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Physical fitness of elite youth sports climbers: Gender differences and correlates of climbing ability

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Abstract

Study aim: This study assessed gender-based differences in physical fitness and the relationships between fitness variables and climbing performance among elite youth sports climbers.

Material and methods: The research sample included 20 climbers: 11 female (age: 14.82 ± 1.47 years; body mass: 50.92 ± 5.91 kg; body height: 164.27 ± 5.33 cm) and 9 male (age: 14.67 ± 1.41 years; body mass: 57.36 ± 3.67 kg; body height: 173.44 ± 5.71 cm). Generic fitness tests included jump ergometry, the Y-balance test and the adapted Grant foot-raise test. Sport-specific tests included hangboard assessments (maximum finger hang, rate of force development (RFD) and hang time), pull-ups and toe-to-bar exercises. Independent *t*-tests identified gender differences, while Pearson's correlation coefficients assessed variable relationships.

Results: Males outperformed females in the squat jump ($p = 0.04$) and countermovement jump ($p = 0.03$), and the RFD test for the right hand ($p = 0.01$). Correlation analysis showed that in females, climbing performance was associated with Y-balance test scores (right leg: $r = 0.79$; left leg: $r = 0.87$), maximum finger strength (left hand: $r = 0.76$, $p < 0.01$), maximum relative force ($r = 0.80$, $p < 0.01$), and hang time ($r = 0.65$, $p < 0.05$). In males, lead climbing correlated with hang time ($r = 0.71$, $p < 0.01$) and bouldering with RFD (left hand: $r = 0.76$, $p < 0.05$).

Conclusions: These findings reveal significant gender differences and gender-specific performance predictors, highlighting the need for tailored training programmes during developmental stages.

Keywords: Climbing – Generic fitness – Young athletes – Specific fitness

Introduction

The increased participation of children and youth in competitive climbing highlights the popularity of the sport and increases the interest in research examining the participation of this unique population of children. However, most research focuses on the physical fitness of adults (Draper et al. 2021; Ginszt et al., 2023; MacKenzie et al., 2020), and only a few studies have investigated young climbers (Gilič & Vrdoliak, 2023; Morrison & Schöffl, 2007; Sas-Nowosielski & Gutek, 2022; Trifu et al., 2021; Vrdoliak et al., 2022; Watts et al., 2003).

Anthropometric and physiological determinants, such as finger strength, flexibility, and the power of the upper and lower limbs, explain 39% to 64% of the variance in the climbing ability of adult climbers (Draper et al., 2021; Laffaye et al., 2016; Mermier et al., 2000). This is similar to youth climbers, whose determinants explain 49% of the variance in climbing ability (Nichols et al., 2018), while adding training and experience characteristics to the model explains 82% (Vasile & Stanescu, 2023). The power, strength and endurance of finger flexors and shoulder girdle are recognized as important predictors of climbing ability (Faggian et al., 2024; Langer et al., 2023). However, complex models indicate that in bouldering performance, the strength and power of the lower limbs play a similar role as the upper body in both adults (Winkler et al., 2023) and youth (Nichols et al., 2018). These examples demonstrate

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that prior studies incorporated diverse variables, resulting in the identification of a variety of components of climbing ability.

Current studies show that men climbers have greater grip strength, lower body fat, faster muscle growth, and more power than women (Ginszt et al., 2023). Also, Philipe (2012) suggested that male climbers have greater maximal strength related to body mass and force-time integral in continuous test performance then women. The study had a small sample size, and these gender differences may not apply to young climbers, as they have not yet reached maturity.

Indeed, the maturation process, specifically the pubertal growth spurt, is a critical factor when examining gender differences in physical performance (Abbassi, 1998). Recent research by Chun et al. (2024) using the superimposition by translation and rotation model found that peak height velocity occurs at approximately 11.5 years for girls and 13.5 years for boys, although variations exist across different populations and contexts. This highlights the importance of considering population-specific developmental timelines when analysing youth athletic performance.

These developmental differences are further reflected in sport-specific studies. Research by Vrdoljak et al. (2022) found no significant gender differences in specific fitness tests among young climbers, suggesting that performance disparities observed in adults may not yet manifest due to the ongoing maturation process. Furthermore, the study by Gilić & Vrdoljak (2023) identified a relationship between forearm capacity and maturity offset in girls but not in boys, reinforcing the notion that girls often experience earlier maturation in sports climbing. As pointed out by the authors, the result could be related to earlier maturation of girls in sports climbing, which has been proven in research by Morrison & Schoffl (2007), who examined physiological responses to rock climbing in youth climbers.

