MASTER´S THESIS

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Comparative analysis of bouldering-specific performance determinants between advanced male and female boulderers

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Introduction

Bouldering and the wider climbing sport have experienced rapid and continued worldwide growth in recent years. In its short history, climbing and its sub-disciplines, such as sport climbing, ice climbing and bouldering, have evolved from fringe outdoor activities primarily practiced by mountaineers and thrill-seekers, into recreational and competitive sports with most of today's climbers practicing climbing indoors.

Bouldering is one sub-discipline in the climbing sport and is performed on smaller rock formations (boulders) or artificial climbing walls without the use of rope or harness. It involves climbing short (<6 m), often more than vertical (overhanging) routes or "problems" starting on a pre-determined start-hold and ending with both hands on an established finishing hold or by standing on top of the boulder (Hatch & Leonardon, 2022). Attempts in bouldering typically last ~30s and consists of 5-10 powerful and technically demanding moves requiring intense effort (Laffaye et al., 2014; Stien et al., 2021; White & Olsen, 2010).

The growth in popularity of climbing sports has coincided with rapid development of and increased accessibility to indoor climbing facilities (Climbing Business Journal, 2022; Outdoor Foundation, 2022; Wigfield Daniel & Snelgrove Ryan, 2021), with bouldering being one of the most popular climbing disciplines, accounting for 63% of new North American climbing gyms in 2021 (Climbing Business Journal, 2022). The Norwegian climbing federation reported a more than doubling in members of organized climbing clubs from 2010 to 2020, with simultaneous growth in female members constituting 44% (Skaugvoll, 2021). In 2019, female athletes represented 46% of the international federation of sport climbing's (IFSC) licensed athletes. The interest and competitiveness of climbing sports is expected to continue to grow, with the sport debuting as an Olympic event under the Tokyo 2020 summer Olympics and slated to return for the Paris 2024 games, garnering the sport greater recognition. As the number of participants and competitors continue to increase, so too has the demand for science-based strategies, and methods for improving performance.

The research produced in the most recent decades has demonstrated climbing performance to be the result of a combination of variables including anthropometric (Macdonald & Callender, 2011; Mermier et al., 2000; Michailov, 2009), physical and physiological (MacKenzie et al., 2020; Macleod et al., 2007), as well as technical (Magiera et al., 2013) and psychological variables (Hardy & Hutchinson, 2007; Llewellyn et al., 2008). Distinct differences in demand have also been demonstrated between climbing disciplines (Fanchini et al., 2013; Saul et al., 2019; Stien et al., 2019; White & Olsen, 2010). Boulderers have in multiple studies displayed higher levels of peak force and rapid force production in the finger flexors and prime movers (shoulder, back, arm muscles) compared to their sport-climbing counterparts (Fryer et al., 2017; Laffaye et al., 2014; Levernier et al., 2020; Stien et al., 2019). The extent to which upper body strength and power differ between male and female boulderers remains unclear, but upper body strength has been shown to be higher in male sport climbers when compared to their female counterparts (MacKenzie et al., 2020). This difference may be expected, as women tend to have a lower proportion of lean muscle tissue and fiber volume in the upper body (Miller et al., 1993). Finger flexor strength to body mass ratio is generally accepted as a key factor for bouldering and climbing performance (Amca et al., 2012; Baláš et al., 2012; Ceyhan et al., 2021; Fanchini et al., 2013; López-Rivera et al., 2022), and is frequently tested using climbing-specific tests. Finger flexor strength has been demonstrated to be one of the primary factors differentiating elite, advanced and intermediate climbers (Laffaye et al., 2016). Furthermore, research suggests that finger flexor strength may differ between the sexes in elite climbers (Watts, 2004). As bouldering difficulty increases, so does the demand for finger flexor strength and the ability to generate force quickly through the fingers to maintain contact with the holds, and transfer force generated by the prime movers to the holds during climbing moves (Fanchini et al., 2013; Levernier & Laffaye, 2019b; Stien et al., 2019). The ability to rapidly generate force is commonly known as rate of force development (RFD). This performance measure is determined by both neurological adaptation as well as muscular properties (Levernier & Laffaye, 2019b). RFD has been demonstrated to be greater among boulderers when compared to sport climbers (Stien et al., 2019).

Flexibility is also generally regarded to be integral to bouldering performance, as a greater range of motion in the lower limbs may give the athlete access to more footholds and more advantageous positions to generate force from. While the importance of flexibility in climbing is widely recognized, the extent to which it contributes to improving climbing performance remains unclear and has yet to be definitively determined (Draper et al., 2009; Draper et al., 2021). Furthermore, the role of flexibility in performance between the sexes may differ and is not yet defined, with some studies indicating a higher level of flexibility among female climbers (Giles et al., 2021; Grant et al., 2001; Grant et al., 1996).

Bouldering is a multifaceted sport, with high physical demands in movements which require a whole-body approach to performance improvement (Saul et al., 2019). Assessing whole-body skeletal muscle force capacity can offer valuable insight into the physical demands of bouldering. Previous research conducted in non-climbing sports has demonstrated significant relationships between dynamic performance measures relevant to bouldering performance, including agility, speed and strength, with whole-body skeletal muscle force capacity (Wang et al., 2016).

