}$ ***48.0 ± 3.6***
* ***Basketball***	57.7 ± 11.3	$^{\underline{N}}$ ***58.0 ± 11.2***	^{N} ***56.4 ± 8.0***	^{N} ***58.7 ± 10.5***
Hockey	50.3 ± 5.8	51.2 ± 6.5	52.3 ± 7.3	52.5 ± 7.0
* ***Netball***	50.4 ± 9.2	$^{\underline{B}}$ ***46.6 ± 3.1***	^{B} ***47.9 ± 3.7***	^{B} ***49.3 ± 3.9***
Unilateral: Right (W.kg^{-1})				
$\underline{*}$ ***All***	***32.5 ± 5.2*** ^{C2}	***32.1 ± 4.7*** $^{\underline{C1,C2}}$	***33.2 ± 4.5*** $^{\underline{P2}}$	***33.4 ± 5.1*** $^{P1,\underline{P2}}$
$\underline{*}$ ***Male***	$^{\underline{F}}$ ***35.4 ± 3.5***	$^{\underline{F}}$ ***34.6 ± 2.7***	$^{\underline{F}}$ ***35.4 ± 3.0***	$^{\underline{F}}$ ***36.1 ± 3.5***
$\underline{*}$ ***Female***	$^{\underline{M}}$ ***28.9 ± 3.5***	$^{\underline{M}}$ ***29.0 ± 2.7***	$^{\underline{M}}$ ***30.4 ± 3.0***	$^{\underline{M}}$ ***29.9 ± 3.5***
$\underline{*}$ ***Basketball***	$^{\underline{N}}$ ***36.5 ± 6.5***	$^{\underline{N}}$ ***35.6 ± 5.9***	$^{H, N}$ ***36.3 ± 5.3***	$^{H, N}$ ***37.1 ± 6.2***
$\underline{*}$ ***Hockey***	31.5 ± 3.9	31.2 ± 3.5	^{B} ***32.0 ± 3.9***	^{B} ***32.0 ± 4.3***
$\underline{*}$ ***Netball***	$^{\underline{B}}$ ***29.4 ± 3.7***	$^{\underline{B}}$ ***29.5 ± 2.6***	^{B} ***31.2 ± 3.2***	^{B} ***31.0 ± 3.5***
Unilateral: Left (W.kg^{-1})				
* ***All***	***32.5 ± 5.3*** ^{C2}	***32.8 ± 5.6*** ^{C2}	***33.1 ± 4.9***	***33.8 ± 5.5*** $^{P1, P2}$
$\underline{*}$ ***Male***	$^{\underline{F}}$ ***35.2 ± 5.3***	$^{\underline{F}}$ ***35.9 ± 5.6***	$^{\underline{F}}$ ***35.6 ± 4.9***	$^{\underline{F}}$ ***36.8 ± 5.5***
$\underline{*}$ ***Female***	$^{\underline{M}}$ ***29.2 ± 4.3***	$^{\underline{M}}$ ***29.0 ± 2.5***	$^{\underline{M}}$ ***30.0 ± 2.4***	$^{\underline{M}}$ ***30.2 ± 3.1***
* ***Basketball***	^{N} ***36.2 ± 6.4***	$^{H, \underline{N}}$ ***37.1 ± 7.1***	^{N} ***36.4 ± 5.7***	36.7 ± 7.2
Hockey	31.6 ± 4.4	^{B} ***31.8 ± 4.0***	32.4 ± 3.9	33.0 ± 4.8
* ***Netball***	^{B} ***29.5 ± 4.6***	$^{\underline{B}}$ ***29.4 ± 2.3***	^{B} ***30.5 ± 2.9***	31.6 ± 3.2
Unilateral: ASI (%)				
All	5.5 ± 5.7	4.9 ± 5.1	4.5 ± 4.7	6.0 ± 6.9
Male	5.7 ± 5.5	5.1 ± 3.3	4.7 ± 4.7	6.9 ± 5.0
Female	5.3 ± 4.5	4.6 ± 3.6	4.3 ± 3.7	5.0 ± 4.6
Basketball	6.5 ± 6.4	5.3 ± 3.8	6.1 ± 5.3	8.9 ± 6.0
Hockey	4.6 ± 3.6	3.9 ± 2.5	3.2 ± 3.0	5.9 ± 3.7
Netball	5.9 ± 5.3	6.0 ± 4.1	4.6 ± 4.2	2.7 ± 2.2

Note:

