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Sex-specific associations between joint-specific isometric strength and jump performance in high-performance athletes

Asociaciones específicas según el sexo entre la fuerza isométrica específica de cada articulación y el rendimiento en el salto en atletas de alto rendimiento

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Abstract

This study aimed to analyze how isometric strength in lower limb joints correlates with neuromuscular performance and to establish sex-specific descriptive values. A total of 99 high-performance athletes participated. Jump heights were measured in squat jump (SJ), countermovement jump (CMJ), and drop jump (DJ), alongside isometric strength in lower limb muscles. Results revealed sex differences ($p<0.001$) in jump height, CMJ demonstrates the highest values across both sexes (male: 37.00 cm; female: 28.89 cm), followed by the SJ (male: 27.07 cm; female: 34.34 cm) and DJ (male: 26.46 cm; female: 33.25 cm). Males exhibited greater relative strength in hip adduction, external rotation, extension, flexion, and knee flexion. Correlations showed that in females, knee extensor strength had the highest association with all jumps ($p<0.01$; $r=0.475$-0.589), together with knee flexors, plantar flexors and ankle dorsal flexors in the three jumps, hip extensors in DJ and hip flexors in CMJ and DJ ($p<0.05$; $r=0.411$-0.531). In males athletes, no significant differences is observed but a positive correlation in external and internal hip rotation or hip extension. These data allow us to individualize physical preparation according to sex, as well as to emphasise strength work on specific muscle groups in order to optimise the athlete's performance.

Keywords: sport performance; jump test; isometric strength; dynamometry; sex.

Resumen

Este estudio tuvo como objetivo analizar cómo la fuerza isométrica en las articulaciones de las extremidades inferiores se correlaciona con el rendimiento neuromuscular y establecer valores descriptivos específicos por sexo. Un total de 99 atletas de alto rendimiento participaron en el estudio. Se midieron las alturas de salto en el squat jump (SJ), countermovement jump (CMJ) y drop jump (DJ), junto con la fuerza isométrica en los músculos de las extremidades inferiores. Los resultados revelaron diferencias entre sexos ($p < 0.001$) en la altura de salto. El CMJ mostró los valores más altos en ambos sexos (hombres: 37,00 cm; mujeres: 28,89 cm), seguido del SJ (hombres: 27,07 cm; mujeres: 34,34 cm) y del DJ (hombres: 26,46 cm; mujeres: 33,25 cm). Los hombres presentaron mayor fuerza relativa en la aducción de cadera, rotación externa, extensión, flexión y flexión de rodilla. Las correlaciones mostraron que, en mujeres, la fuerza de los extensores de rodilla tuvo la mayor asociación con todos los saltos ($p < 0.01$; $r = 0.475$–0.589), junto con los flexores de rodilla, flexores plantares y dorsiflexores del tobillo en los tres saltos, los extensores de cadera en el DJ y los flexores de cadera en el CMJ y DJ ($p < 0.05$; $r = 0.411$–0.531). En atletas masculinos no se observaron diferencias significativas, pero sí una correlación positiva en la rotación externa e interna de la cadera y en la extensión de cadera. Estos datos permiten individualizar la preparación física según el sexo, así como enfatizar el trabajo de fuerza en grupos musculares específicos con el fin de optimizar el rendimiento del atleta.

Palabras clave: rendimiento deportivo; test de salto; fuerza isométrica; dinamometría; sexo.

Introduction

Neuromuscular performance, as defined by López-Chicharro & Fernández-Vaquero (2023) and Haff & Triplett 2016), refers to the nervous system's ability to regulate and control muscle contraction. This involves the efficient transmission of signals from the central nervous system (cerebral cortex and spinal cord) to the motor units of skeletal muscles. Action potentials propagate along motor neurons, transmitting electrochemical signals across the neuromuscular synapse and releasing neurotransmitters like acetylcholine, which stimulate muscle contraction. Understanding this concept is essential for developing training programs that optimize muscle strength and power in athletes.

