Open hand vs. half-crimp: Do climbers assume differences in their own maximal finger strength that do not exist?

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ABSTRACT

Many climbers believe that they are stronger in crimp finger position than in open hand position. However, the crimp grip is associated with higher pulley forces, increasing the risk of finger injuries. If a climber turns out not to be stronger in crimp than in open hand position - as they might have assumed - the open hand grip, which is easier on the pulleys, should be used whenever possible. Therefore, this study aimed to determine how accurate climbers could assess their maximal finger flexor strength in half-crimp and open hand positions. We assumed that the accuracy of self-assessment increases with skill level. Finger strength data along with self-assessment questionnaires were collected from 38 intermediate, 36 advanced climbers and 11 elite athletes. Our results revealed that advanced climbers significantly overestimated their strength in the half-crimp position compared to the open hand on average by 9.8% for the non-dominant hand. Such an overestimation, albeit not significant, was also found among intermediate and elite climbers (5.6% and 6.3%). The inaccurate estimate may be because we did not explicitly inform participants that they would be tested on a 23mm deep rung where they could place their entire distal phalanx. The crimp position might be stronger than the open hand position on less deep rungs - supporting their estimation. No significant differences in self-assessment accuracy were observed between groups. Thus, we cannot conclude that higher skilled climbers assess their strength capacities more accurately. For all skill levels and both sexes, slightly higher forces in open hand than in half-crimp position were found. Hence, we confirm that for deeper hold depths, using an open hand position has no force disadvantage when compared to the half-crimp. Accordingly, we recommend adopting an open hand position on rungs on which almost the entire distal phalanx can be placed.

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Introduction

The introduction of sports climbing as an Olympic discipline in Tokyo 2021 has led to more and more researchers turning their attention to climbing. In the course of this development, researchers are debating metrics that characterize climbing performance and that can differentiate between different skill levels. Draper et al. (2016) have suggested five different skill levels, including lower grade, intermediate, advanced, elite, and higher elite, each linked to specific values on the International Rock Climbing Research Association (IRCRA) scale. The IRCRA scale was established as a standardized system for characterizing the difficulty level of climbing routes and therefore to facilitate comparisons across different studies and to enable statistical analyses. The IRCRA levels have been considered in various studies on finger strength: For instance, it has been shown that elite female rock climbers exhibited higher peak finger strength compared to advanced female climbers (Giles et al., 2021). Similarly, in male climbers, it has recently been reported that elite climbers have significantly higher maximal finger strength than advanced climbers, while advanced climbers also have higher finger strength than intermediate climbers (Vereide et al., 2022). These studies confirm the positive correlation between climbing level and finger strength that has been reported by others, who used slightly different categorizations for climbing level (Baláš, Mrskoč, et al., 2014; Levernier & Laffaye, 2021).

The increased research activity can also be attributed to the growing popularity of climbing and related sports. Between 2008 to 2020, the number of Swiss people who go climbing, bouldering, mountaineering, ice climbing or freeclimbing has doubled (Bürgi et al., 2021). Consequently, climbing injuries have become a notable area of concern. The upper extremities are predominantly affected by climbing injuries (Backe et al., 2009; Lum & Park, 2019, for a comprehensive overview on climbing injuries, please see V. Schöffl et al., 2022), with pulley injuries being among the most common (Logan et al., 2004; Lutter et al., 2020; V. Schöffl et al., 2015). Vigouroux et al. (2006) utilized a biomechanical model to calculate the forces acting on an individual finger's tendon and pulleys during the crimp and open hand finger position. Their findings indicated that the forces exerted on the pulleys were higher in a crimp grip compared to the open hand. I. Schöffl et al. (2009) examined the finger pulley system using cadaveric fingers subjected to loading in both the crimp grip and open hand. Like Vigouroux et al. (2006) they concluded that forces on the pulleys were greater in the crimp position compared to the open hand. In addition, Schweizer (2001) reported that the forces acting on the pulleys during maximal crimping are close to the limit of what the pulleys can tolerate. Based on these findings, a suitable preventive measure for pulley injuries would be to avoid using the crimp grip.