- ***Bold italics*** indicate significance at $p < 0.05$, ***bold italics with underlining*** indicate significance at $p < 0.01$.
- An 'ˣ' preceding time (All) headings represents a significant interaction of time×sex or time×sport.
- An '*' preceding time (All), sex and sport row headings represents significant main effects of time, sex or sport.
- M and F represent significant sex differences between males and females, respectively.
- B, H, and N represent significant sport differences between basketball, hockey and netball, respectively.
- P1, P2, C1, and C2 represent significant time differences *between preseason-1, preseason-2, competition-1 and competition 2, respectively.*
- *Abbreviations: ASI = asymmetry index score.*

variant (bilateral CMJ), improvements in HJ performance were observed for the whole sample and across jump variations (Tables 3–4). This coincided with increased CMJ impulse across jump variations in females at competition compared to preseason and increased unilateral power outputs across the sample (Tables 5–6). Significant sex-based differences were identified across all jump performance and lower limb function measures, with males consistently outperforming females (Tables 3–6). Sport-specific effects were evident in HJ distance and lower limb function metrics, with basketballers consistently demonstrating higher values than both hockey players and netballers (Tables 3–6). Lower limb asymmetry showed minimal change over time, and the direction of asymmetry varied considerably both within and between jump types over the season (Tables 7–8; Figures 1–2).

Sex-based differences

Males consistently outperformed females in both bilateral and unilateral CMJ and HJ metrics across all timepoints (Table 3–6). On average, males exhibited greater normalised CMJ heights (Table 3), longer normalised HJ distances (Table 4), and significantly higher normalised peak power and impulse across all CMJ variations (Tables 5–6), supporting consistent sex-based differences in lower limb neuromuscular function previously reported in the literature.[5] These disparities highlight potential sex-based differences in muscle morphology and neuromechanical characteristics which have been documented previously. Males typically possess thicker muscles with longer fascicle lengths, enabling greater force-production and power output.[7,46] Greater countermovement squat depths during

Table 7. Kappa coefficients for the changes in asymmetry direction between timepoints for vertical and horizontal jumping performance (height and distance, respectively).

	P1 & P2	P2 & C1	C1 & C2	P1 & C1	P1 & C2	P2 & C2
CMJ						
All	0.41	***0.12***	***0.12***	***0.18***	0.40	0.25
Male	0.61	0.26	0.26	***0.05***	0.42	0.26
Female	***0.19***	***<u>−0.07</u>***	***<u>−0.03</u>***	0.33	0.38	***<u>−0.03</u>***
Basketball	0.80	0.29	0.33	0.24	0.20	0.33
Hockey	0.24	***<u>−0.02</u>***	***0.15***	***<u>−0.02</u>***	0.39	***0.15***
Netball	0.20	0.20	***−0.20***	0.20	0.52	***−0.20***
HJ						
All	0.42	***0.15***	0.47	***0.11***	0.42	0.47
Male	0.39	***0.15***	0.24	***<u>−0.04</u>***	0.34	0.24
Female	0.27	***0.14***	0.76	0.28	0.52	0.76
Basketball	0.31	0.35	***0.17***	***0.03***	***0.17***	***0.17***
Hockey	0.38	***0.13***	0.63	***0.00***	0.38	0.63
Netball	0.55	***0.00***	0.60	0.40	0.80	0.60

Note: ***bold italics*** indicate slight agreement (0.01–0.20) and ***<u>bold italics with underlining</u>*** indicate poor agreement (≤ 0).
Abbreviations: CMJ = countermovement jump, HJ = horizontal jump, P1 = preseason 1, P2 = preseason 2, C1 = competition 1, C2 = competition 2.

CMJs have also been observed in males,[5] increasing the vertical range over which the COM can be accelerated during the propulsive phase. This provides more time to develop concentric force and increase net impulse, which is directly associated with greater take-off velocity and, consequently, jump height.[5,47] The neuromuscular sex-based differences observed through CMJ testing should be carefully interpreted in applied settings, where they hold important implications for training individualisation, technique remediation, and talent identification.

Sport-specific differences

Differences were observed between sports in HJ performance and CMJ neuromuscular outputs. Basketball and hockey athletes consistently outperformed netball athletes in HJ distance (Table 4), while basketball players consistently exhibited superior performance in normalised CMJ power and impulse measures compared to both netballers and hockey players (Tables 5–6). It is also important to note that no significant sport-based differences were observed in CMJ height, suggesting that normalised vertical jump height may be less sensitive to sport-specific demands than measures of power or impulse. Previous research has highlighted sport-specific differences in neuromuscular jump strategies. Laffaye et al.[9] reported athletes in outdoor sports (e.g., soccer and baseball) tended to adopt force-dominant movement strategies to maximise impulse under time constraints, whereas indoor athletes (e.g., volleyball and basketball) relied more on time-dominant strategies where temporal constraints were less influential. Chalitsios et al.[4] however, identified contrasting movement approaches, with soccer players typically using greater CMJ squat depth (time-dominant) and basketballers demonstrating higher rates of force development (force-dominant). These contrary findings suggest that athlete movement strategies may be more strongly influenced by sport-specific task constraints than by environmental factors, such as