Vertical jump tests are widely used to evaluate neuromuscular performance, fatigue, and athlete readiness over time, as well as to track progress and customize training strategies (Bishop et al., 2023). These tests provide insights into explosive and reactive strength, intermuscular coordination (Di Domenico et al., 2024), and typically induce low levels of fatigue in athletes (Jiménez-Reyes et al., 2014; Sánchez-Medina & González-Badillo, 2011). Three primary types of vertical jump tests are commonly conducted: (i) countermovement jump (CMJ) (Van-Hooren & Zolotarjova, 2017); (ii) drop jump (DJ) (Komi & Bosco, 1978); and (iii) squat jump (SJ) (Van-Hooren & Zolotarjova, 2017). These tests have shown associations with essential physical abilities such as sprinting (Rodríguez-Rosell et al., 2017; Vescovi & McGuigan, 2008) change of direction (Barnes et al., 2007), performance monitoring (Markwick et al., 2015), and injury risk detection, particularly in the case of DJ (Noyes et al., 2005). In this sense, the CMJ and DJ tests are notable for their ability to engage the stretch-shortening cycle (SSC). This cycle involves a rapid eccentric muscle contraction, followed by a brief isometric phase, and then a concentric muscle contraction. These phases synergistically enhance concentric force production through mechanisms like elastic energy utilization and reflex muscle activity (Pedley et al., 2017; Turner & Jeffreys, 2010). Specifically, the drop jump relies on the development of essential biomotor capacities such as maximal strength, speed of force development, SSC function, and leg stiffness (Pedley et al., 2017).

Strength measurements play a crucial role in evaluating an athlete's response to training programs and assessing their current performance levels (Kraska et al., 2009). The primary tests used for this purpose include the maximal dynamic strength test, often measured by the one-repetition maximum test (1RM) (Verdijk et al., 2009) and individual strength-velocity profiles (Samozino et al., 2012). However, given that muscle contraction can be divided into eccentric, isometric and concentric (Wilson et al., 1994). Isometric tests using dynamometry are valuable for assessing neuromuscular performance and adaptation to strength training at different joint angles in a safe, efficient, and less fatiguing manner (Baena-Raya et al., 2023). In this regard, higher muscular strength is associated with numerous benefits across various athletic disciplines and can reduce the risk of injury (Case et al., 2020). For instance, weaker hip abduction and external rotation strength have been linked to increased anterior cruciate ligament injury risk (Khayambashi et al., 2016), and deficiencies in hip abduction strength may contribute to iliotibial band syndrome in long-distance runners (Mucha et al., 2017). Additionally, athletes with patellofemoral pain syndrome often show delayed recruitment or reduced activation of hip abductors like the gluteus medius (Barton et al., 2013).

The relationship between specific muscle group strength and neuromuscular performance has been explored in a limited number of studies. Nuzzo et al. (2008) found that single-joint isometric testing poorly predicts performance in multi-joint explosive movements like the CMJ. Studies have also shown that isometric strength in specific joints, such as knee extension, correlates moderately ($r \approx 0.50$) in athletes participating in team sports like basketball and football (Requena et al., 2009; Ugarkovic et al., 2002), whereas higher correlations ($r > 0.88$) are observed across athletes from various disciplines (De Ruiter et al., 2006). These findings suggest that the ability to generate a neural impulse before maximal joint isometric contraction is positively associated with dynamic tasks (De Ruiter et al., 2006). However, it remains unclear whether other muscle groups may exhibit similar correlations with neuromuscular performance, which could potentially aid in injury prediction.

Given the limited data on the relationship between isometric joint strength and neuromuscular performance, there is a critical need to investigate this connection and understand potential differences between sexes. This will enable the development of individualized training programmes. In this context, this research aims to analyze how isometric strength in lower limb joints correlates with neuromuscular performance and to establish sex-specific descriptive values. The study hypothesizes that certain muscle groups' strength directly impacts on athletes' neuromuscular performance. Therefore, lower strength application in specific muscle groups, based on these descriptive values, could lead to reduced performance. Additionally, the study proposes that sex differences exist, highlighting the necessity to tailor training programs according to athletes' sex to optimize performance.

Material and methods

Sample

The study involved 99 high-performance athletes (37 females and 62 males). The participants were either competing at the international level or were members of their respective national teams. The athletes participated in a variety of sports, including combined events in athletics, badminton, judo, karate, walking, rugby 7-a-side, surfing, and triathlon (Table S1). Male athletes were 26.1±5.1 years old, 181.3±7.9 cm height, with a BMI of 18.1±2.4 kg/m2 and body mass of 74.1±10.9 kg. Female athletes were 23.2±7.0 years old, 170.2±5.9 cm height, with a BMI of 19.2±3.3 kg/m2 and body mass of 58.1±13.2 kg.