The difficulty of a boulder problem or climbing route is generally described using traditional numeric or alphanumeric grading scales. These grades are used to indicate the difficulty of the climb. To facilitate statistical analysis and comparisons between different grading scales, the International Rock Climbing Research Association (IRCRA) offers a comparative grading scale that converts grades to a numeric value, allowing for easier analysis of data related to climbing difficulty (Draper et al., 2015). Self-reported climbing ability (highest achieved grade in a given format) is extensively used withing the climbing literature and has been demonstrated to be a valid representation of actual climbing ability (Draper, Dickson, Blackwell, Fryer, et al., 2011). A widely used method of ascent reporting is the redpoint style. This style sets no limitation on practice attempts or technical information on the route or problem, allowing the athlete to perform close to maximal physical and technical effort.

Although the interest and participation in climbing sports is on the rise, the scientific understanding of climbing and the different disciplines is still in its infancy and relatively unexplored compared to other more established sports. This is demonstrated by approximately 70% of the research published on physiological and psychological factors related to climbing performance having been published in the last 10 years (Giles et al., 2021). The limited research is particularly evident in regard to our understanding of female performance determinants and characteristics. Despite a substantial number of female participants in the sport (American Alpine Club, 2019; Outdoor Foundation, 2022; Sport England, 2022; Wigfield Daniel & Snelgrove Ryan, 2021), few studies include female participants, with many failing to report results of female climbers not as part of a combined sample (Stien et al., 2022). Consequently, little is known about how performance characteristics and determinants may differ between the sexes (Grant et al., 2001; MacKenzie et al., 2020; Stien et al., 2022).

Greater understanding of performance determinants for bouldering and potential sex differences can provide researchers, athletes, and coaches valuable information in how to better structure, individualize, prioritize, and optimize for improving bouldering performance.

This study aims to assess how physical determinants in bouldering may differ between the sexes among similarly skilled boulderers. Based on previous findings indicating higher upper body strength in male climbers, it was hypothesized that male boulderers would exhibit greater upper body strength and power compared to female boulderers, and that this attribute would be a stronger predictor of bouldering performance in male boulderers (H1). Additionally, male boulderers were expected to demonstrate greater finger flexor strength to body mass ratio and subsequently exhibit greater RFD in the finger flexors (H2), as previous research has found male climbers to have greater finger strength. Further, based on previous research on lower limb flexibility in climbers, it was hypothesized that female boulderers would have greater lower limb flexibility compared to males (H3).

Materials and Methods

Experimental approach

A physical fitness test protocol was designed to examine differences in bouldering-specific physical performance characteristics among male and female boulderers. The physical test protocol consisted of the following tests: (1) Maximum hip flexion measured using the adapted Grant foot raise test, (2) whole-body skeletal muscle force-generating capacity using the isometric mid-thigh pull (IMTP), (3) maximal finger-grip strength and RFD measured as the maximum voluntary isometric contraction (MVIC) of the finger flexors during unilateral isometric pull-down on a 19 mm edge, (4) upper body power using the powerslap test, (5) maximal hip abduction measured using the lateral foot reach test, and (6) upper body maximal pulling strength assessed through a unilateral isometric maximal pull-down using a full hang grip.

Participants

After screening, a total of twenty-four (N = 24) advanced boulderers (IRCRA: 16-21; Draper et al., 2015), evenly distributed between the sexes (Male = 12, Female = 12) were recruited through their local climbing gym (Table 1). Participants were screened through the following inclusion criteria: bouldering redpoint level >6A Fontainebleau grading scale (16 IRCRA) or ≤7A+ Fontainebleau grading scale (21 IRCRA), minimum bouldering experience of 1 year, weekly bouldering-related training the past 3 months, free from climbing related injury the last 6 months. All participants were provided with written and verbal descriptions of the testing procedures, their rights as participants, and the possible risks involved with physical testing. All participants were over 18 years old (between 19 and 43 years) and signed an informed consent form prior to testing. Participants were asked to refrain from consuming alcohol for 24 hours and caffeine for 6 hours prior to testing, as well as to avoid climbing or other exhaustive exercise for 48 hours before testing. The research protocol was in accordance with the ethical guidelines of Nord University and approved by the Norwegian Center for Research Data (reference number: 131037) and conformed to the principles outlined in the Declaration of Helsinki on human research.

Table 1. Anthropometric data, self-reported performance level (IRCRA scale), bouldering experience, weekly training volume (n = 24). Data presented as mean (± SD).

Participant Characteristics	**Men (n = 12)**		**Women (n = 12)**	
	Mean (SD)	*Range*	*Mean (SD)*	*Range*
Age (years)	27.2 (6.4)	19.0-43.0	27.6 (4.5)	21.0-37.0
Height (cm)	179.8 (7.7)*	165.1-191.5	170.7 (5.2)	163.5-181.0
Arm span (cm)	183.0 (8.8)*	163.5-194.5	170.1 (4.2)	160.5-176.0
Body mass (kg)	77.7 (7.3)*	64.8-87.8	66.2 (5.2)	52.3-71.8
Body Fat (%)	14.0 (3.7)*	8.9.18.8	25.5 (5.7)	14.50-32.40
BMI (kg/m^2)	24.1 (1.5)	20.6-26.2	22.8 (2.4)	18.3-27.0
Ape index (arm span/height)	1.01 (0.01)*	0.99-1.02	1.0 (0.02)	0.96-1.05
Performance level (IRCRA)	19.5 (0.9)	17.0-20.0	18.7 (1.8)	16.0-21.0
Active years climbing	3.0 (1.8)*	1.0-8.0	6.2 (4.0)	1.0-13.0
Training volume (Sessions/week)	3.4 (1.0)	1.5-5.0	3.0 (0.6)	2.0-4.5

Abbreviation: BMI, body mass index. IRCRA, International rock climbing research association comparative grading scale.