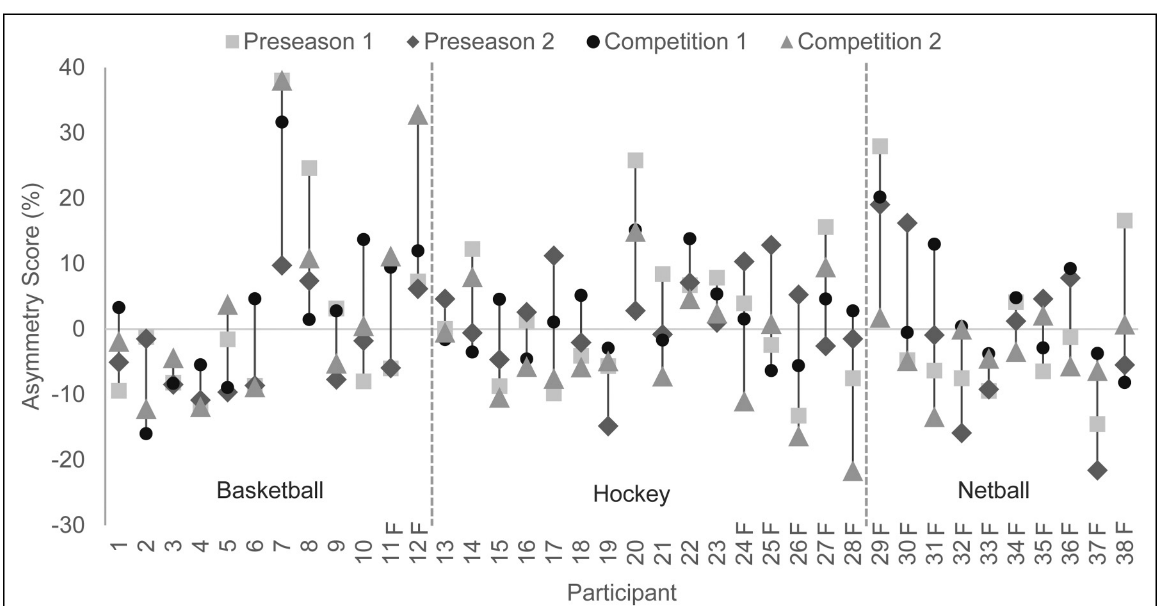

Figure 1. Individual asymmetry scores for countermovement jump height at each of the four timepoints across the season. Positive values indicate right-limb dominance in the task and negative values indicate left-limb dominance. *Abbreviations: F = female.*

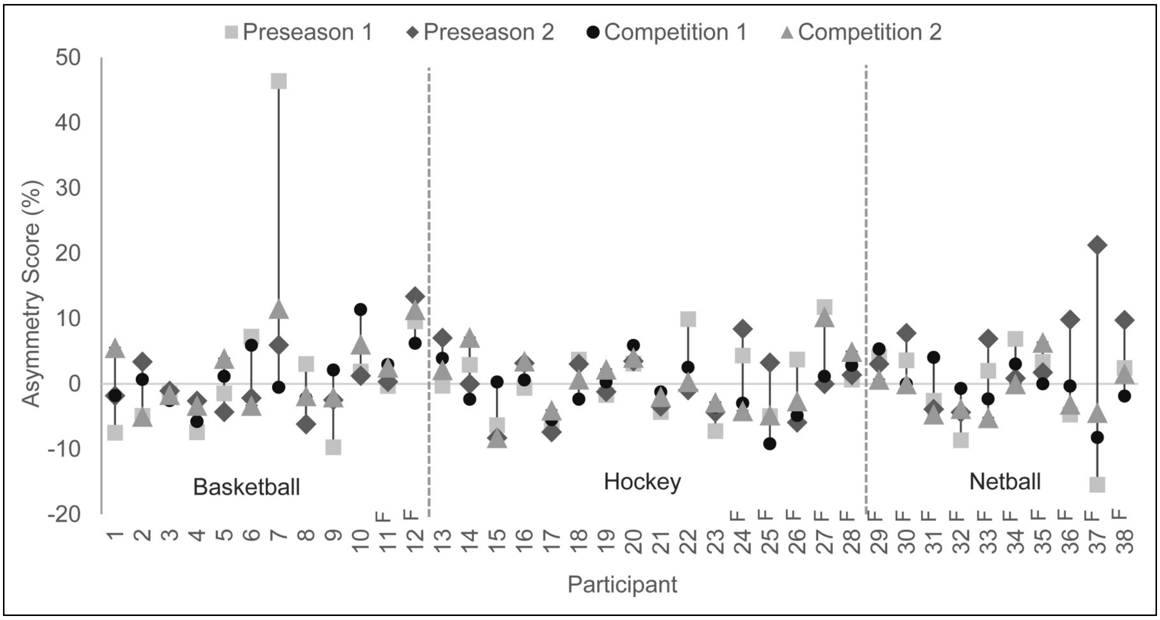

Figure 2. Individual asymmetry scores for horizontal jump distance at each of the four timepoints across the season. Positive values indicate right-limb dominance in the task and negative values indicate left-limb dominance. *Abbreviations: F = female.*