This study presents the first large sample of descriptive data for elite young competitive climbers from Slovakia. The aim of the study was to assess physical fitness and gender differences of elite youth sports climbers. Additionally, the aim was to investigate the gender-specific associations between specific and generic fitness tests and climbing ability.

Material and methods

Participants

The research sample included 20 young sport climbers, members of the Slovak national climbing team. The sample was divided according to gender; 11 females (age: 14.82 ± 1.47 years; body mass: 50.92 ± 5.91 kg; height: 164.27 ± 5.33 cm) and 9 males (age: 14.67 ± 1.41 years; body mass: 57.36 ± 3.67 kg; height: 173.44 ± 5.71 cm). Self-reported lead climbing ability for girls ranged from 6c+ to 9a in the French grading system, with corresponding International Rock Climbing Research Association (IRCRA) lead scores between 16 and 29. For bouldering, their ability ranged from 6C to 7C+, with IRCRA bouldering scores between 19 and 25. The average IRCRA score for girls was 21, which corresponds to the elite ability level on the IRCRA scale (Draper et al., 2015). For boys, lead climbing ability ranged from 6c+ to 8a+, with IRCRA lead scores between 16 and 24. In bouldering, their ability ranged from 7A to 8A, with IRCRA scores between 19 and 26. The average IRCRA score for boys was 22, which corresponds to an advanced ability level on the IRCRA scale. The weekly training subsidy for the climbers represented 8-9 hours of training load on average.

Biological age was calculated by subtracting maturity offset from chronological age. The formula for MO was: MO= -7.999 + (0.003 × (age (years) × height (cm)) (Moore, 2015).

Procedures

Subjects were asked to restrain from heavy physical activity for 24 hours before testing. At the beginning of the testing a diagnosis of body composition was performed using bioelectrical impedance with the InBody 230 analyser (Biospace, Seoul, North Korea). Diagnostic of body composition was performed with a focus on body mass (BM), body height (BH), body fat (BF), body fat percentage (BFP), body mass index (BMI) and basal metabolic rate (BMR). To ensure the highest possible objectivity of the results, the pre-test and post-test measurements were taken at the same time of the day. Subsequently, participants performed an individual warm-up, which consisted of a 5-minute general warm-up. In the first phase, climbers completed jump ergometry, the y-balance test for lower limbs and an adapted Grant foot raise test. Before the start of the second phase, there was a 15-minute specific warm up on the wall, involving 5 minutes of an easy climbing traverse followed by 10 min of progressive bouldering (50–80% of their maximum). During the warm-up bouldering, the participants had a minimum of 1-min rest between problems and 10 min of rest before testing according to Hermans et al. (2022). In the second phase, climbers completed specific tests on a hangboard (maximum finger hang test, finger RFD test, finger hang test, all out test) and pull-ups together with toes to bar.

Specific tests were performed using a Climbro hangboard (Climbro Ltd., Sofia, Bulgaria) mounted on a vertical hanging platform. Climbro has integrated force sensors (sample rate 100 Hz) and the phone application Climbro providing instructions and real-time feedback about force and time of muscle contraction. Tests were conducted on both the standard 3 cm depth rung and a modified version with a 0.7 cm manufacturer-provided reduction, resulting in a final hold depth of 2.3 cm.

Adapted Grant foot raise test

An adapted Grant foot raise is one way to assess the mobility of a climber performing a high step. The climber stands 23 cm from a wall, behind a line drawn with tape, and presses hands against the wall, with palms flat at about shoulder width. The climber slides the toes up the wall as high as possible with the hip externally rotated slightly and the inside edge of the big toe pressing against the wall. The highest distance from the ground to the top of the toe is measured. The average of three test trials for both legs was recorded and normalized to limb length according to the testing methodology of Draper et al. (2009).

Maximal finger strength test

The test is aimed at evaluating the maximum finger strength. The test is performed by applying the maximum force that the tested person can generate with one hand on a 2.3 cm-deep hold with an open grip. The tested person stands under the hold with arms at approximately 180° shoulder flexion with slightly flexed elbow and knees and grabs the hold with the chosen arm and open grip. After the start signal sounds, the tested person gradually loads the hold by bending the knees with the feet still touching the ground, so that the chosen hand is weighed the most. The test person must not "pull" by bending the elbow of the chosen arm. The tested person has 5 seconds to load the hold as much as possible. The test ends automatically after two repetitions with each arm. If the tested person is able to hang on the hold during the test, an additional load is added according to the method of Michailov et al. (2018).