*Significant difference ($p < 0.05$)

Methodology

When arriving at the testing laboratory, participants were informed verbally about the testing procedure and signed the informed consent form. A short interview was conducted about the participants bouldering ability, training volume and years of climbing experience (Table 1).

Bouldering ability was determined as the highest self-reported redpoint bouldering grade using the Fontainebleau grading scale, which was subsequently converted to the IRCRA numerical grading scale (IRCRA) (Draper, Canalejo, et al., 2011). Training volume was defined as the number of sessions per week spent bouldering, including supplementary exercises with the aim to improve bouldering performance. Climbing experience was reported as the cumulative number of years spent actively participating in climbing sports. All testing took place between November and December 2022.

Height was measured to the nearest 0.5 cm using a wall-mounted stadiometer without shoes, feet together. Arm span was measured to the nearest 0.5 cm as the distance between the left middle finger and right middle finger while arms were abducted horizontally at shoulder height facing the wall. Arm span to height ratio (arm span/height), in climbing referred to as ape index, was subsequently calculated. To ensure consistent results, body mass and body fat percentage were measured twice using a Tanita InnerScan V BC-545N (Tanita, Tokyo, Japan). If there was a deviation greater than 0.5kg or 1.0% body fat between the two measurements, a third measurements was taken, and the mean of the three measurements was used. Body mass index (BMI) was also calculated. All tests performed measuring force and RFD (2, 3, 6) were measured using a 1000 Hz force cell (Model: ST – A – 1t, Ergotest Innovation A/S, Porsgrunn, Norway). The force output data was recorded with the software MuscleLab (v. 10.222.104.5260, Ergotest Innovation A/S, Porsgrunn) and raw data was exported to Excel (v. 2212, Microsoft Corporation, Redmond, WA, USA) for further analysis. Peak force (F_{peak}) and flexibility test results were recorded as both absolute and normalized values (divided by body mass or height, respectively), as a measure of relative peak force (RPF) and flexibility relative to height to account for differences in individual limb length.

To determine the optimal and most effective testing procedure, two pilot studies were conducted, each with a sample size of two (total N = 4). Ethical standards were followed in the treatment of participants in the pilot study.

A 15 min general warm-up involving light-to-moderate intensity compound movements and stretching was performed. The warm-up movements were self-selected by the participant, with instructions to avoid fatigue. All tests were performed twice with the highest value achieved in two attempts representing the participant’s test score. Each test was separated by 3-min rest intervals. During rest intervals, participants were allowed to familiarize themselves with the next testing movement at a low intensity avoiding fatigue. This was done to minimize the likelihood of technical failure and injury. All verbal instructions and encouragement were given by the same researcher to ensure a standardized testing process. The testing order and time between attempts was also standardized to minimize the effect of fatigue.

Hip flexion was measured by performing the adapted Grant foot raise test, with the participant standing 23 cm away from and facing the wall, palms flat to the wall at shoulder width and height, lifting the right foot as high as possible, guided by a prefixed vertical line (Draper et al., 2009).

Whole-body skeletal muscle force-generating capacity was assessed as the peak force produced during a 3-s isometric pull. The force sensor was attached to a baseplate and straight steel bar using a chain. The researcher demonstrated the testing position to the participants, who were directed to stand on the baseplate and position their feet approximately shoulder width apart while bending at the hip and knee to a degree that felt stable and natural for them (James et al., 2017). The length of the chain was adjusted to ensure that the chain was in tension while standing in the test position holding the bar with a double overhand grip at the mid-point of the hip joints and knee (Dos'Santos et al., 2019). Before each attempt, the participant was instructed to pull as fast and hard as possible for the entire 3 s. The command to start was given with no tension in the system.

Maximal finger flexor strength was assessed as the 2 s unilateral MVIC of the dominant hand on a 19-mm edge while seated. All tests were performed using the “half crimp” grip, in which the angle of the proximal interphalangeal joint is at 90° with an extension of the distal interphalangeal as described by Levernier and Laffaye (2019a). To minimize potential unwanted movement and prevent the participant from pulling themselves off the chair during testing, the participant was securely fastened to the testing chair across the thighs and around the waist. Testing was performed using the Tindeq V-Ring (BLIMS AS, Trondheim, Norway) 19 mm edge. The V-Ring and force sensor was fixed above the shoulder of the participant, and adjusted to the position of the participants’ shoulder abducted at 130° and elbow flexed at 50° (Figure 1)(Baláš et al., 2014). The same force data was used in the analysis of the early phase of muscle contraction, with rate of force development (RFD) of the finger flexors being calculated as the force generated during the first 200 ms (RFD_{200}) from onset, and total RFD as

95% of F_{peak} ($RFD_{95\%}$) from onset (Levernier & Laffaye, 2019b). The participant was instructed to "pull as hard and as fast as possible" to optimize the results of both MIVC and RFD.