playing indoor versus outdoors. While the findings of this study may reflect sport-specific movement strategy demands, analysis of CMJ force-time history metrics describing jump strategy is required for confirmation.[38] Furthermore, they are likely influenced by the uneven distribution of males and females across sport sub-groups. The basketball cohort was predominately male (83%), netball exclusively female (100%), and although the hockey group was mixed, it was still male-skewed (69%; Table 1). As such, the observed differences may partially, or fully, reflect underlying sex-based disparities rather than purely sport-specific effects. Nevertheless, developing sport-specific sex-based benchmarks remains crucial for accurately interpreting performance metrics and guiding training interventions in applied sport environments.

Table 8. Kappa coefficients for the changes in asymmetry direction between vertical and horizontal jumping performance at each timepoint.

	P1	P2	C1	C2
All	0.32	0.22	***0.15***	0.43
Male	0.23	***0.19***	***−0.05***	0.34
Female	0.46	***0.14***	0.41	0.53
Basketball	0.47	0.27	***0.12***	0.67
Hockey	***0.13***	***−0.02***	***0.13***	***0.15***
Netball	0.44	0.40	0.20	0.60

Note: ***bold italics*** indicate slight agreement (0.01–0.20) and ***bold italics with underlining*** indicate poor agreement (≤ 0).
Abbreviations: P1 = preseason 1, P2 = preseason 2, C1 = competition 1, C2 = competition 2.

Longitudinal differences

Significant seasonal changes were observed in HJ performance and unilateral CMJ power and impulse, but improvements in CMJ performance were only evident in females and netballers and in a single task variant. Participants significantly improved normalised HJ distance across bilateral and unilateral variations, as well as unilateral CMJ power, and impulse during the competition phase compared to the preseason phase (Table 4–6). This likely reflects improvements in athlete's horizontal force production capacity. Interestingly, these improvements in bilateral HJ distance continued throughout the season. Improvements during preseason are often expected due to a focus on regaining strength and power characteristics that typically decline during periods of reduced off-season training loads.[15,48–50] However, the continued increase in normalised bilateral HJ distance during the competitive phase may indicate a presence of a match-play stimulus that is not fully replicated by pre-season strength and conditioning practices. The pattern of improvements in HJ performance was observed across all three sports and may be linked to their shared reliance on sagittal plane movements such as sprinting, cutting, and deceleration.[51]

In contrast to the consistent improvements observed in HJ performance and unilateral lower limb function, seasonal improvements in bilateral CMJ height and impulse were not consistently observed across groups and there were no significant changes in bilateral CMJ power. Females (and netballers, who comprise most of the female cohort), however, demonstrated improvements in normalised CMJ height and, by extension net impulse, from preseason to competition, while males (as well as basketball and hockey) showed none or delayed improvements (Table 3–6). This trend may reflect greater detraining effects during the off-season in female athletes, particularly in netball, which has a more clearly defined longer off-season than basketball or hockey. As such, these athletes may require a more targeted block of vertical force training to restore pre-season neuromuscular function or increase their off-season vertical loading stimulus. These findings emphasise the importance of tailoring training strategies to sex-specific needs and seasonal training history, especially for sports with well-defined off-seasons where neuromuscular detraining is more likely.

Asymmetry trends

Inter-limb asymmetry scores remained relatively consistent across the season, with no significant main effects of time observed for HJ distance or CMJ height, power or impulse asymmetry scores (Tables 3, 5–6). While the mean magnitude of asymmetry in both vertical and horizontal jumping measures remained largely consistent (Tables 3–6), scores calculated from normalised CMJ height were larger (7.0–9.5%; Table 3), than those from HJ distance (3.1–6.0%; Table 4), CMJ impulse (3.8–5.0%; Table 5) and CMJ peak power (4.5–6.0%; Table 6). Despite CMJ height producing larger asymmetry scores and classifying more individuals as having "high to extreme" asymmetry (Table 2), the HJ identified the only significant change across the season, with declining asymmetry scores from preseason to the competition phase (Tables 3–6). This may be partly explained by greater within-test variability in the CMJ, as higher CVs were observed for the CMJ (1.5–6.6%) than for the HJ (0.9–3.6%), suggesting that CMJ height (potentially when derived using the flight-time method) may lack the sensitivity required to detect meaningful changes (Table 3). Consequently, relatively large fluctuations in asymmetry may go undetected using CMJ height, whereas HJ distance appears more sensitive for detecting smaller but meaningful changes over time.