Finger RFD test

This test evaluates the rate of finger force development on the standard 2.3 cm hold using an open grip position. The arm and body positioning follow the protocol outlined in the maximal finger strength test. After the start signal sounds, the tested person must pull as fast and hard as possible, abruptly bending both knees and arms during a 5 s period. The test ends after making 2 attempts with each hand. RFD was calculated as an absolute value, expressed as the ratio of the force measured at 200 ms to the time interval, following the methodology of Michailov & Balaš (2023).

Finger hang test

The test is aimed at evaluating strength endurance of forearm muscles. The test is performed on a 30 mm deep edge with a 12 mm radius wooden hold. The tested person stands under the hold and grabs the hold with both hands placed shoulder-width apart. After the start signal sounds, the tested person hangs onto the hold for as long as possible. The result was measured with accuracy of 0.1, according to the testing methodology of Draper et al. (2021).

All out test

The four-minute all-out test was conducted to determine critical force (IM CF), defined as the mean force output during the last three repetitions. The fatigue index (IM FI) was calculated as the percentage decrease in force relative to the initial value, while total impulse from all contractions (IM W) was used to estimate total muscle work.

After the start signal, the tested person applied maximal force for 7 seconds per repetition, with a 3-second rest period in which they were allowed to shake their hand to simulate real climbing conditions. The test consisted of 24 repetitions and concluded after the final work phase. The arm and body positioning followed the protocol outlined in the maximal finger strength test, ensuring consistency across all tests. The test is performed with the dominant hand only according to McClean et al. (2023).

Maximum pull-up test

The tested person performs the maximum number of pull-ups from full arm extension to chin above the board on a wooden or metal bar 2.5 cm in diameter according to McKenzie et al. (2020). The distance between hands was from 1 to 1.5 times that of the shoulder-width grip.

Jump ergometry

Jump ergometry was performed using the Ortojump device. Jump ergometry included 3 tests: countermovement jump (CMJ), squat jump (SJ), and countermovement jump free arms (CMJFA). The tests were used to measure the explosive strength of lower limbs. CMJFA was performed by climbers standing upright between two photoelectric beams with hands free by the body. They moved downwards with knees bending to approximately 90° and performed a maximal upward movement jump with arm swing. The CMJ was performed the same way, but hands were placed on the climbers' hips. SJ was conducted in the same setting, but athletes started the jump after 3 seconds from a position with approximately 90° bent knees and without any downward movement. During the flight phase, in selected tests the lower limbs were extended. Athletes performed three trials for CMJ, SJ and CMJFA, with a one-minute rest between the trials and a 5-minute rest between the tests. The best score (cm) from CMJ, SJ and CMJFA was taken for analysis.

Y-balance test for lower limbs (YBT)

The YBT requires the athlete to balance on one leg whilst simultaneously reaching as far as possible with the other leg in three separate directions: anterior, posterolateral, and posteromedial. Therefore, this test measures the athlete's strength, stability and balance in various directions. The YBT composite score was calculated by summing the three reach directions and normalizing the results to the lower limb length. Reliability and validity of this test were confirmed by Alshehre et al. (2021).

Toes to bar

The tested participants performed the maximum number of toes to bar on a wooden or metal bar with a 2.5 cm diameter, without a set time limit or tempo. From hanging on the bar, the participant bent the trunk until the toes touched the bar. For a valid repetition, the lower limbs must be extended.

Bioethical committee

The study was organized according the guidelines of the Declaration of Helsinki. Obtaining the participant's written consent was the precondition for their participation in the project. The research was approved by Ethics Committee of Pavol Jozef Šafárik University in Košice (No. 1/2022).

Statistical analysis

Normality of the distribution was checked by the Kolmogorov-Smirnov test, which proved the normality of studied variables. A *t*-test was used to evaluate any gender differences (male vs. female) in all study variables. Additionally, to determine whether a statistically significant difference was of practical significance, the magnitude-based Cohen's effect size (ES) was calculated, with modified qualitative descriptors (trivial ES: <0.2; small ES: 0.21–0.60; moderate ES: 0.61–1.20; large ES: 1.21–1.99; and very large ES: >2.0) (Hopkins et al., 2009). Pearson's correlation coefficients were used to evaluate the correlations between variables. All analyses were conducted using the Statistica v15 package (TIBCO, Palo Alto, CA), and a p level of 0.05 was applied.

Results

Descriptive statistics and gender differences in anthropometric and generic fitness variables are presented in Table 1. Males had greater body mass and body height, while they had a lower body mass percentage. Males achieved better results in squat jump and countermovement jump compared to females.