Onset was determined as the moment force increased with more than 4 N within 5 ms. Increase in force was calculated as the difference between the moving average of 5 samples, determining onset as the third sample within the 5 ms sampling window. Other studies have used similar methods in determining onset by visually analyzing the force-time curve (Levernier & Laffaye, 2019b; Stien et al., 2019) using a set threshold of ~4 N within a 5 ms window (Levernier & Laffaye, 2019a; Stien et al., 2021). The 1000 Hz sampling frequency used in this study made the moving average an objective and highly efficient method of determining a clear onset of force.

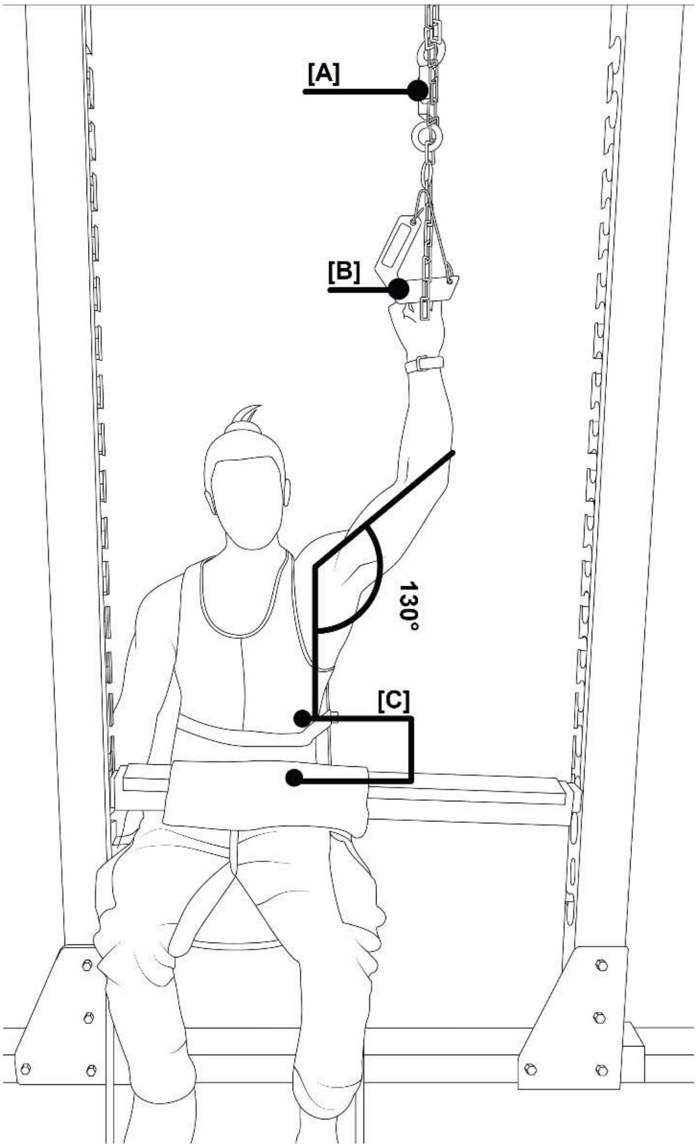

Figure 1. *Testing position of unilateral MVIC and maximal unilateral isometric pull-down. [A] 1000hz frequency force cell secured with chain; [B] Tindeq V-Ring; [C] Firmly secured above the waist and over the thighs.*

Upper body power was assessed using the powerslap test (Draper, Dickson, Blackwell, Priestley, et al., 2011). The test participant starts hanging from straight arms (dead hang) on a 32 mm (Metolius Climbing, Bend, Oregon, USA) rounded edge. The participant's hands were spaced shoulder width apart using a self-selected grip variant, knees bent with the feet behind the climber and elevated from the ground (Draper et al., 2021). In one continuous movement, without any lower body momentum, the participant executes an explosive pull-up movement and slaps the scaled board located above the edge as high as possible using one hand (Draper, Dickson, Blackwell, Priestley, et al., 2011; Draper et al., 2021). The backboard was overhanging at 13° and marked with lines spaced 1 cm apart. Test attempts were filmed at 60 fps and analyzed using the open-source video annotation software Kinovea (v. 0.9.5) to zoom and slow down the test footage to achieve the most accurate test score to the closest cm. Results were measured in maximal cm reached and scaled as the static reach with one arm at 90° elbow flexion divided by maximal distance reached.

The lateral foot reach test was performed to assess maximal lateral hip abduction (Draper et al., 2009). The active start position consisted of the participant standing on a climbing hold with the right foot while gripping a steel bar that was adjusted to a height so that the participant could stand with a straight right foot and keep 90° elbow flexion. Using an overhand grip, the participant completed the test by keeping the right knee in an externally rotated position, while horizontally extending the left leg to maximal hip abduction. The participant was allowed to extend the arms to a dead hang during the test, but not allowed to move the arms from the starting position. The measurement was taken from directly below the right foothold to the outside edge of the extended foot.