A priori power analyses were conducted using G*Power 3.1. For between-group comparisons (men vs. women), independent-samples t-tests were planned. Assuming a large effect size ($d = 0.80$), $\alpha = 0.05$, two-tailed testing, and power of 0.80, the required minimum sample was 52 participants (26 per group). For associations between variables, bivariate correlations were performed. Assuming a medium effect size ($r = 0.30$), $\alpha = 0.05$, and power of 0.80, the required minimum sample was 84 participants. The final sample of 99 athletes exceeded these thresholds, ensuring adequate statistical power for all analyses.

The number of valid observations differed between variables due to occasional missing or excluded measurements. Data were excluded when athletes were unable to complete a specific test (e.g., discomfort or scheduling constraints), or when recordings did not meet predefined quality criteria (e.g., technical issues or inconsistent force application). For transparency, the number of valid observations for each analysis is reported in the corresponding tables. Correlational analyses were conducted using pairwise deletion, allowing all available data to be used for each variable combination.

The athletes who participated in the study were drawn from the High Performance Centre in Madrid, Spain. Athlete exclusion criteria included those who had not been cleared for competition due to injury. The study was approved by an independent institutional ethics committee (University of Extremadura (166//2023)). Following the explanation of the procedures in verbal and written form, the participants were required to sign an informed consent form. In the event that the participant was under the age of 18, parental or guardian consent was required.

Procedure

Research design was explicitly reported following the recommendations of Ibáñez and Feu (2026). The measurements were conducted at the Performance Analysis Unit of the Madrid High Performance Centre, Spain, between March 2023 and January 2025. All athletes were previously acquainted with the tests to be conducted, as they regularly incorporated them into their training regimens. Furthermore, the tests were administered on two consecutive days to mitigate the potential influence of physical and mental fatigue on the assessments. On the first day, the jumping tests were conducted, followed by the dynamometry tests on the following day. All measurements were taken between 9 a.m. and 2 p.m. The athletes were tested at different times throughout the year in each specific sport. However, the sample only included athletes tested during the competitive period of the season. This was done to ensure that the athletes were in optimal physical condition and at or near their peak performance.

Jump test

Jump tests were conducted utilising the OptoGait photocell sensor (OptoGait, Microgate, Bolzano, Italy), which has previously been employed in similar studies (Prieske et al., 2019). The jump height (i.e. maximal jump height via flight time calculation ($h = gt_f^2/8$), where h is jump height (m), t_f is flight time (s), and g is gravitational acceleration) from three different jump types were analysed: (i) CMJ: from a standing position and initiates a downward movement, which is immediately followed by an upward movement leading to takeoff (Martín-Miguel et al., 2026); (ii) SJ: the athlete descends to a semi-squat position and holds this position for approximately 3 seconds before takeoff (Van-Hooren & Zolotarjova, 2017) and (iii) DJ: the athlete drops from a platform and immediately executes a vertical jump in contact with the ground. The study places particular emphasis on a brief period of ground contact with minimal leg flexion (Komi & Bosco, 1978), with a height of 40 cm, in accordance with the methodology proposed by Markwick et al. (2015). A total of five attempts were made at each jump, with a 20-second interval between each attempt. The best and worst results were eliminated, and a weighted average of the remaining three jumps was calculated, following the methodology proposed in previous studies (Martín-Miguel, Martínez-Ortega, et al., 2025).

Strength test

Prior to the start of the tests, weight was analysed using the Tanita bc-601 scale with a tolerance of ±100 grams. The dynamometric force tests were performed using the Chronojump force sensor (Chronojump, BoscoSystem, Madrid, Spain), which was previously used in studies by Resende et al. (2020). This device has a maximum resistance of 500 kg, with a 24-bit resolution analog-to-digital converter and a frequency of 160 Hz. The sensor was secured to the stretcher with 25 kiloNewton carabiners, and a 200-kilogram resistance buckle fastening strap was used. The perpendicular distance between the force sensor and the centre of the joint was determined and the degree of opening was adjusted using a goniometer to measure the minimum degree of opening. In addition, a subjective perception was obtained to determine the extent to which the subjects could exert force.