Table 1. Descriptive statistics and gender differences in anthropometric and generic fitness variables

Variable	Female (n = 11)	Male (n = 9)	t-test		Effect sizes	
	Mean ± SD	Mean ± SD	t-value	p	ES	95% CI
Age (years)	14.82 ± 1.47	14.67 ± 1.41	0.23	0.82	0.53	−0.78, 0.99
aPHV (years)	15.50 ± 0.66	15.03 ± 0.65	1.61	0.12	0.72*	−0.19, 0.63
SA (years)	7.45 ± 2.50	6.78 ± 1.56	0.70	0.49	0.31	−0.57, 1.2
TH (hours)	8.45 ± 3.47	8.22 ± 1.79	0.18	0.86	0.08	−0.80, 0.96
BM (kg)	50.92 ± 5.91	57.36 ± 3.67	−2.84	0.01	1.28**	0.31, 2.24
BH (m)	164.27 ± 5.33	173.44 ± 5.71	−3.71	0.00	1.67**	0.65, 2.69
BMI	18.85 ± 1.86	19.06 ± 1.20	−0.29	0.77	0.13	−0.75, 1.01
BFP (%)	11.86 ± 7.11	6.42 ± 2.09	2.21	0.04	0.99*	0.06, 1.93
TB (#)	11.45 ± 6.33	13.56 ± 5.29	−0.79	0.44	0.36	−0.53, 1.25
PU (#)	15.18 ± 5.55	18.78 ± 4.94	−1.51	0.15	0.68*	−0.23, 1.59
SJ (cm)	29.79 ± 3.52	33.27 ± 3.67	−2.16	0.04	0.97*	0.04, 1.90
CMJ (cm)	31.58 ± 3.68	35.39 ± 3.30	−2.41	0.03	1.08*	0.14, 2.03
CMJA (cm)	42.21 ± 20.33	41.71 ± 5.22	0.07	0.94	0.03	−0.85, 0.91
YB L (%)	225.96 ± 359.02	113.22 ± 7.18	0.94	0.36	0.42	−0.47, 1.31
YB R (%)	120.05 ± 6.28	115.20 ± 7.12	1.62	0.12	0.73*	−0.18, 1.64

Legend: SA – sport age; aPHV – age at peak height velocity; TH – training hours; BM – body mass; BH – body height; BMI – body mass index; BFP – body fat percentage; TB – toes to bar ; # – reps ; PU – pull ups; SJ – squat jump; CMJ – countermovement jump without arms; CMJA – countermovement jump with arms; YB L – composite Y-balance test left leg; YB R – composite Y-balance test right leg, * moderate effect size; ** large effect size

Descriptive statistics and gender differences in specific fitness variables are shown in Table 2. Males and females did not differ in specific variables except for the rate of force development of the left hand, where males achieved better results.

The gender-stratified magnitude of correlations, while controlling for maturity offset between climbing ability and anthropometric and generic fitness variables, is presented in Table 3. Lead performance was not correlated with any of the variables. Bouldering climbing performance was correlated with body mass (negative direction), body mass index (negative direction), body fat (negative direction), and y-balance test on both legs (positive direction), which was evident only in females.

In Table 4 the gender-stratified magnitude of correlations, while controlling for maturity offset between climbing ability and sport-specific fitness variables, is presented. In females, lead performance was associated with MS FM L (positive direction), IM FM (positive direction), and HT (positive direction), while bouldering performance was associated with MS FM L (positive direction) and MS FM R (positive direction). In males, lead performance was associated with hang time positive direction), while bouldering performance was correlated with RFD L (positive direction).

Discussion

The primary aim of the study was to assess physical fitness and gender differences of elite youth sports climbers. A secondary aim was to identify gender-specific correlations between specific and generic fitness assessments and climbing ability. Following the aims, this study has several important findings: (i) male and female climbers do not differ in sport-specific tests; (iii) performance is influenced by anthropometric indices in both genders; (iv) females showed statistically significant and higher correlation coefficients (r > 0.60) between climbing ability and sport-specific variables, indicating stronger practical relationships.