In the opinion of the authors, many climbers believe that they are stronger in the crimp finger position than in the open hand position. This belief leads them to favour crimping various holds because they assume that the supposedly lower force in an open hand position would otherwise cause them to fall. However, this assumption of lower finger strength in an open hand position could be wrong. Hence, we were interested in comparing assumed and measured maximal finger strength in different finger positions.

The deviation between assumed and measured finger strength may depend on the expertise of the climber, i.e. the skill level. Indeed, earlier research demonstrated that individuals with higher expertise in climbing exhibited superior climbing-specific abilities compared to those with lower expertise. Pijpers & Bakker (1993) reported that advanced climbers displayed greater accuracy in perceiving the upper limit of reaching when standing at a climbing wall than novice climbers. Whitaker et al. (2020) discovered that with increasing skill level, climbers exhibited greater accuracy in assessing whether they could execute single moves on a climbing wall. They concluded that more skilled climbers possessed a more accurate perception of their body's capabilities in a climbing environment. Additionally, the study revealed that as climbing level increases the ability to remember visual aspects such as hold arrangements and motor sequences for climbing routes also increases. Additional to individual climbing moves, abilities like recalling visual details and motor sequences are crucial in climbing, as it is essential to plan movements before starting the ascent. Advanced climbers also exhibited a superior visual memory for the arrangements of holds than less skilled climbers (Boschker et al., 2002; Pezzulo et al., 2010). Likewise, evidence from research in other sports suggests that there is a positive correlation between expertise and perceptual skills. For instance, elite basketball players were able to predict the success of free throws at a basket earlier than novices (Aglioti et al., 2008). Similarly, trained child gymnasts showed a more precise judgement of their vertical jump-and-reach and horizontal jumping ability than non-trained children (Peker et al., 2021). All these studies examined cognitive skills or complex movement sequences, but none of them examined self-assessment of a specific physical attribute, such as finger strength.

Based on the findings of the aforementioned research, we hypothesized that climbers of a higher level would more accurately self-assess their finger strength differences between the half-crimp and open hand positions compared to climbers of a lower level. Due to the minimal additional effort required, we also asked our participants to estimate the differences they expected between their dominant and non-dominant hands. We assumed that less skilled climbers might rate themselves stronger in the dominant hand, although no significant difference between the hands were reported for different skill levels including non-climbers (Levernier & Laffaye, 2021).

Methods

Study design

A cross-sectional study design was chosen to compare climbers of different levels. Data was collected during the Climbing World Championships in Bern in August 2023. The Sensory-Motor Systems Lab was part of the Village of Experiences and ran a Hands-on-Science booth to show the audience of the World Championships what is currently done in climbing research. Interested visitors who met the inclusion criteria were invited to participate in the measurements. Further data was collected in November 2023, when Swiss elite climbers from a professional training group were assessed at the Sensory-Motor Systems Lab in Zurich. To take part in the testing, participants had to be active in at least one climbing discipline and be at least 16 years old. All participants, or their legal guardians in the case of persons under the age of 18, gave written informed consent to participate in this study. The protocol was approved by the local ethics committee of ETH Zurich (EK-2023-N-157) and complied with the Declaration of Helsinki.