A 15-minute warm-up was performed, including joint range of motion, myofascial release with a foam roller, and muscle activation with a mini-band. The dynamometer was attached to the ankle with a strap for all tests, except for the ankle flexion tests, which were attached to the metatarsals. The procedure was carried out in accordance with the results of previous studies (Courel-Ibáñez et al., 2020; Torrontegui et al., 2023). The test was then performed with an isometric effort, in which the subject exerted the maximum possible force for a period of 6-8 seconds, depending on the duration of the observed decrease in force. The left and right limbs were alternated to avoid cooling of the opposite limb. Each leg was rested for 30 seconds. Strong verbal encouragement and visual feedback were used to motivate the subjects. The average number of repetitions performed was two. The most successful force application was selected from the different repetitions performed. Maximal isometric strength was expressed as relative strength in Newtons per kilogram (N/kg), allowing comparisons to be made within a group regardless of their differences in body mass (Case et al., 2020).

The tests were conducted in strict accordance with the instructions provided by Martín-Miguel, Torrontegi-Ronco, et al. (2025) to ensure methodological consistency: (i) Hip adduction. From the supine position, with the knees extended, ankles off the stretcher and hands attached to the sides of the stretcher with 3 fingers, the subject performed the maximum lateral force possible in the adduction movement. (ii) Hip abduction. From the lateral decubitus position, with arms resting on the stretcher without holding on, leg down and not exerting force at an angle of 90º to the knee, the subject performed a maximum lateral force in the abduction movement. (iii) Internal hip rotation. From a sitting position and the hip at 90º. The knee was fixed to prevent displacement. From this initial position, the subject performed the maximum rotational force possible. The hands were placed on the stretcher. (iv) External hip rotation. The same protocol was followed as in the previous one. The axis of the hip joint was fixed perpendicular to the axis of the pulley, but in the opposite direction to how the hip internal rotation was assessed. (v) Hip flexion. In the supine position, hip flexed between 80-90º with knee flexion at 90º, hands at the sides grasped with three fingers. The athlete was instructed to do a maximum hip flexion trying to bring the knee to the sternum. (vi) Hip extension. In prone position on the stretcher, knee at 0º of flexion, ankles off the stretcher, hands at the sides of the stretcher grasped by three fingers. He was instructed to exert maximum force by bringing the heel to the ceiling without flexing the knee. (vii) Knee extension. In the supine position, hip extended, knee off the table with a flexion of 140-150°, hands at the sides grasped with three fingers, asked to perform a maximum knee extension. (viii) Knee flexion. In prone position, hip extended, knee flexed between 80-90º, hands at the sides grasped with three fingers, asked to perform a knee flexion. (ix) Ankle plantar flexion. Supine, hands on the sides of the stretcher gripping, trap on the foot without shoes, held at metatarsal level, asked to perform maximum plantar flexion. (x) Ankle dorsal flexion. Supine, hands on the sides of the stretcher gripping, trap on the foot without shoes, held at metatarsal height, asked to perform maximum dorsal flexion.

Statistical analysis

In order to ascertain the normality of the variables, Kolmogorov-Smirnov test for female athletes and Shapiro-Wilk test for male athletes were conducted. Descriptive analysis was performed to determine the mean and standard deviation, together with the 95% confidence interval. Low, mean and high values were determined by calculating the 25th, 50th and 75th percentile. The Student's t-test for independent samples was used to analyse the differences between sex and jump height and relative strength of the different tests, the magnitude of these differences was measured using Cohen's effect size (ES), ES of 0.2, 0.6, 1.2, 1.2, 2.0, and 4.0 were considered small, moderate, large, very large, and extremely large, respectively (Hopkins et al., 2009). In addition, the mean difference was analysed for the difference between sexes. To find out the association between SJ, CMJ, and DJ jump height and the strength of the different joint movements was calculated using Pearson's correlation coefficients (r), the values of $r < 0.1$ indicate trivial, $0.1 \le r < 0.3$ small, $0.3 \le r < 0.5$ medium, $0.5 \le r < 0.7$ large, $0.7 \le r < 0.9$ very large, and $r \ge 0.9$ extremely large correlations (Hopkins et al., 2009). The significance level was set at $p<0.05$. Pearson correlation coefficients were calculated separately for female and male athletes. For each correlation, exact p values, 95% confidence intervals, and the number of valid observations were reported. Multiple comparisons were controlled using the Benjamini–Hochberg false discovery rate procedure. Differences between correlation coefficients in female and male athletes were examined using Fisher's r-to-z transformation for independent samples. The calculations were conducted in JASP v.0.17.3.