Reductions in HJ asymmetry scores during the competition phase coincided with improved HJ performance (Table 4), which may support previous findings that inter-limb asymmetry negatively impacts jump performance.[11,20] Concurrent improvements in lower limb function metrics, however, suggest that neuromuscular adaptations may also contribute to performance gains and reductions in asymmetry. Previous research has documented larger asymmetry scores at mid-season due to match congestion and reduced training.[11,12] Declining HJ asymmetry up to the start of the competition phase followed by a small increase in asymmetry at the end of the competition phase in males, particularly basketballers, may therefore reflect accumulating fatigue during match-heavy periods. The equal magnitude of change in both limbs, however, may have prevented a detectable change in asymmetry.

The presence of large standard deviations across all asymmetry metrics (Tables 3–6) suggests high inter-individual variability, despite the apparent group-level stability which may be partly due to variability in the direction of asymmetry. Kappa coefficients, indicating directional consistency (or lack thereof), ranged from poor to substantial agreement for CMJ height and HJ distance asymmetry scores (Tables 7), indicating that the same limb was not consistently favoured over time. For instance, one participant (31) displayed the same magnitude of CMJ height asymmetry throughout the competition phase; however, the right limb was favoured at the start (+13%) and the left limb was favoured at the end (−13%). Similar directional inconsistencies were observed between tasks within the same session, with over 30% of the sample favouring different limbs in the CMJ versus HJ at three of four time points (Table 8). These task-specific discrepancies reinforce previous findings that vertical and horizontal jump tests reflect distinct neuromuscular strategies.[12,52,53] Therefore, it is recommended that CMJ and HJ displacements are not used interchangeably when monitoring asymmetry.

Kappa values in this study were generally higher than those reported previously,[12] potentially reflecting differences in participant age, training experience and testing frequency. While Fort-Vanmeerhaeghe et al.[12] assessed youth athletes (aged 14–18) across three timepoints, the current study tracked university athletes (aged 18–23) across four timepoints, possibly yielding more stable asymmetry profiles in a more experienced and physically mature cohort. Interestingly, directional consistency was influenced by both sex and sport. Females changed limb preference more often between timepoints, but less between tasks. While basketball players showed the most stable limb preference across timepoints and hockey players were the most inconsistent across tests. These longitudinal sport differences may be influenced by movement demand variability between positional roles within each sport, however, the implications of directional asymmetry consistency on performance and injury risk are still unclear.

Strengths and limitations

The inclusion of four timepoints allowed for more granular tracking of intra-mesocycle trends, such as the within-phase changes in HJ performance and CMJ impulse, which may have been missed in less frequent testing designs. This longitudinal approach offers a more detailed understanding of how jump performance, lower limb function and inter-limb asymmetry fluctuate across a competitive season. The integration of both CMJ and HJ testing, across bilateral and unilateral formats, also enabled a more comprehensive assessment of jump capacity and asymmetry profiles than has been captured in most previous work.

Despite the usefulness of this research, some limitations should be considered when interpreting its findings. Firstly, a more diverse sample of sporting backgrounds, particularly those involving varying degrees of cyclic and acyclic movement patterns, may have revealed additional findings, especially regarding jumping asymmetry.[54] Secondly, there was a strong sex bias within the basketball and netball cohorts, meaning that observed sport effects could not be fully interpreted independently from sex effects. To overcome this, the sex of the sample would need to be homogenous, or the sample size expanded to investigate the three-way interactions (sex×sport×time). An additional testing session was included in the current study compared to previous longitudinal investigations[10,11,17,34]; however, due to scheduling constraints, some athletes were assessed earlier within each mesocycle than others, which may have influenced intra-season comparisons.

The study did not account for player position, experience level, individual fitness or weekly training loads of which could influence jump performance and asymmetry trends. While all players followed similar training programmes, achieving true homogeneity in weekly load and fitness levels across sexes and sports is unfeasible. Previous research has shown positional demands in sports such as netball and basketball can lead to individual differences, with midcourt athletes who are exposed to more frequent running and sprinting, demonstrating faster sprinting and change of direction capabilities than defenders who engage in more vertical-oriented activities, such as guarding and interceptions.[2,55,56] Future studies should aim to integrate weekly load and fitness profiling to improve the practical relevance of seasonal fluctuations in jump performance and asymmetry.

The current investigation used the flight time method to determine jump height due to an issue identifying a clear body-weight phase within the pre-season data. Although the flight-time method has demonstrated highly validity and reliability compared to the impulse method,[39–41] it may lack the sensitivity required to detect subtle differences or asymmetries correctly. Furthermore, HJ tests were performed without the use of a force platform, which limited the ability to perform kinetic analysis. Additionally, the study did not quantify jump technique or strategy which may have influenced inter-individual variation in performance or asymmetry outcomes, particularly given the influence of technique on impulse generation in the CMJ and HJ.

To address non-normality in the data a log transformation was applied, however, this procedure requires input values to be greater than zero. As a result, asymmetry scores were analysed as absolute values, thereby removing directional context. While kappa coefficients were used to quantify directional consistency, the exclusion of direction from asymmetry magnitude analyses may have contributed to the lack of significant differences in asymmetry over time.