Testing procedure

The testing procedure in Bern at the Climbing World Championships started with a questionnaire about age, size, handedness, climbing experience, preferred discipline, maximal self-reported red-point and flash grade (ever, in the last three months, indoor, outdoor), and if they had injuries that could limit their performance. The red-point grade describes the level of difficulty that a climber can climb if having as many attempts as necessary, while the flash grade indicates the level of difficulty that can be successfully climbed on the first attempt. The participants had also to self-estimate their maximal force ($\widetilde{F}$) of the right and left finger flexors in open hand as well as in half-crimp position. Assuming that the participants were not able to state their absolute maximal finger forces, they were asked to estimate their force in relation to the left hand in open grip ($\widetilde{F}^{open}_{left}$ = 100%). If participants thought to be 10% stronger with the right hand in the open grip position, they had to mention 110%. In accordance, 90% meant that participants thought themselves to be 10% weaker. They were asked to compare the right hand open ($\widetilde{F}^{open}_{right}$), the left hand in half-crimp ($\widetilde{F}^{halfcrimp}_{left}$) and the right hand in half-crimp ($\widetilde{F}^{halfcrimp}_{right}$) to the reference. After completing the questionnaire, the participants were asked to warm up their fingers and shoulders. They were provided with a guided warm-up video and several finger-specific warm-up tools. For the following force measurements, we used an instrumented campus board. The campus board consisted of two panels in order to be able to measure the forces in the direction of gravity for each hand. The forces were measured using weighing cells (3135 0 Micro Load Cell CZL635, Phidgets Inc., Canada), which were connected in pairs at three points to each panel. The board was inclined by 20° to the vertical axis and had 7 pairs of rungs which were 23mm deep, each 150mm apart (see Figure 1). Data was collected at 1000Hz. After calibrating the campus board, a measurement error of less than 2N was determined, which was not exceeded even with lateral forces (tested with up to 180N). The participants were allowed to use chalk before each measurement. In the beginning, the body weight was determined. The participant selected a pair of rungs at a suitable height, placed both hands on it and hung on it with straight arms and without swinging for a few seconds. The measured total force equals the gravitational force of the climber and by dividing it by gravitational acceleration results in the climber's body weight in kilograms. To determine the maximal finger strength ($Fmax$) the participant chose a rung at a suitable height, placed the to-be-measured hand on it and bent the knees so that the elbow and wrist stayed straight according to the execution that others have considered valid and reliable (Baláš, Panáčková, et al., 2014; Michailov et al., 2018; van Bergen et al., 2023). The participants had to transfer as much weight as possible from their feet to their fingers. If participants were able to lift their feet from the ground, additional weights were given to hold in the other hand. This procedure was done for each hand and finger position in the following order: right hand in open finger position ($Fmax^{\mathrm{open}}_{\mathrm{right}}$), left hand in open finger position ($Fmax^{open}_{left}$), right hand in half-crimp ($Fmax^{halfcrimp}_{right}$) and left hand in half-crimp position ($Fmax^{halfcrimp}_{left}$).

The elite climbers, who came to the laboratory in Zurich, had to fill out the same questionnaire as the participants in Bern. Afterwards, they were asked to do the same warm-up routine as before a normal training session and their body weight was determined. Following brief instructions on the campus board and the measurement procedures, the testing began. A four-minute break was provided between each measurement as recovery time and to enable the simultaneous measurement of three climbers. The testing started with a power slap test (Draper et al., 2011). The climbers hung on a rung of a suitable height, then pulled themselves explosively upwards and slapped with one hand as high as possible against the campus board. To facilitate undisturbed movements and prevent injuries, the rungs on the upper two boards of the campus board were removed. The measurements started with a right-hand slap, immediately followed by a slap with the left hand. After a four-minute break,