Table 2. Descriptive statistics and gender differences in specific fitness variables

Variable	Female (n = 11)	Male (n = 9)	t-test		Effect sizes	
	Mean ± SD	Mean ± SD	t-value	p	ES	95% CI
IL (score)	21.82 ± 3.54	22.11 ± 2.52	−0.21	0.84	0.09	−0.79, 0.97
IB (score)	22.45 ± 1.92	22.78 ± 2.59	−0.32	0.75	0.15	−0.74, 1.03
MS FM L (Fmax; rel)	85.96 ± 10.98	87.56 ± 11.49	−0.32	0.76	0.14	−0.74, 1.02
MS FM R (Fmax; rel)	85.82 ± 8.54	90.56 ± 11.31	−1.07	0.30	0.48	−0.41, 1.37
IM FM (Fmax; rel)	82.82 ± 12.09	86.00 ± 14.79	−0.53	0.60	0.24	−0.65, 1.12
IM W (kg.s)	4127 ± 830	4853 ± 1386	−1.45	0.16	0.65*	−0.25, 1.56
IM FI (%)	49.27 ± 8.87	48.33 ± 10.05	0.22	0.83	0.10	−0.78, 0.98
IM CF (kg; rel)	42.09 ± 9.48	44.78 ± 12.77	−0.54	0.60	0.24	−0.64, 1.13
HT (sec)	75.27 ± 20.16	74.67 ± 16.44	0.07	0.94	0.03	−0.85, 0.91
RFD L (kg/s)	130.82 ± 29.32	147.22 ± 35.59	−1.13	0.27	0.51	−0.39, 1.40
RFD R (kg/s)	122.09 ± 29.83	158.00 ± 25.78	−2.84	0.01	0.82*	0.31, 2.24
GR L (%)	132.55 ± 8.26	127.33 ± 14.65	1.00	0.33	0.45	−0.44, 1.34
GR R (%)	126.82 ± 7.43	138.56 ± 20.58	−1.77	0.09	0.79	−0.12, 1.71

Legend: IL – IRCRA lead; IB – IRCRA boulder; MS FM L – maximum finger strength maximal relative force left hand; MS FM R – maximum finger strength maximal relative force right hand; IM FM – intermittent all-out test maximal relative force; IM W – intermittent all-out test impulse from all contractions; IM FI – intermittent all-out test fatigue index; IM CF – intermittent all-out test critical force; HT – hang time both hands; RFD L – rate of force development left hand; RFD R – rate of force development right hand; GR L – GRANT test normalized left leg; GR R – GRANT test normalized right leg; * moderate effect size

Table 3. Gender-stratified magnitude of correlations, controlling for maturity offset between climbing ability and anthropometric and generic fitness variables

Variable		IL	IB	SA	TH	BM	BH	BMI	BFP	TB	PU	SJ	CMJ	CMJA	YB L
IB	M	0.63	1.00												
	F	0.57	1.00												
SA	M	0.66	0.35	1.00											
	F	−0.37	−0.73*	1.00											
TH	M	0.24	0.47	0.41	1.00										
	F	0.55	0.11	−0.39	1.00										
BM	M	−0.52	−0.33	−0.36	0.11	1.00									
	F	−0.49	−0.78**	0.82**	−0.46	1.00									
BH	M	0.04	−0.40	0.05	−0.03	0.36	1.00								
	F	−0.45	−0.55	0.71*	−0.38	0.62	1.00								
BMI	M	−0.47	0.09	−0.34	0.13	0.53	−0.60	1.00							
	F	−0.38	−0.70*	0.68*	−0.38	0.93***	0.28	1.00							
BFP	M	−0.30	0.16	−0.02	0.42	0.40	−0.42	0.72*	1.00						
	F	−0.42	−0.65*	0.63	−0.43	0.90***	0.30	0.95***	1.00						
TB	M	0.49	0.38	0.36	0.07	−0.42	−0.57	0.18	−0.19	1.00					
	F	0.36	0.20	−0.27	0.61	−0.43	−0.05	−0.49	−0.65*	1.00					
PU	M	0.62	0.23	0.52	0.02	−0.54	−0.05	−0.41	−0.68*	0.78*	1.00				
	F	0.19	0.13	−0.31	0.69*	−0.37	−0.09	−0.42	−0.57	0.89***	1.00				
SJ	M	0.15	0.21	0.28	0.14	−0.25	−0.73*	0.46	0.10	0.90**	0.54	1.00			
	F	0.32	0.42	−0.25	0.45	−0.58	−0.15	−0.65*	−0.71*	0.46	0.60	1.00			
CMJ	M	0.26	0.30	0.30	0.10	−0.25	−0.69*	0.43	0.04	0.95***	0.61	0.98***	1.00		
	F	0.41	0.50	−0.51	0.49	−0.73*	−0.39	−0.71*	−0.75*	0.37	0.50	0.92***	1.00		
CMJA	M	0.56	0.51	0.38	0.15	−0.26	−0.40	0.16	−0.26	0.94***	0.79*	0.78*	0.87**	1.00	
	F	0.17	−0.10	−0.08	0.27	0.29	0.13	0.27	0.20	0.13	0.36	0.00	0.04	1.00	
YB L	M	−0.35	−0.36	−0.66	−0.15	0.35	0.05	0.25	−0.31	0.18	0.13	0.19	0.18	0.21	1.00
	F	0.44	0.87***	−0.45	−0.15	−0.52	−0.21	−0.54	−0.55	0.30	0.16	0.35	0.31	−0.03	1.00
YB R	M	−0.12	−0.40	−0.44	−0.19	0.57	0.45	0.08	−0.35	0.05	0.11	−0.05	0.00	0.17	0.82**
	F	0.44	0.79**	−0.67*	0.22	−0.86	−0.55	−0.79**	−0.76*	0.19	0.12	0.40	0.48	−0.36	0.56