Practical applications

While jump performance and lower limb function in vertical and horizontal jumping improved from preseason to competition testing, the unilateral HJ was the only test to identify improvements within preseason. This indicates suboptimal neuromuscular characteristics and/or jump strategy due to insufficient training stimulus within the preseason phase. Comparatively, sporting demands change during the competition phase due to the increase in match play and decrease in training load. The competition phase may also provide a stimulus not fully replicated in training due to more intensive, sport-specific vertical and horizontal force production requirements during match play. Practitioners should, therefore, consider strategies to develop and maintain force production capacities, particularly following off-season periods where detraining effects are likely to occur. Furthermore, researchers should aim to expand the understanding of horizontal force production in HJs to match the insight currently available for vertical force production in CMJs.[38]

The variability in inter-limb asymmetry direction across timepoints and tasks reinforces the importance of using both HJ and CMJ assessments to capture a comprehensive asymmetry profile. Horizontal force production can be indicated by HJ performance, which may not be fully captured by CMJs. Practitioners should consider utilising both HJs and CMJs to ensure sex- and sport-specific performance and asymmetry trends are not overlooked. These insights can help inform training prescription, athlete monitoring and return-to-play decisions throughout the season.

Conclusion

This study provides novel insights into the seasonal variation of jump performance, lower limb neuromuscular function and inter-limb asymmetry across sex and sport in university team-sport athletes. While vertical CMJ performance remained largely stable across the season, improvements in HJ distance and unilateral CMJ power and impulse were observed, highlighting the sensitivity of these metrics to training adaptations. These findings support the use of HJ testing as a complementary tool to the CMJ, particularly for detecting longitudinal changes in horizontal force production capacity. Consistent sex-based differences were observed, with males outperforming females across all performance and force-related metrics. Sport-based differences also emerged, particularly in HJ and unilateral CMJ outputs, though these were potentially confounded by unequal sex representation within teams. This underscores the importance of developing sport-specific, sex-sensitive reference values in applied settings. Inter-limb asymmetry magnitudes appeared consistent at the group level; however, large individual variability and poor directional consistency were identified across timepoints and test types.

The HJ demonstrated greater sensitivity than the CMJ in detecting meaningful changes in asymmetry over time, likely due to lower measurement variability. Directional inconsistencies in asymmetry, particularly among females and between jump tasks, reinforce the need to monitor both magnitude and direction in athlete profiling. Collectively, these findings highlight the utility of multi-directional jump assessments for longitudinal athlete monitoring. Practitioners should consider both task- and sex-specific factors when interpreting performance and asymmetry trends across a season. Future research should aim to incorporate kinetic analysis, position-specific demands and jump technique to further contextualise performance changes and asymmetry expression in team sport environments.

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Ethical considerations

Nottingham Trent University's Human Invasive Ethics Committee (ID: 1535801, version 1.0, dated: 19/07/2022).

Consent to participate

Written informed consent was obtained by all participants of this research.

Author contributions

Amy O, Parkinson: research concept and study design, data collection, data analysis and interpretation, writing the manuscript and final approval of the article to be published; Paul J. Felton: research concept and study design, data analysis and interpretation, writing the manuscript and final approval of the article to be published; Charlotte L. Apps: research concept and study design, data collection and interpretation, reviewing/editing manuscript drafts and final approval of the article to be published; John G. Morris: research concept and study design, data analysis and interpretation and reviewing/editing manuscript drafts.

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Data availability statement

The research data is presented in the paper.