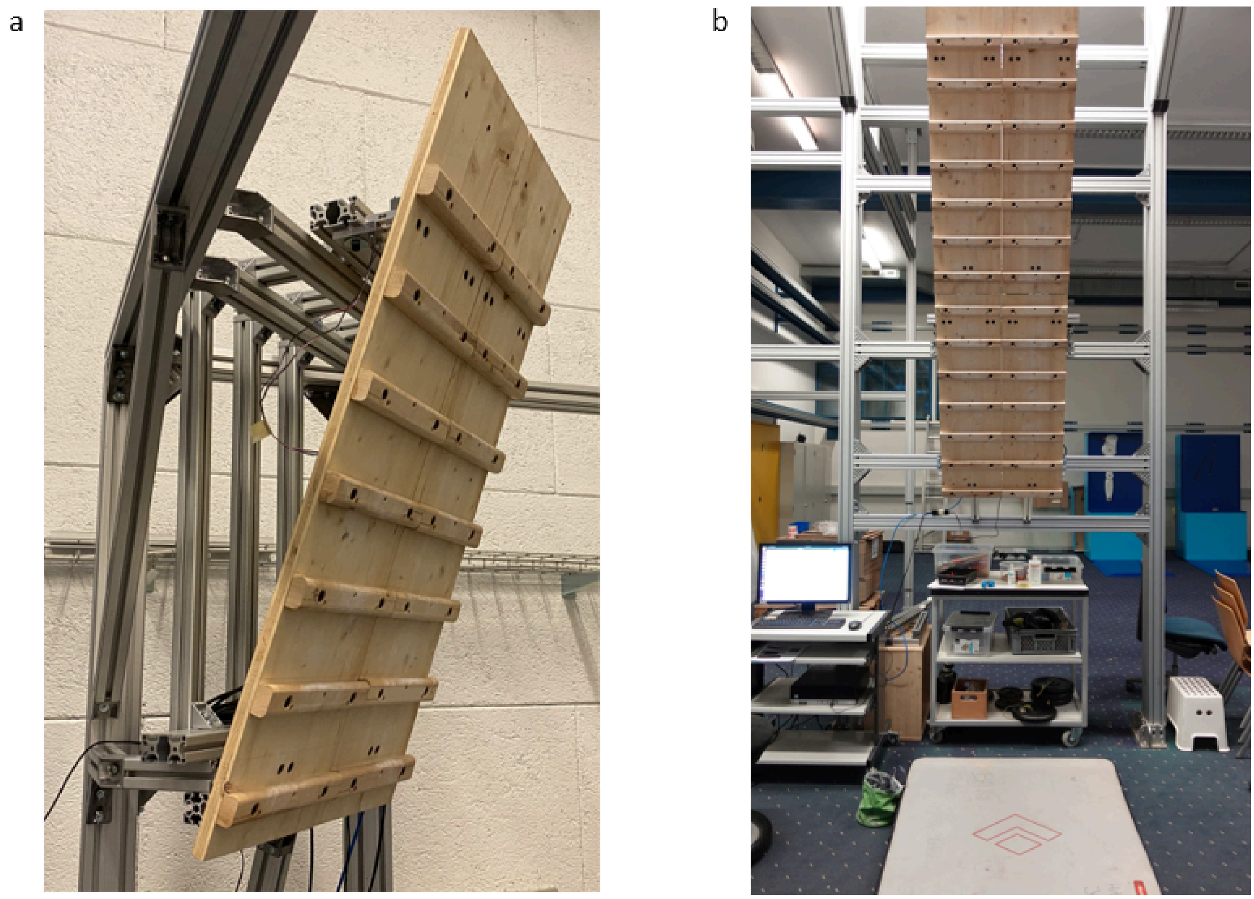

Figure 1 (a) The upper two panels of the campus board fixed to the frame of the booth used at the Climbing World Championships in Bern and (b) the set-up of the full-size campus board in the laboratory in Zurich.

the power slap test was repeated, this time in the reverse order of the hands. Maximal finger strength was then assessed using the same method as with the participants in Bern. The only difference was that the elite climbers executed each hand and finger position twice, resulting in four blocks of maximal finger strength measurements in the following order: open hand position starting with right hand and then the left hand, half-crimp position starting with right hand and then the left hand, open hand position starting with left hand and then right hand and half-crimp position starting with left hand and then the right hand. A four-minute break was provided after each maximal finger strength block. After this initial set of measurements, a brief pause was necessary to reattach the rungs of the upper two boards. Subsequently, the measurements continued with the 1-4-7 exercise. The climbers hung with both hands on a predefined rung and then moved only with one hand upwards to the fourth and seventh rung while the other hand remained on the starting rung. This exercise was first carried out with the right hand, followed immediately by the left hand. After another break, the 1-4-7 exercise was repeated, starting now with the left hand, followed by the right hand. Classical laddering exercises completed the measurement session. The two sets of measurements for each finger position and hand taken with the elite climbers enabled an analysis of the reliability between two measurements within the same session, using the intra-class correlation ($ICC_{2,1}$) (Shrout & Fleiss, 1979). ICC values ranged between 0.97 and 0.99, indicating a high level of consistency between the two measurement sets performed by the elite climbers.