Legend: Gender-stratified magnitude of correlations, controlling for maturity offset between climbing ability and anthropometric and generic fitness variables. (SA – sport age; aPHV – age at peak height velocity; TH – training hours; BM – body mass; BH – body height; BMI – body mass index; BFP – body fat percentage; TB – toes to bar ; # – reps; PU – pull ups; SJ – squat jump; CMJ – countermovement jump without arms; CMJA – countermovement jump with arms; YB L – composite Y-balance test left leg; YB R – composite Y-balance test right leg; *denotes p<0.05; ** denotes p<0.01; *** denotes p<0.001)

The results revealed significant gender differences in generic fitness and anthropometric indices in favour of boys. The results showed that boys are taller and more muscular compared to girls, which is in line with general biological characteristics (Armstrong et al., 2023). These findings are further supported by other studies that compared anthropometric and physical fitness characteristics among young climbers across different climbing disciplines (Nichols et al., 2018; Vrdoljak & Gilić 2022; Sas-Nowosielski & Gutek, 2022; Watts et al. 2003), and are in line with anthropometric profiles reported by Watts et al. (2003), For instance, Sas-Nowosielski & Gutek (2022) identified comparable inter-gender differences in strength conditioning profiles among junior boulderers, speed, and lead climbers. Additionally, Watts et al. (2003) found that 90 young competitive climbers were similar to adult climbers, i.e., short stature, low body weight, and low body fat percentage, which is consistent with our findings. A comparison of the results of girls and boys with adult climbers shows that elite youth climbers exhibit similar anthropometric characteristics to those of top adult male and female climbers (Balaš et al., 2012; Michailov et al.,

Table 4. Gender-stratified magnitude of correlations, controlling for maturity offset between climbing ability and sport-specific fitness variables

	Gender	IL	IB	MS FM L	MS FM R	IM FM	IM W	IM FI	IM CF	HT	RFD L	RFD R	GR L
IB	M	0.63	1										
	F	0.57	1										
MS FM L	M	0.00	0.12	1									
	F	0.76**	0.68*	1									
MS FM R	M	0.13	0.28	0.69	1								
	F	0.61	0.79**	0.86**	1								
IM FM	M	0.06	0.22	0.68	0.45	1							
	F	0.82**	0.61	0.87***	0.89***	1							
IM W	M	0.34	0.56	0.18	0.39	0.63	1						
	F	0.4	−0.09	0.2	0.31	0.58	1						
IM FI	M	−0.54	−0.56	−0.24	−0.48	−0.13	−0.65	1					
	F	0.22	0.44	0.13	−0.01	−0.1	−0, 72*	1					
IM CF	M	0.4	0.48	0.53	0.58	0.61	0.83**	0.85	1				
	F	0.37	0.06	0.46	0.55	0.7	0.89***	−0.77	1				
HT	M	0, 71*	0.48	0.1	0.32	−0.12	0.34	−0, 88**	0.62	1			
	F	0, 65*	0.53	0, 64*	0.66*	0.63	0.32	−0.09	0.48	1			
RFD L	M	0.28	0, 76*	0.32	0.26	0.26	0.17	−0.06	0.11	−0.06	1		
	F	−0.24	−0.42	−0.17	−0.04	0	0.24	−0.36	0.28	−0.09	1		
RFD R	M	0.25	0.33	−0.6	−0.03	−0.59	0.02	−0.13	−0.24	0.11	0.25	1	
	F	−0.5	−0.03	−0.08	0.08	−0.18	−0.26	−0.26	0.04	−0.22	0.21	1	
GR L	M	0.42	0.67	−0.43	0.03	−0.16	0.22	−0.01	−0.15	0.06	0.56	0	1
	F	−0.23	0.14	0.13	0.31	0.15	0.08	−0.33	0.33	−0.08	0.44	0.80**	1
GR R	M	0.47	0.41	−0.45	0.15	−0.23	0.15	−0.01	−0.18	0.1	0.3	0.78*	0.88**
	F	−0.01	−0.13	−0.06	−0.14	−0.04	−0.28	0.46	−0.37	−0.46	−0.06	−0.12	−0.32