Strength in the upper back, arm, and shoulder (prime movers) were measured as the 4 s maximal isometric unilateral pull-down (max pull-down) of the dominant arm. The test was performed seated with the participant firmly secured to the chair. The Tindeq V-ring was attached above the shoulder with the same elbow flexion and shoulder abduction to that of the MIVC finger flexor test (Figure 1), with the participant gripping the V-ring with a closed hand grip.

Statistical Analysis

Data was processed with the use of SPSS statistical software (version 27, SPSS Inc., Chicago, IL, USA) and is presented as mean (± SD). Stepwise multiple univariate linear regression analysis was performed on both male and female bouldering groups to determine the relationship between bouldering performance (IRCRA) and physical test variables (IMTP, finger flexor MIVC, finger flexor RFD_{200}, Max pull-down and $\mathrm{powerslap}_{\mathrm{scaled}}$). Bouldering ability was set as dependent variable, while other variables were treated as independent. Normality of residuals was assessed with the Shapiro-Wilk test (both $p > 0.077$). The Skewness and kurtosis of residuals for the male and female group were assessed. For the male group, the skewness was -0.561 (absolute z-score of 0.88) and the kurtosis was 0.623 (absolute z-score of 0.98). For the female group, the skewness was 1.250 (absolute z-score of 1.02) and the kurtosis was -1.181 (absolute z-score of 0.96). Autocorrelation was evaluated using the Durbin-Watson test (1.22 – 2.40).

Group differences were determined using independent sample t-tests, with the Mann-Whitney U test utilized when normality assumptions were not met. Normality was assessed with the Shapiro-Wilk test (all $p \geq 0.233$) as well as visually (histogram, Q-Q plot). Except for RPF in the female IMTP test (Shapiro-Wilk test 0.033), all performance variables were normally distributed (range 0.233 – 0.998). The ranges of skewness and kurtosis were -0.904 – 1.339 (absolute z-scores |0.41 – 0.61|) and -0.977 – 2.648 (absolute z-scores |0.23 – 0.62|), respectively. Outliers were identified using boxplot graphing, and extreme outliers were excluded from analysis. Specifically, one male participant was excluded from the powerslap test analysis as an extreme outlier, and two female participants were also excluded from the powerslap analysis for failing to complete the test. The alpha level for statistical significance was set at 0.05.

Results

Stepwise multiple regression analyses of the physical strength and power test variables (IMTP, finger flexor MIVC, finger flexor RFD_{200}, max pull-down, $\mathrm{powerslap}_{\mathrm{scaled}}$) found only the max-pulldown test in the male group ($F(1,9) = 5.553$, $p = .043$) to be a significant predictor of performance level ($\beta = .62$, $p = .043$), accounting for 38.2% of the variance. For the female group regression model ($F(1,8) = 21.359$, $p = .002$), only finger flexor MIVC was found to be a significant predictor of performance level ($\beta = .85$, $p = .002$), accounting for 72.8% of the variance. Independent t-tests (Table 2) showed RPF, RFD and power variables to be significantly higher in male boulderers. No statistically significant differences were observed in hip flexion or hip abduction between the sexes.

Table 2. Results of independent sample t-tests, presented as mean ± SD with effect size (ES) presented as Cohen's *d*.

	Male	**Female**			
	Mean ± SD (n)	**Mean ± SD (n)**	**T(df)**	***P***	**ES**
Finger flexor MIVC_{RPF}	6.6* ± 1.2 (12)	5.4 ± 1.0 (12)	2.737 (22)	0.012	1.116
Finger flexor MIVC F_{peak}	510.8† ± 80.5 (12)	352.9 ± 64.9	5.290 (22)	<0.001	2.160
$\text{RFD}_{\text{200ms}}$	1715.4† ± 355.4 (12)	1242.8 ± 248.5 (12)	3.775 (22)	0.001	1.541
$\text{RFD}_{95\%}$	485.3† ± 76.5 (12)	335.2 ± 61.9 (12)	5.284 (22)	<0.001	2.157
Max pull-down	10.4† ± 1.5 (12)	7.3 ± 1.6 (11)	5.083 (22)	<0.001	2.075
Powerslap (scaled)	159.3* ± 21.5 (11)	123.0 ± 38.7 (10)	2.690 (19)	0.014	1.175
Powerslap (cm)	82.9† ± 9.5 (11)	58.0 ± 17.9 (10)	3.965 (19)	0.001	1.733
Adapted foot raise	65.1 ± 6.4 (12)	60.1 ± 9.2 (12)	1.569 (22)	0.131	0.641
Lateral foot reach	102.2 ± 3.5 (12)	104.2 ± 3.6 (12)	-1.373 (22)	0.184	-0.560
IMTP	28.3* ± 4.2 (12)	22.4 ± 6.4 (12)	23.000 ^{A}	0.005	0.341 ^{B}

^{A} **= Mann-Whitney U.** ^{B} **=** η^2. RFD_{200}, $\text{RFD}_{95\%}$, powerslap (scaled), powerslap (cm) **Normalized to body mass (n/body mass):** Finger flexor MIVC_{RPF}, finger flexor MIVC F_{peak}, max $\text{pull-down}_{\text{RPF}}$. **Normalized to height,** adapted Grant foot raise (cm/cm height), lateral foot reach (cm/cm height); isometric mid-thigh pull_{RPF} (IMTP).