Data analysis

For the elite athletes, only the first maximal finger force measurement for each hand position and side was used to maintain consistency with the measurements form Bern, were only a single measurement was taken. The same analysis was then carried out for all data records. The self-reported red-point grade for their preferred climbing discipline indoors in the last three months was chosen for further analysis as in other studies (e.g., Giles et al., 2021). In climbing research, it has been common practice to relate finger strength to body weight (e.g., Baláš, Mrskoč, et al., 2014; Fryer et al., 2015). Therefore, the measured force values were divided by the bodyweight of the climber. To compare the estimated values ($\widetilde{F}$) with the measured values ($Fmax$), $Fmax$ was normalized by the maximal force measured in the left hand, open hand position ($Fmax_{left}^{open}$):

$$\widehat{F}_x = \frac{Fmax_x}{Fmax_{left}^{open}} * 100\% \quad (1)$$

where x refers to either open finger position for the right hand, half-crimp position for the left hand or half-crimp position for the right hand. To compare the dominant (dom) and non-dominant (ndom) hand, $\widetilde{F}$ and $\widehat{F}$ were transformed according to the handedness of the climber stated in the questionnaire. To evaluate the estimated and measured differences between the dominant and non-dominant hand in open finger position the following calculations were done:

$$\delta\widetilde{F}_{dom,ndom}^{open} = \widetilde{F}_{dom}^{open} - \widetilde{F}_{ndom}^{open} \quad (2)$$

$$\delta\widehat{F}_{dom,ndom}^{open} = \widehat{F}_{dom}^{open} - \widehat{F}_{ndom}^{open} \quad (3)$$

$$\Delta F_{dom,ndom}^{open} = |\delta\widetilde{F}_{dom,ndom}^{open} - \delta\widehat{F}_{dom,ndom}^{open}| \quad (4)$$

For the other hypotheses, the values were calculated in the same way resulting in the following variables.

Variables to explain difference between dominant and non-dominant hand in half-crimp position:

$$\delta\widetilde{F}_{dom,ndom}^{half\ crimp},\ \delta\widehat{F}_{dom,ndom}^{half\ crimp},\ \Delta F_{dom,ndom}^{half\ crimp} \quad (5)$$

Variables to explain difference between half-crimp and open hand for the dominant hand:

$$\delta\widetilde{F}_{dom}^{half\ crimp,open},\ \delta\widehat{F}_{dom}^{half\ crimp,open},\ \Delta F_{dom}^{half\ crimp,open} \quad (6)$$

Variables to explain difference between half-crimp and open hand for the non-dominant hand:

$$\delta\widetilde{F}_{ndom}^{half\ crimp,open},\ \delta\widehat{F}_{ndom}^{half\ crimp,open},\ \Delta F_{ndom}^{half\ crimp,open} \quad (7)$$

Statistics

All statistical analyses were done with R (R Project for statistical computing, version 4.3.1) and statistical significance was accepted at $p < 0.05$. To check for normality and homogeneity, a Shapiro-Wilk test and Levene's test were conducted for the measured and estimated force data. Furthermore, a one-way ANOVA with Bonferroni post-hoc correction was used to analyse differences in (measured) maximal finger forces between the groups of intermediate, advanced and elite climbers for each hand and finger position and for men and women separately. Cohen's f was used to describe the effect size of the ANOVA, whereas $f < 0.25$ was considered a small effect, $f < 0.4$ a medium effect and $f > 0.4$ a large effect size (Cohen, 1988). A pairwise t-test was conducted to assess distinctions within the measured force data between the open hand and half-crimp finger position for both the dominant and non-dominant hands for men and women separately.