References

1. Delextrat A, Badiella A, Saavedra V, et al. Match activity demands of elite spanish female basketball players by playing position. *Int J Perform Anal Sport* 2015; 15: 687–703.
2. Fox A, Spittle M, Otago L, et al. Activity profiles of the Australian female netball team players during international competition: implications for training practice. *J Sports Sci* 2013; 31: 1588–1595.
3. Taylor JB, Wright AA, Dischiavi SL, et al. Activity demands during multi-directional team sports: a systematic review. *Sports Med* 2017; 47: 2533–2551.
4. Chalitsios C, Nikodelis T, Panoutsakopoulos V, et al. Classification of soccer and basketball Players' jumping performance characteristics: a logistic regression approach. *Sports* 2019; 7: 163.
5. McMahon JJ, Rej SJE and Comfort P. Sex differences in countermovement jump phase characteristics. *Sports* 2017; 5: 8.
6. Rice PE, Goodman CL, Capps CR, et al. Force– and power–time curve comparison during jumping between strength-matched male and female basketball players. *Eur J Sport Sci* 2017; 17: 286–293.
7. Alegre LM, Lara AJ, Elvira JLL, et al. Muscle morphology and jump performance: gender and intermuscular variability. *J Sports Med Phys Fitness* 2009; 49: 320–326.
8. Eisenmann J and Malina R. Age- and sex-associated variation in neuromuscular capacities of adolescent distance runners. *J Sports Sci* 2003; 21: 551–557.
9. Laffaye G, Phillip W and Tombleson T. Countermovement jump height: gender and sport-specific differences in the force-time variables. *J Strength Cond Res Natl Strength Cond Assoc* 2014; 28: 1096–1105.
10. Bishop C, Read P, Chavda S, et al. Magnitude or direction? Seasonal variation of interlimb asymmetry in elite academy soccer players. *J Strength Cond Res* 2020; 36: 1031–1037.
11. Bishop C, Weldon A, Hughes J, et al. Seasonal variation of physical performance and inter-limb asymmetry in professional cricket athletes. *J Strength Cond Res* 2021; 35: 941–948.
12. Fort-Vanmeerhaeghe A, Bishop C, Buscà B, et al. Seasonal variation of inter-limb jumping asymmetries in youth team-sport athletes. *J Sports Sci* 2021; 39: 2850–2858.
13. Bishop C, Brashill C, Abbott W, et al. Jumping asymmetries are associated with speed, change of direction speed, and jump performance in elite academy soccer players. *J Strength Cond Res* 2019; 35: 1841–1847.
14. Bishop C, Read P, McCubbine J, et al. Vertical and horizontal asymmetries are related to slower sprinting and jump performance in elite youth female soccer players. *J Strength Cond Res* 2021; 35: 56–63.
15. Cormie P, McGuigan MR and Newton RU. Adaptations in athletic performance after ballistic power versus strength training. *Med Sci Sports Exerc* 2010; 42: 1582–1598.
16. Lamas L, Ugrinowitsch C, Rodacki A, et al. Effects of strength and power training on neuromuscular adaptations

and jumping movement pattern and performance. *J Strength Cond Res* 2012; 26: 3335–3344.