* = Significantly different $p < 0.05$

† = Significantly different $p < 0.01$

The finger flexor MIVC to Max pull-down ratio was compared using an independent sample t-test. The analysis revealed a significant difference between the two groups (Figure 2), with female boulderers (0.74 ± 0.07) having significantly higher finger flexor MIVC to Max pull-down ratio than male boulderers (0.63 ± 0.10); t(21) = 2.896, p = 0.008, *d* = 1.182.

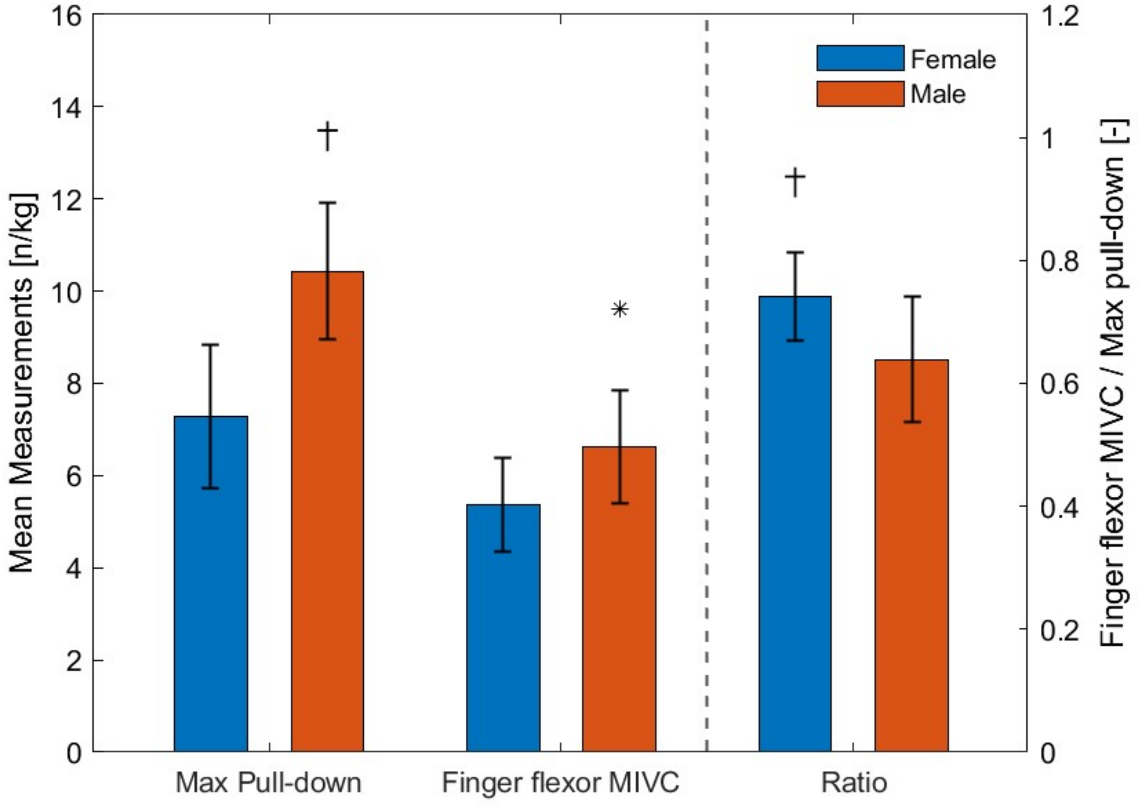

Figure 2: Mean Max Pull-down, Finger flexor MIVC and Finger flexor MIVC to Max Pull-down ratio of male and female boulderers.
** = Significantly different p < 0.05*
† = Significantly different p <0.01

The results in Table 1 present the anthropometric variables, self-reported experience, and performance levels of both the male and female bouldering groups, including means, standard deviations, and range, as well as significant differences between the groups. Among the experience variables, only years of climbing experience showed a significant difference, with the female group having participated in climbing sports significantly longer (MD = 3.250 ± 1.271, t(21) = 2.556, p = 0.18, *d* = 0.75). The other experience variables, i.e., weekly training volume and redpoint grade, did not show significant differences between the two groups.

Discussion

The present study aimed to investigate the potential sex differences in physical determinants of similarly skilled boulderers. The findings showed that advanced male boulderers demonstrated significantly greater upper body strength and power (scaled and absolute), as well as finger flexor strength to body mass ratio and RFD, compared to their female counterparts. Further, the results revealed that the max pull-down test was the greatest predictor of bouldering performance (38.02%) in advanced male boulderers, while finger flexor MIVC was the greatest predictor (72.7%) in advanced female boulderers. These results support H1, which suggested that upper body strength and power would be higher and a greater predictor of performance among male boulderers when compared to female boulderers, and H2, which posited that finger flexor strength and RFD would be higher in male boulderers. H3, which proposed greater flexibility in the lower limbs among female boulderers, was not supported as neither hip flexion nor hip abduction was found to be significantly different between the sexes.