Cohen's d was used to determine the effect size, whereas |d| < 0.02 was considered as a negligible effect, |d| < 0.5 as a small effect, |d| < 0.8 as a medium effect and |d| > 0.8 as a large effect (Cohen, 1988). Linear regression and the corresponding Spearman's correlation coefficient (ρ) were used to assess the relationship between climbing level and maximal finger force. Correlation coefficients < 0.3 were considered as very weak, coefficients between 0.3 and 0.5 as weak, coefficients between 0.5 and 0.7 as moderate and coefficients > 0.7 as strong correlations (Cohen, 1988). To compare $\delta\widetilde{F}$ and $\delta\widehat{F}$ within the three ability groups (men and women combined) a pairwise t-test was conducted for each condition of interest and Cohen's d was used to determine the effect size. For the comparison of ΔF between the intermediate, advanced, and elite groups, a one-way ANOVA with Bonferroni post-hoc correction was used for the corresponding conditions. Cohen's f was used to describe the effect size. In addition, the same analysis was repeated for men and women separately although elite women were not considered as the group size was minimal (n = 2). A two-way ANOVA with Bonferroni post-hoc correction was conducted to investigate the effect of skill level and sex on the absolute difference (ΔF).

Results

Participants

In total, 196 visitors of the Climbing World Championships joined the measurements at the campus board. In addition, 11 Swiss elite climbers who take part in national and international competitions were recruited to ensure a broader range of skills. Due to previous injuries on the fingers and the associated persistent limited performance or due to incomplete questionnaires, 82 participants (visitors of the Championships) had to be excluded from the study. The remaining 125 participants (86 men and 39 women) could be considered for the evaluation of the effect of skill level on maximal finger strength. Considering the IRCRA reporting scale (Draper et al., 2016), participants were classified according to their self-reported climbing grade as lower grade, intermediate, advanced, or elite. As in the lower grade the number of participants was minimal (n=1), comparison of groups was made between intermediate, advanced, and elite ability groups. To evaluate the effect of skill level on self-estimation, a further 39 participants had to be excluded as they did not answer the self-estimation question correctly. Thus, a total of 85 climbers (60 men and 25 women) from intermediate, advanced, and elite skill levels were included in the self-estimation evaluation (see Table 1).

Table 1
Mean values [SD] of age, anthropometric characteristics, climbing experience and self-reported climbing ability of participants included in the self-estimation evaluation

		Age (years)	Height (cm)	Bodyweight (kg)	Years of climbing experience	Climbing hours per week	Red Point (IRCRA grade)
Intermediate	Male (n = 31)	31.6 [8.7]	177.1 [9.0]	72.5 [9.8]	9.6 [9.1]	3.3 [1.9]	15.0 [1.8]
	Female (n = 7)	28.3 [5.4]	166.9 [4.3]	59.9 [7.4]	6.2 [3.5]	1.4 [1.3]	13.0 [1.0]
Advanced	Male (n = 20)	30.5 [11.6]	176.6 [7.0]	69.5 [6.6]	9.5 [9.3]	6.2 [3.4]	20.6 [1.4]
	Female (n = 16)	31.6 [10.6]	164.6 [3.7]	60.8 [6.7]	11.1 [7.9]	6.0 [4.5]	17.1 [1.9]

		Age (years)	Height (cm)	Bodyweight (kg)	Years of climbing experience	Climbing hours per week	Red Point (IRCRA grade)
Elite	Male (n = 9)	19.0 [1.9]	175.7 [5.4]	71.1 [7.2]	10.3 [4.0]	12.1 [2.4]	24.6 [1.5]
	Female (n = 2)	19.0 [2.8]	170.0 [0.0]	68.0 [4.3]	10.0 [1.4]	10.0 [1.4]	23.0 [0.0]