Results

As illustrated in Table 1, the SJ, CMJ and DJ values exhibit notable differences between males and females ($p < 0.001$, ES = 0.92-1.16). The CMJ consistently demonstrates the highest jump height across both sexes (male: 37.00 cm; female: 28.89 cm), followed by the SJ (male: 27.07 cm; female: 34.34 cm) and DJ (male: 26.46 cm; female: 33.25 cm).

Table 1. Descriptive analysis of CMJ, SJ and DJ descriptive values indicating sex differences

	Sex	N	Mean (SD)	95% CI		Percentile			p	ES	MD
				Upper	Lower	25th	50th	75th			
SJ	F	34	27.07 (5.68)	29.05	25.09	24.50	27.00	31.18	< 0.001	1.16	7.27
	M	62	34.34 (6.57)	36.01	32.67	30.30	33.95	40.02			
CMJ	F	37	28.89 (6.47)	31.05	26.73	25.50	29.00	32.60	< 0.001	1.20	8.11
	M	62	37.00 (6.93)	38.75	35.24	32.50	37.00	42.20			
DJ	F	37	26.46 (7.56)	28.99	23.94	22.70	27.00	30.20	< 0.001	0.92	6.79
	M	62	33.25 (7.22)	35.09	31.42	27.57	33.00	38.52			

SJ: Squat jump; CMJ: Countermovement jump; DJ: Drop jump; 95% IC: Confidence interval 95%; p: p-value; ES: Effect size; MD: Mean difference; F: Female; M: Male.

The data in Table 2 indicates significant differences in the strength of the lower limbs between males and females. These differences are observed in hip adduction, hip external rotation, hip extension, hip flexion and knee flexion, with males exhibiting greater strength than females. Furthermore, greater force was applied in knee extension (female: 8.88 N/kg; male: 9.55 N/kg) and less force in hip external rotation (female: 2.08 N/kg; male: 2.32 N/kg).

Table 2. Descriptive analysis of isometric strength tests descriptive values indicating sex differences

	Sex	N	Mean (SD)	95% CI		Percentile			p	ES	MD
				Upper	**Lower**	**25th**	**50th**	**75th**			
Hip abduction	F	36	2.41 (0.53)	2.59	2.23	2.08	2.49	2.75	0.885	- 0.03	- 0.02
	M	62	2.39 (0.60)	2.54	2.24	1.95	2.29	2.77			
Hip adduction	F	37	2.28 (0.49)	2.45	2.12	1.92	2.27	2.52	< 0.001	0.83	0.49
	M	62	2.78 (0.65)	2.94	2.61	2.26	2.79	3.16			
Hip external rotation	F	37	2.08 (0.43)	2.22	1.94	1.87	2.00	2.24	0.013	0.51	0.23
	M	62	2.32 (0.47)	2.44	2.20	2.07	2.32	2.54			
Hip internal rotation	F	37	3.04 (0.57)	3.23	2.85	2.51	2.94	3.48	0.909	- 0.02	- 0.01
	M	62	3.03 (0.59)	3.18	2.88	2.60	3.10	3.49			
Hip extension	F	37	2.94 (0.71)	3.18	2.71	2.48	2.93	3.49	0.029	0.44	0.35
	M	62	3.29 (0.85)	3.51	3.08	2.67	3.38	3.85			
Hip flexion	F	36	3.57 (0.78)	3.83	3.31	2.96	3.56	4.22	0.007	0.54	0.49
	M	62	4.06 (0.98)	4.31	3.81	3.58	3.92	4.76			
Knee extension	F	36	8.88 (1.51)	9.39	8.37	8.13	8.86	9.62	0.072	0.37	0.67
	M	56	9.55 (2.02)	10.09	9.01	8.49	9.65	10.61			
Knee flexion	F	36	3.27 (0.92)	3.59	2.96	2.63	3.24	3.84	0.008	0.56	0.57
	M	57	3.84 (1.07)	4.12	3.56	3.04	3.74	4.48			
Ankle plantar flexion	F	29	8.45 (2.07)	9.24	7.67	7.29	8.23	9.75	0.606	0.12	0.26
	M	54	8.71 (2.30)	9.34	8.08	7.12	8.95	10.33			
Ankle dorsiflexion	F	29	5.59 (1.42)	6.13	5.05	4.49	5.78	6.69	0.937	- 0.02	- 0.03
	M	55	5.57 (1.51)	5.97	5.16	4.39	5.80	6.45			
Knee extension supine	F	15	7.79 (1.16)	8.44	7.15	6.92	7.58	8.11	0.016	0.87	0.90
	M	30	8.69 (0.96)	9.05	8.33	8.13	8.87	9.19			