Upper body strength being a greater predictor of male bouldering performance (H1) is consistent with previous findings by MacKenzie et al. (2020) on climbers within a wide performance range (5a-8a male climbers and 5a-7b+ female climbers), in which maximum pull-ups accounted for 59% of variation in climbing ability among men, and only 8% within female climbers, with the bent arm hang instead accounting for the greatest variance in female climbers. Greater upper body strength and reliance for bouldering performance in male boulderers is likely to be the result of both distinct sex differences in lean muscle tissue distribution and volume in the upper body (Miller et al., 1993), allowing for a greater force production. Climbing technique and bouldering steepness preferences favoring more upper body intense climbing may also have resulted in greater upper body strength adaptations.

The results of the powerslap test found the male bouldering group to demonstrate significantly higher reach in both scaled and absolute measurements, supporting H1, although the test did not demonstrate a significant relationship with bouldering ability. The results of the powerslap test are consistent with the significantly higher upper body strength exhibited by the male bouldering group in the max pull-down test. The male group (82.9 ± 9.5) performed comparable to that of the advanced (77.5 ± 20.9) and elite (89.7 ± 11.6) (Australian/NZ grade 24.8 ± 3.6: IRCRA 18 ± 4.2) combined sex sample in the previous study by Draper et al. (2011), while the female bouldering group (58.0 ± 17.9) performed similarly to that of higher advanced female rock climbers (63.2 ± 18.6) (Giles et al., 2021). However, it should be noted that two female participants were excluded from the data analysis due to their inability to complete the test, and one male extreme outlier was also excluded. The powerslap test specifically requires a high level of ballistic upper body strength, which is consistent with the characteristics of bouldering movements.

The present study's findings of finger flexor MIVC_{RPF} being a greater predictor of bouldering performance in female climbers is also in line with findings in non-bouldering specialists, where relative grip strength was found to explain more than 50% of redpoint climbing performance (Baláš et al., 2012). Notably, the finger flexor MIVC F_{peak} of the female group in this study (352.9 ± 64.9) closely compares with higher advanced female climbers (IRCRA 19.3 ± 0.9) (356.8 ± 53.5) in the previous study by Giles et al. (2021). The higher intensity and overhanging nature of bouldering likely accounts for finger flexor MIVC_{RPF} being a greater predictor of performance in female boulderers than in sport climbers (Stien et al., 2019), as bouldering generally requires greater upper body and finger peak force output. Interestingly, the female group exhibited a significantly higher ratio of finger strength to upper body strength compared to the male group, which demonstrates a larger discrepancy in strength proportions between male and female boulderers (Figure 2).

Rate of force development of the finger flexors has previously been identified as a highly important performance variable in bouldering (Fanchini et al., 2013; Stien et al., 2019). Stien et al. (2019) demonstrated that boulderers had significantly higher RFD than lead climbers. In line with H2, both early phase (200 ms) and total RFD (force between onset and 95% of maximum force) were significantly higher in the advanced male boulderer group (Table 2). However, neither RFD variable significantly predicted bouldering performance in either group. Comparing the RFD results of the present study with those of previous studies is challenging, due to the lack of studies on boulderers and of a standardized method for assessing finger flexor RFD. The most appropriate comparison for RFD_{200} is the study by Stien et al. (2019), which measured RFD bilaterally from onset of force to the peak force output (Mean ± SD 1537 ± 548), although the bouldering group studied ($N = 16$) only included one female boulderer, making an inter-sex comparison irrelevant. It can be hypothesized that some of the variance in RFD in the male group of the present study is explained by a higher redpoint grade (Table 1) when compared to the study by Stien et al. (IRCRA 17.85 ± 3.4). The cause of the observed differences in RFD between the sexes in the present study cannot be determined with certainty. However, it can be assumed that differences in training method and climbing style may have some causal effect on the difference in RFD_{200}, as the early phase of RFD (<200 ms) is primarily the result of neuromuscular adaptation from training, increasing motor unit-firing rate, improving RFD and muscle properties such as fiber-type (Levernier & Laffaye, 2019a; Aagaard et al., 2002). Further, differences in architectural muscle structure (number of type II and I muscle fiber), muscle volume and tendon muscle-stiffness relates more to differences in the later phase of the RFD curve and maximal strength (Levernier & Laffaye, 2019a; Miller et al., 1993; Tillin et al., 2010; Watts, 2004; Aagaard et al., 2002).

Flexibility in the lower limbs in the way of flexion, abduction and external rotation of the hip was hypothesized to be a greater predictor of bouldering performance among advanced female boulderers (H3). The hypothesis was not supported, as no significant difference in hip flexion or abduction was found between male and female advanced boulderers. Flexibility in the lower body has previously been linked to climbing performance (Draper et al., 2009) and is generally considered a key performance indicator (Watts, 2004), specifically hip flexion, abduction and external rotation of the hip (Draper et al., 2009; Watts, 2004). Greater range of motion resulting from enhanced flexibility and mobility in the lower body may provide more advantageous technical positions or foot holds for movement, possibly enabling effective offloading of weight from the fingers and prime movers, which in turn can lead to successful performance. Female climbers are colloquially considered to exhibit greater range of motion than male climbers, but with the findings of this study and the limited available research there is nothing to support this notion when studying advanced boulderers. The results of this study not finding flexibility to be a predictor of bouldering performance is similar to previous findings on climbing performance (MacKenzie et al., 2020; Mermier et al., 2000) and further underlines the suggestion by Draper et al. (2009) that there might be a threshold for the importance of flexibility which is met by advanced and elite climbers, and when met no longer finds improvement in flexibility critical for performance. The participant group of the present study being advanced boulderers may suggest that this threshold was met. Further research is needed to determine potential differences in flexibility between male and female boulderers across different performance levels. Additionally, exploring the role of flexibility in relation to technique in both male and female boulderers during climbing movements may also give a more realistic and sport-specific view of flexibility as a performance determinant.