Legend: Gender-stratified magnitude of correlations, controlling for maturity offset between climbing ability and sport-specific fitness variables. (IL – IRCRA lead; IB – IRCRA boulder; MS FM L – maximum finger strength maximal relative force left hand; MS FM R – maximum finger strength maximal relative force right hand; IM FM – intermittent all-out test maximal relative force; IM W – intermittent all-out test impulse from all contractions; IM FI – intermittent all-out test fatigue index; IM CF – intermittent all-out test critical force; HT – hang time both hands; RFD L – rate of force development left hand; RFD R – rate of force development right hand; GR L – Grant test normalized left leg; GR R – Grant test normalized right leg; *denotes p<0.05; ** denotes p<0.01; *** denotes p<0.001

2009). These patterns were consistent regardless of sex and align with our current findings, suggesting that certain anthropometric characteristics may be inherent to successful youth climbers, regardless of gender. However, gender-specific developmental patterns, such as greater muscle mass and height in boys, are still apparent even within this relatively homogeneous athletic population.

The lower body fat in boys likely contributes to the better strength-to-weight ratio, which is advantageous in climbing, as previously shown in studies by Baláš et al. (2012, 2016) and Ginszt et al. (2023). Moreover, tissue composition such as body fat percentage showed negative correlations with climbing ability, especially in females. This indicates that girls with lower fat percentages tend to perform better in bouldering, supporting the findings of Baláš (2016) and Philippe et al. (2012).

In recent years, climbing has evolved significantly towards a more dynamic sport, characterized by explosive movements, jumps, and coordination-intensive sequences (Watts 2022; White & Olsen 2010). Explosive strength of lower limbs is necessary for performing dynamic climbing steps, bounces and jumps typical of the sport discipline of bouldering (Ebenchorch et al., 2022; Langer et al., 2023). According to the results of the squat jump and countermovement jump tests, boys demonstrated significantly better explosive strength of the lower limbs compared to girls. Specifically, males achieved higher values in the squat jump ($p = 0.04$, $ES = 0.97$) and countermovement jump ($p = 0.03$, $ES = 1.08$), indicating moderate to large

effect sizes. Previous studies that also examined young climbers (Nichols et al., 2018; Vrdoljak & Gilić 2022) also confirmed the better vertical jump performance in favour of boys, which may be due to higher muscle mass, followed by hormonal functions, particularly testosterone. Additionally, during puberty, the hormonal changes in boys, especially increased testosterone production, further enhance muscle development and strength, leading to superior vertical jump performance (Crewther et al., 2022). This is also linked to their skeletal and muscular growth patterns, which play a crucial role in explosive movements such as jumping (Ben Mansour et al., 2021; Rogol et al., 2000).

In sports like climbing, this can influence performance in dynamic moves, but sport-specific adaptations can often minimize the impact of these differences over time. These differences underline the necessity to adapt training in adolescence, with a focus on motor skill development, injury prevention (especially for girls with earlier maturation), and periodized strength conditioning for boys. Coaches should also monitor psychosocial effects related to body image and performance pressure during puberty.

When we look at sport-specific fitness tests, there are no, or negligible, gender differences between boys and girls, which may be due to the selected research sample. Similar findings were also recorded in a study by Vrdoljak et al. (2022), where in a climbing-specific test there were no intersexual differences in youth elite climbers. This may be due to the nature of the structure of sport climbing performance, which requires the development of specific abilities in a similar way in boys and girls (Vrdoljak et al., 2022). Notably, climbing-specific fitness tests are designed to assess forearm endurance and grip strength, areas where the difference between boys and girls may be smaller compared to more strength-dependent activities like jumping. Another reason may be the selection of talents for sports. In Slovakia, according to data from the Slovak Mountaineering Association, more girls than boys took part in children's and youth climbing competitions last year (60% of the total number of youth competitors were girls), which could have led to a better selection of talents for the Slovak national team from the girls' categories. This is related to the decrease of participants between U14 to U16 age categories for boys. Factors contributing to gender differences include hormonal influences, differences in growth spurts, muscle mass development, and talent identification biases. Understanding these helps coaches tailor training strategies, e.g., incorporating strength training earlier in girls and emphasizing neuromuscular coordination during rapid growth in boys. Therefore, this broader pool from which girls were selected may have led to identifying girls of higher performance, and consequently girls' climbing performance was comparable to that of boys. Similarly, there is no gender difference in climbing ability (IRCRA scale), which can be explained by the fact that climbing often emphasizes technique, balance, and coordination, skills that are not as dependent on raw power. Since technique is a learned skill (Orth et al. 2016), both boys and girls can develop climbing proficiency at similar rates, regardless of physiological differences.