95% IC: Confidence interval 95%; p: p-value; ES: Effect size; MD: Mean difference; F: Female; M: Male.

The correlation matrix indicates significant positive strength–jump correlations were observed only in female athletes. In females, SJ was associated with knee extension and ankle plantar flexion; CMJ with hip flexion, knee extension, knee flexion, ankle plantar flexion, and ankle dorsiflexion; and DJ with hip extension, hip flexion, knee extension, knee flexion, and ankle plantar flexion strength (all pFDR < .05; Tables 3–4). No correlation remained significant in male athletes after FDR correction, however, external hip rotation show the highest correlation (r = 0.266-0.303), with also a positive correlation observed in internal hip rotation, hip extension, ankle plantar flexion and ankle dorsal flexion (r = ~2-3). Nonetheless, formal comparisons between sexes did not support statistically significant sex differences in the strength–jump associations. Fisher's *r*-to-*z* tests identified nominal sex differences for knee extension–CMJ (Z = 2.253, p = 0.024) and hip flexion–DJ (Z = 2.272, p = .023). However, neither remained significant after FDR correction across 30 tests (all pFDR ≥ .364; Table S[2]).

Table 1. Pearson correlation matrix between jumping and isometric strength tests in female athletes

	SJ	CMJ	DJ	Hip Adduction	Hip Abduction	External Hip Rotation	Internal Hip Rotation	Hip Extension	Hip Flexion	Knee Extension	Knee Flexion	Ankle Plantar Flexion	Ankle Dorsal Flexion
SJ	1	0.979	0.535	0.127 (0.526)	-0.069 (0.701)	0.238 (0.294)	0.137 (0.526)	0.214 (0.319)	0.343 (0.101)	0.527* (0.016)	0.411 (0.058)	0.528* (0.028)	0.411 (0.092)
CMJ		1	0.668	0.129 (0.494)	-0.003 (0.988)	0.251 (0.190)	0.227 (0.221)	0.293 (0.131)	0.427* (0.028)	0.589* (0.002)	0.495* (0.011)	0.464* (0.028)	0.450* (0.028)
DJ			1	0.157 (0.353)	0.197 (0.276)	0.277 (0.139)	0.196 (0.276)	0.411* (0.027)	0.531* (0.009)	0.475* (0.011)	0.498* (0.010)	0.453* (0.027)	0.377 (0.073)

Values are Pearson's correlation coefficients, followed in parentheses by the Benjamini–Hochberg false discovery rate-adjusted p value (pFDR); *: p < .05; **: p < .01; ***: p < .001; SJ: Squat jump; CMJ: Countermovement jump; DJ: Drop jump.

Table 2. Pearson correlation matrix between jumping and isometric strength tests in male athletes.

	SJ	CMJ	DJ	Hip Adduction	Hip Abduction	External Hip Rotation	Internal Hip Rotation	Hip Extension	Hip Flexion	Knee Extension	Knee Flexion	Ankle Plantar Flexion	Ankle Dorsal Flexion
SJ	1	0.970	0.824	0.057 (0.662)	0.158 (0.288)	0.303 (0.160)	0.230 (0.160)	0.238 (0.160)	0.145 (0.288)	0.163 (0.288)	0.197 (0.238)	0.271 (0.160)	0.238 (0.160)
CMJ		1	0.828	0.098 (0.451)	0.183 (0.210)	0.304 (0.102)	0.268 (0.102)	0.253 (0.102)	0.178 (0.210)	0.175 (0.218)	0.185 (0.210)	0.278 (0.102)	0.265 (0.102)
DJ			1	0.011 (0.933)	0.210 (0.206)	0.266 (0.122)	0.209 (0.206)	0.270 (0.122)	0.097 (0.565)	0.084 (0.596)	0.173 (0.284)	0.189 (0.284)	0.318 (0.122)

Values are Pearson's correlation coefficients, followed in parentheses by the Benjamini–Hochberg false discovery rate-adjusted p value (pFDR); *: p < .05; **: p < .01; ***: p < .001; SJ: Squat jump; CMJ: Countermovement jump; DJ: Drop jump.