17. Fort-Vanmeerhaeghe A, Bishop C, Buscà B, et al. Seasonal variation of inter-limb jumping asymmetries in youth team-sport athletes. *J Sports Sci* 2021; 39: 2850–2858.
18. Bishop C, Read P, Brazier J, et al. Effects of interlimb asymmetries on acceleration and change of direction speed: a between-sport comparison of professional soccer and cricket athletes. *J Strength Cond Res* 2021; 35: 2095.
19. Brumitt J, Mattocks A, Loew J, et al. Preseason functional performance test measures are associated with injury in female college volleyball players. *J Sport Rehabil* 2020; 29: 320–325.
20. Fort-Vanmeerhaeghe A, Bishop C, Buscà B, et al. Inter-limb asymmetries are associated with decrements in physical performance in youth elite team sports athletes. *PloS One* 2020; 15: e0229440.
21. Fort-Vanmeerhaeghe A, Milà-Villarroel R, Pujol-Marzo M, et al. Higher vertical jumping asymmetries and lower physical performance are indicators of increased injury incidence in youth team-sport athletes. *J Strength Cond Res* 2022; 36: 2204.
22. MacSweeney ND, Shaw JW, Simkin GP, et al. Jumping asymmetries and risk of injuries in professional ballet. *Am J Sports Med* 2024; 52: 492–502.
23. Madruga-Parera M, Bishop C, Read P, et al. Jumping-based asymmetries are negatively associated with jump, change of direction, and repeated sprint performance, but not linear speed, in adolescent handball athletes. *J Hum Kinet* 2020; 71: 47–58.
24. Madruga-Parera M, Bishop C, Beato M, et al. Relationship between interlimb asymmetries and speed and change of direction speed in youth handball players. *J Strength Cond Res* 2021; 35: 3482–3490.
25. Steidl-Müller L, Hildebrandt C, Müller E, et al. Limb symmetry index in competitive alpine ski racers: reference values and injury risk identification according to age-related performance levels. *J Sport Health Sci* 2018; 7: 405–415.
26. Bishop C, Abbott W, Brashill C, et al. Bilateral vs. Unilateral countermovement jumps: comparing the magnitude and direction of asymmetry in elite academy soccer players. *J Strength Cond Res* 2022; 36: 1660.
27. Carvalho A, Brown S and Abade E. Evaluating injury risk in first and second league professional Portuguese soccer: muscular strength and asymmetry. *J Hum Kinet* 2016; 51: 19–26.
28. Gonzalo-Skok O, Moreno-Azze A, Arjol-Serrano JL, et al. A comparison of 3 different unilateral strength training strategies to enhance jumping performance and decrease inter-limb asymmetries in soccer players. *Int J Sports Physiol Perform* 2019; 14: 1256–1264.
29. Jordan MJ, Aagaard P and Herzog W. Lower limb asymmetry in mechanical muscle function: a comparison between ski racers with and without ACL reconstruction. *Scand J Med Sci Sports* 2015; 25: e301–e309.
30. Moreno-Azze A, Arjol-Serrano JL, Falcón-Miguel D, et al. Effects of three different combined training interventions on jump, change of direction, power performance, and inter-limb asymmetry in male youth soccer players. *Sports* 2021; 9: 158.
31. Parkinson AO, Apps CL, Morris JG, et al. The calculation, thresholds and reporting of inter-limb strength asymmetry: a systematic review. *J Sports Sci Med* 2021; 20: 594–617.
32. Bishop C. Interlimb asymmetries: are thresholds a usable concept? *Strength Cond J* 2021; 43: 32–36.
33. Dos'Santos T, Thomas C and Jones PA. Assessing interlimb asymmetries: are we heading in the right direction? *Strength Cond J* 2021; 43: 91–100.
34. Bishop C, Read P, Bromley T, et al. The association between interlimb asymmetry and athletic performance tasks: a season-long study in elite academy soccer players. *J Strength Cond Res* 2022; 36: 787–795.
35. Lees A, Vanrenterghem J and Clercq DD. Understanding how an arm swing enhances performance in the vertical jump. *J Biomech* 2004; 37: 1929–1940.
36. Chavda S, Turner A, Comfort P, et al. A practical guide to analyzing the force-time curve of isometric tasks in excel. *Strength Cond J* 2020; 42: 26–37.
37. McMahon JJ, Suchomel TJ, Lake JP, et al. Understanding the key phases of the countermovement jump force-time curve. *Strength Cond J* 2018; 40: 96–106.
38. Anicic Z, Janicijevic D, Knezevic OM, et al. Assessment of countermovement jump: what should we report. *Life Basel Switz* 2023; 13: 190–190.
39. Balsalobre-Fernández C, Glaister M and Lockey RA. The validity and reliability of an iPhone app for measuring vertical jump performance. *J Sports Sci* 2015; 33: 1574–1579.
40. Moir GL. Three different methods of calculating vertical jump height from force platform data in men and women. *Meas Phys Educ Exerc Sci* 2008; 12: 207–218.
41. Słomka KJ, Sobota G, Skowronek T, et al. Evaluation of reliability and concurrent validity of of two optoelectric systems used for recording maximum vertical jumping performance versus the gold standard. *Acta Bioeng Biomech* 2017; 19: 141–147.
42. Pérez-Castilla A, Fernandes JFT, Rojas FJ, et al. Reliability and magnitude of countermovement jump performance variables: influence of the take-off threshold. *Meas Phys Educ Exerc Sci* 2021; 25: 227–235.
43. Koo TK and Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med* 2016; 15: 155–163.
44. Cohen J. A coefficient of agreement for nominal scales. *Educ Psychol Meas* 1960; 20: 37–46.
45. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Psychol* 2013; 4: 863–863.
46. Mangine GT, Fukuda DH, LaMonica MB, et al. Influence of gender and muscle architecture asymmetry on jump and sprint performance. *J Sports Sci Med* 2014; 13: 904–911.

47. Kirby TJ, McBride J, Haines T, et al. Relative net vertical impulse determines jumping performance. *J Appl Biomech* 2011; 27: 207–214.
48. Cormie P, McBride JM and McCaulley GO. Power-Time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *J Strength Cond Res* 2009; 23: 177–186.
49. Cormie P, McGuigan MR and Newton RU. Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Med Sci Sports Exerc* 2010; 42: 1731–1744.
50. Jakobsen MD, Sundstrup E, Randers MB, et al. The effect of strength training, recreational soccer and running exercise on stretch–shortening cycle muscle performance during countermovement jumping. *Hum Mov Sci* 2012; 31: 970–986.
51. Manouras N, Papanikolaou Z, Karatrantou K, et al. The efficacy of vertical vs. Horizontal plyometric training on speed, jumping performance and agility in soccer players. *Int J Sports Sci Coach* 2016; 11: 702–709.
52. Bishop C, Lake J, Loturco I, et al. Interlimb asymmetries: the need for an individual approach to data analysis. *J Strength Cond Res* 2021; 35: 695–701.
53. Bishop C, Pereira LA, Reis VP, et al. Comparing the magnitude and direction of asymmetry during the squat, countermovement and drop jump tests in elite youth female soccer players. *J Sports Sci* 2020; 38: 1296–1303.
54. Kalata M, Maly T, Hank M, et al. Unilateral and bilateral strength asymmetry among young elite athletes of Various sports. *Medicina (Mex)* 2020; 56: 683.
55. Chandler PT, Pinder SJ, Curran JD, et al. Physical demands of training and competition in collegiate netball players. *J Strength Cond Res* 2014; 28: 2732–2737.
56. Graham S, Duthie G, Aughey R, et al. Comparison of physical profiles of state-level netball players by position. *J Strength Cond Res* 2020; 34: 2654–2662.