Effect of skill level on maximal finger strength

Across all four conditions, climbing level had a significant effect on the maximal finger force ($F(2,82) = 23.87 - 33.78$, $p < 0.001$, $f = 0.76 - 0.91$) for men. When considering the average across the four conditions, advanced male climbers were 10.4% (in relation to bodyweight) stronger than the intermediate male climbers (significantly stronger in every condition between 8.8% and 11.7%, see Table 2 and Supplementary Table 3). The contrast between male advanced and male elite climbers was even more pronounced, with a mean difference of 19.9% ($p < 0.001$ for all conditions). For women, climbing level also had a significant effect on the maximal finger force ($F(2,36) = 8.98 - 15.1$, $p < 0.001$, $f = 0.71 - 0.91$) for all four conditions. Advanced female climbers were on average 14.0% (in relation to bodyweight) stronger than intermediate female climbers (significantly stronger in every condition between 12.7% and 15.1% see Table 2 and Supplementary Table 3). Elite female climbers were 12.4% stronger than intermediate female climbers when comparing the non-dominant hand in open position ($p = 0.038$). For the other comparisons between elite and intermediate female climbers as well as between elite and advanced female climbers no significant differences were detectable. When examining the differences between open hand and half-crimp finger positions within each hand and climbing level individually, no significant differences were observed for both men and women, except in the case of the elite females using the non-dominant hand: In open hand position, 4.3% higher forces were observed compared to the half-crimp position ($t = -9.38$, $p = 0.011$, $d = 1.42$, see Table 2). For all four conditions, a moderate correlation with climbing level was found for the measured forces in both men and women (see Figure 2 a-d).

Table 2
Mean measured force values [SD] for the four measured conditions in relation to bodyweight (% BW)

		Dominant hand, open	Non-dominant hand, open	Dominant hand, half-crimp	Non-dominant hand, half-crimp
Intermediate	Male (n = 45)	64.9% BW [9.4% BW]	64.6% BW [8.7% BW]	63.2% BW [12.5% BW]	61.4% BW [13.9% BW]
	Female (n = 13)	47.9% BW [8.6% BW]	49.1% BW [9.2% BW]	47.1% BW [9.2% BW]	45.9% BW [10.5% BW]
Advanced	Male (n = 26)	75.4% BW* [15.0% BW]	73.3% BW* [15.5% BW]	74.9% BW* [14.0% BW]	72.2% BW* [15.2% BW]
	Female (n = 23)	63.0% BW* [8.0% BW]	61.8% BW* [6.0% BW]	61.7% BW* [8.8% BW]	59.5% BW* [9.0% BW]

		Dominant hand, open	Non-dominant hand, open	Dominant hand, half-crimp	Non-dominant hand, half-crimp
Elite	Male (n = 14)	94.6% BW** [13.1% BW]	94.2% BW** [16.4% BW]	94.0% BW** [13.6% BW]	92.3% BW** [17.1% BW]
	Female (n = 3)	55.8% BW [1.5% BW]	61.5% BW* [2.6% BW]	60.8% BW [4.1% BW]	57.2% BW [3.3% BW]