Skilled climbers often exhibit superior coordination, balance, and movement efficiency, which can minimize the need for brute strength (Orth et al., 2016). However, advanced climbing techniques can help mitigate these differences. Women climbers who focus on developing their technique often achieve high levels of performance, demonstrating that technical skill can compensate for physical strength (Millet et al., 2024) (Baláš et al., 2014).

Results of correlations between climbing ability and generic tests showed that bouldering climbing ability was associated with body indices and balance test only in females. Advanced climbing performance is associated with lower body fat percentage (Baláš 2016). Baláš et al. (2012) also noted a negative relationship between body fat percentage and climbing ability, with a higher dependence showing in favour of women.

The strong relationship between women's bouldering performance and balance and strength skills included in the Y-balance test may indicate that balance skills are important for women to perform well in bouldering. The YBT assesses dynamic balance and requires strength and stability in the hip, knee and ankle joints. Lee et al. (2014) observed that the strength of the hip extensors, knee flexors, and hip abductors was positively correlated with performance on the YBT, particularly in the posterior reach directions for females. This relationship underscores the significance of lower-limb strength in tasks that require dynamic stability and postural control, which are essential for controlling body position, efficient weight transfer, and maintaining secure contact with small footholds. These factors also influence the ability to push off footholds with force during bouldering. Therefore, better results for women in the YBT may indicate better performance in bouldering. This corresponds to the findings of Augste et al. (2021), who pointed out that the top 20 women in the world cup ranking needed fewer attempts to climb slabs for which balance skills are required than the top 20 men. Also, this result may be due to differences in difficulty of climbing routes regarding climbers' gender.

Correlations of climbing ability and specific climbing tests showed that there were more evident and stronger associations between climbing ability and sport-specific variables among females than in males. This suggests that in the context of climbing ability, sport-specific variables (such as grip strength, finger endurance, or body positioning skills) are more strongly correlated with the performance of female climbers compared to male climbers. In simpler terms, a woman's success in climbing may depend more on these specific skills and physical traits than a man's success, where other variables might play a greater role. This could indicate that sport-specific training might have a more direct impact on enhancing climbing ability

for women, while for men, ability might be influenced by a broader set of factors, possibly including general physical fitness or technique. Philipe et al. (2012) found that in female climbers, specific physical characteristics such as finger strength and muscle endurance had stronger associations with climbing ability. In contrast, male climbers exhibited weaker associations between these variables and their climbing ability.

It should be noted that our study has some limitations. The research focused only on elite youth climbers. Therefore, it would be of interest to expand the research to include recreational climbers and to increase the sample size. Most research focuses on the adult population, while research on youth is rare, so it was difficult to compare the performance level of other youth climbers. But on the other hand, research is breaking new ground by focusing on youth climbers in Slovakia, which is a unique contribution to the field. Since there is limited existing research on this specific demographic, the study could offer valuable insights and set a precedent for future research regarding sport climbing ability in Slovakia. Also, these findings have implications beyond national federations, contributing to the global understanding of how training can be optimized for youth climbers across different contexts and developmental systems.

Conclusions

Gender differences, particularly during adolescence, play a crucial role in shaping the athletes' capabilities. The results revealed significant gender differences in generic fitness and anthropometric indices in favour of boys. Also, it showed that the boys were taller and more muscular compared to girls and also had better explosive strength of lower limbs. Regarding sport-specific fitness tests, there were negligible intersexual differences. Correlations between climbing ability and generic fitness tests showed an association of body indices, stability, balance and bouldering performance, but only in females. Also, stronger associations between climbing ability and sport-specific variables were observed among females than males. In summary, while generic fitness differences exist between boys and girls in elite youth sports climbing, sport-specific fitness levels tend to be more comparable, suggesting that gender-based training modifications are necessary primarily during periods of rapid physical development, such as puberty. By integrating these findings into training programmes and development strategies, coaches should emphasize strength training and explosive power development in boys during and after puberty, while fostering balance, flexibility, and technical movement efficiency in girls. Individualized progression considering maturity status is essential, along with regular assessments to guide programming.

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