Discussion

The proposal of descriptive values for individualizing athletes' training to enhance performance, prevent injuries, or aid return-to-play has been elaborated by authors like Valenzuela et al. (2020). These authors provided descriptive values in the jump squat test, such as mean power, mean propulsive power, and peak power. For thus, the data provided by this study can complement the descriptive values of other authors, improving athletes' physical preparation. In this sense, the data provided on jumping height show differences in the three events, with CMJ presenting the highest jumping values (females: 28.88±6.46 cm; males: 36.99±6.92 cm), followed by SJ (females: 27.07±5.68 cm; males: 34.34±6.56 cm) and DJ (females: 26.46±7.56 cm; males: 33.25±7.21 cm). However, although several correlations remained significant in female athletes after FDR correction, formal tests comparing the associations between sexes did not identify statistically significant sex differences. Therefore, the apparent sex-specific pattern should be interpreted cautiously and should be considered descriptive and hypothesis-generating rather than evidence of sex-specific mechanisms.

The SSC, predominant in the CMJ (Pedley et al., 2017; Turner & Jeffreys, 2010), compared to the SJ, causes the CMJ height to be higher due to the SSC's ability of the muscle fibres to apply force. In the case of the DJ, which measures biomotor capabilities such as maximal strength, speed of force development, SSC function and leg stiffness (Pedley et al., 2017), the Reactive Strength Index (RSI), calculated as the ratio of ground contact time to jump height, is an important marker for identifying the 'optimal drop height' that generates greater improvements in performance (Ramirez-Campillo et al., 2018). These findings may suggest that the relationship between contact time and jump height is more indicative in this test than jump height alone. On the other hand, relative strength measurements in different joint movements, used for sex comparisons, do not show as pronounced differences as jumping values. However, significant differences are seen in adduction, hip extension, hip flexion, and knee flexion, with males showing greater strength. Higher strength levels impact injury prevention (Lauersen et al., 2018) and return-to-play (Kyritsis et al., 2016). These data support individualized physical preparation based on sex and affected muscle groups, identifying those at greater injury risk.

The correlation between muscle strength and neuromuscular performance is the most significant contribution of this study. While previous studies have shown a positive but low correlation ($r \approx 0.3$) of relative strength in hip extension, plantar flexion, and knee flexion in non-professional male athletes (Konrad et al., 2021), positive correlations have also been found in knee extension in male football players (Requena et al., 2009; Ugarkovic et al., 2002) and in nine male athletes in knee extension (De Ruiter et al., 2006). However, in our sample of high-performance male athletes, a high correlation was not observed; a higher correlation was found in female athletes.

Firstly, Kotsifaki et al. (2021) indicated that the ankle and knee joints contribute more than the hip in vertical jump performance, which might explain the involvement of these joints, especially in female athletes. Plantar and dorsiflexion strength in females seems to have a notable correlation, as indicated by previous studies (Konrad et al., 2021). This may indicate that adequate ankle strength during the final push-off and landing-push-off phases of the DJ may improve athlete performance, particularly the RSI.

Regarding external rotation and hip extension movements, where the gluteus maximus plays a primary role in hip external rotation, hip extension, and momentum during take-off, and the gluteus medius stabilizes the pelvis in the frontal plane (Plummer & Oliver, 2014), there appears to be a stronger relationship in male athletes. This could suggests that greater gluteal strength correlates with better performance compared to other muscles. The lower correlation observed in female athletes for gluteal strength, contrasted with the higher correlation for knee flexors, could be due to reduced gluteal activity. This could increases reliance on secondary hip extensor muscles like the hamstrings, altering the motor pattern to maintain function (Wagner et al., 2010). The influence of the hamstrings, combined with the iliopsoas in hip flexion (Konrad et al., 2021), might further affect this correlation. Thus, greater strength in the hip flexors could imply better jumping performance, although this may be due to less gluteal motor control triggering greater hamstring versus gluteal involvement.