The inclusion of the IMTP in the testing protocol aimed to evaluate the overall whole-body skeletal muscle force production capacity of the participants (Wang et al., 2016). Results did find that the male bouldering group demonstrated significantly higher RPF in the IMTP (28.3 ± 4.2) when compared to the female bouldering group (22.4 ± 6.4). As all participants were previously unfamiliar with the IMTP, and it does not involve a sport-specific movement, it is unlikely that a large discrepancy in learning effect resulted in the between-group difference. Furthermore, since peak force was assessed relative to body mass, it can be assumed that the significantly lower body fat percentage in male boulderers means a higher volume of lean muscle mass to body mass, resulting in a higher relative force output. While the IMTP has not been traditionally used in climbing research, it is widely used in other sports and is reported to relate to various dynamic performance variables such as agility, strength and power (Conlon et al., 2013; Wang et al., 2016). The use of repeated IMTP testing on boulderers may reveal more information on the force capacity of boulderers. Comparisons with previous studies within the sport are currently impossible due to the lack of studies using the IMTP in climbing research. While male boulderers demonstrated significantly higher relative strength in the IMTP, this did not show any significant relationship to bouldering grade.

The present study investigated how physical bouldering determinants and performance characteristics differ between similarly skilled male and female boulderers using a bouldering-specific testing protocol. Previous research has used comparable methods for assessing physical determinants in athletes of different climbing disciplines (Fanchini et al., 2013; Stien et al., 2019) or comparing athletes of different performance levels (Giles et al., 2021; Grant et al., 2001; Laffaye et al., 2016; Mermier et al., 2000). The results of this study demonstrated significant differences in physical characteristics and determinants in similarly skilled male and female boulderers, with males performing significantly better in all assessed strength to body mass variables, as well as power. The study identified upper body strength to body mass ratio as the greatest predictor of variance to grade among male boulderers, while finger flexor strength to body mass ratio was found to be the greatest predictor in the female bouldering group, indicating distinct differences in how physical determinants contribute and are relied on for bouldering performance between sexes. These findings corroborate similar findings in a larger skill range of non-bouldering specialized rock climbers (MacKenzie et al., 2020). Additionally, these findings strengthen the notion that physical determinants only represent one part of bouldering performance (Draper et al., 2021), indirectly highlighting the importance of other factors not tested here, such as technique, strategy, and mental factors (Saul et al., 2019).

Although the present study provides valuable information on the physical determinants and characteristics of advanced boulderers, it is important to recognize its limitations. Methodologically, a potential limitation is the intercorrelation between some test variables, although this is difficult to avoid within performance tests, which may explain why only one variable for each group was found to be a significant predictor of variance to IRCRA grade within the regression model. Moreover, the study focused solely on advanced boulderers, and as a result, the generalization of its findings to other disciplines or performance levels may not be appropriate. Additionally, this study only assessed finger strength in the commonly used four-finger half-crimp position, and thus the results may not be indicative of performance in other grip types found in climbing. Finally, a larger sample size may have revealed an even clearer view of between group differences and variance to IRCRA grade.

Future studies should consider the integration of on-the-wall performance assessment utilizing standardized climbing walls (e.g., MoonBoard, Tension board or Kilter board) with assessment of physical determinants and performance characteristics. This would allow for repeatable performance metrics in the way of identical boulders between climbing facilities, allowing for different sport-specific movements and grip types in order to more accurately assess how physical determinants influence performance. Finally, this study draws attention to the importance of female representation and result reporting in climbing literature (Stien et al., 2022) to better understand how to consider differences in determinants when structuring training for improved performance in boulderers.

Practical Implications

These findings can help coaches and athletes in individualizing and structuring of training and in developing more effective methods for assessing and monitoring boulderers' physical progress. Further, the present study demonstrates the importance of result reporting of both sexes when conducting physical and physiological bouldering specific testing, as distinct differences may be overlooked in a combined sex sample.

Conclusion

Bouldering is a highly physical climbing discipline, requiring well-developed physical and physiological characteristics achieved through consistent and dedicated training to achieve optimal performance. This study found that male boulderers performed significantly higher in strength to body mass variables as well as upper body power and RFD of the finger flexors. Upper-body strength to body mass ratio emerged as the key determinant among advanced male boulderers, while finger strength to body mass ratio was the greatest determinant among advanced female boulderers. No significant difference in lower limb flexibility was observed between the sexes. These findings highlight distinct differences in physical performance and determinants between male and female boulderers of a similar skill level, emphasizing the multifactorial nature of bouldering performance, with physical determinants being just one aspect.

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