The muscles involved in knee extension show the most significant sex difference in the correlation between strength and jump height. In males, the correlation is very low ($r = 0.084$-0.175), while in females it is large ($r = 0.475$-0.589), with the highest correlation between these variables found in female athletes. The sex difference and the stronger relationship between greater knee extensor strength and jump height in female athletes may be due to the Q-angle of the knee. The Q-angle, which is the angle between a line drawn from the anterior superior iliac spine to the center of the patella and a line drawn from the center of the patella to the center of the tibial tubercle (You et al., 2023), influences lower limb biomechanics (Saç & Taşmektepligil, 2018) and basic functions such as jumping (Arundale et al., 2020). This angle is accentuated during the landing phase of a DJ, increasing knee valgus and providing less knee control compared to men (Carson & Ford, 2011).

Therefore, the landing or deceleration phase, also present in the eccentric phase of the CMJ, may explain the sex difference. It is possible that coordination in the deceleration phase of these dynamic movements might be more demanding for the knee muscle groups in females, increasing the relationship between these variables. Yilmaz et al. (2017) indicate that increased quadriceps training decreases the Q-angle as muscle contraction straightens the angle. Additionally, hip abduction strengthening improves knee kinematics by reducing valgus and improving patellar tracking, while hip abduction weakness is linked to altered transverse and frontal plane kinematics in male runners (Mucha et al., 2017). Although no sex differences are observed in baseline relative strength values in knee extension and hip abduction, increased strength training in these muscles for females could be beneficial in reducing the Q-angle and improving dynamic capacity.

Despite the novel results obtained, there are certain aspects to be considered. The large sample of high-performance athletes provides valuable information, however, it would be interesting to increase the sample, especially of female athletes, to analyse whether the correlations persist. Another limiting aspect has been the lack of research on the strength of specific muscle groups and their relationship with performance, which makes it difficult to compare results and explain the observed correlations. Furthermore, although it has been indicated that in female athletes a greater work of certain muscle groups is necessary for a better performance, it is necessary to continue investigating the relationship between strength and neuromuscular performance, in order to be able to explain the differences between sexes and why in female athletes there is a greater correlation than in male athletes.

Practical applications

These findings may help practitioners better individualize strength training based on the associations between joint-specific strength and jump performance. Coaches and strength and conditioning professionals should prioritize assessing isometric strength at specific joints alongside vertical jump tests (SJ, CMJ, DJ) to identify potential neuromuscular deficits.

In female athletes, knee extensors, knee flexors, and ankle musculature (plantar flexors and dorsiflexors) showed the most consistent associations with jump performance. Training programs may therefore prioritize: (i) knee-dominant exercises (e.g., squat variations), (ii) hamstring strengthening (e.g., Nordic exercises), and (iii) ankle-focused work (e.g., calf raises and ankle stiffness drills). Given the associations observed in DJ, additional emphasis should be placed on reactive strength and eccentric control during landing and propulsion.

Hip flexors and extensors were also associated with CMJ and DJ performance in females. Thus, complementary exercises targeting hip flexion and extension (e.g., resisted hip flexion drills, hip thrusts) may further enhance performance.

In male athletes, associations between isolated joint strength and jump performance were generally weaker. However, hip external rotators, hip extensors, and ankle plantar flexors showed relevance across tests. Training strategies may therefore emphasize global force production through multi-joint exercises (e.g., loaded jumps, Olympic weightlifting derivatives), complemented by targeted hip and ankle strengthening.

Overall, both sexes may benefit from comprehensive lower-limb strength development or plyometric training (Cepeda-Sánchez et al., 2024). However, females may require greater emphasis on knee and ankle musculature, whereas males may rely more on global neuromuscular coordination and multi-joint force production. These recommendations should be applied cautiously within a broader framework that accounts for sport-specific demands and individual variability.

Conclusions

The findings of this study suggest that isometric strength in specific lower-limb muscle groups is associated with jump performance, with stronger and more consistent relationships observed in female athletes. In addition, the descriptive values provided (e.g., mean and quartiles) may help identify minimum strength levels required in key muscle groups. Together, these results support the use of joint-specific strength assessment to help individualize training and ensure that athletes reach adequate strength thresholds.

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