* significantly higher than the intermediate group

** significantly higher than the intermediate and advanced group

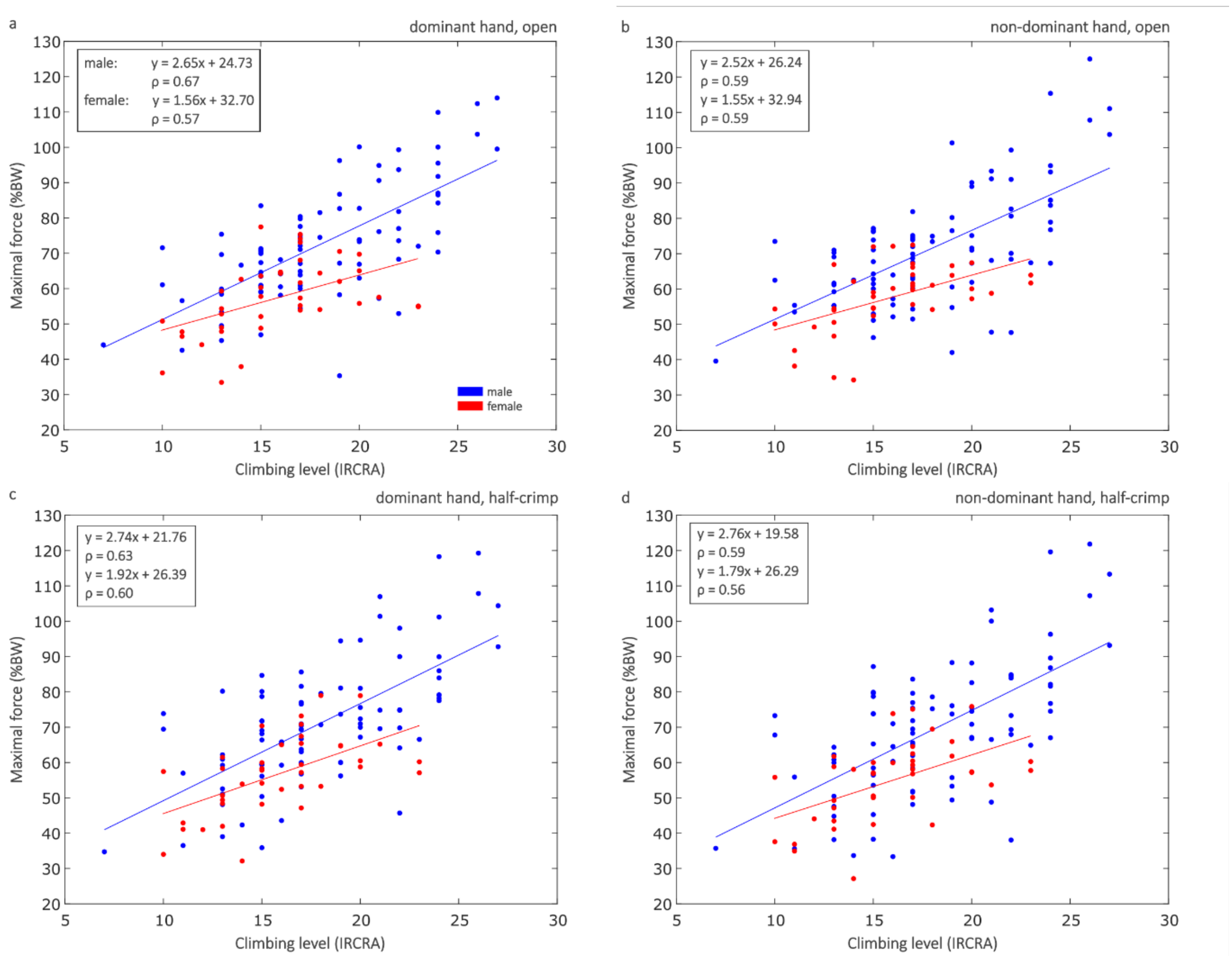

Figure 2 Correlation between the IRCRA climbing level and (a) measured force in dominant hand in open finger position, (b) measured force for non-dominant hand in open finger position, (c) measured force for dominant hand in half-crimp finger position, and (d) measured force for non-dominant hand in half-crimp finger position.

Effect of skill level on self-estimation

When assessing the open hand position, intermediate climbers overestimated their strength in the dominant hand compared to the non-dominant hand by a mean of 12.1% (t(37) = 4.86, p < 0.001, d = 1.06). Advanced climbers also overestimated their strength by 7.2% (t(35) = 3.78, p < 0.001, d = 0.87), whereas no significant difference between estimation and measurement was seen for the elite climbers (see Figure 3 a). A significant effect of climbing level on the absolute difference $\Delta F^{open}_{dom,ndom}$ was observed (F(2,82) = 4.05, p = 0.021, f = 0.31). Post-hoc testing, however, did not reveal statistically significant differences between specific climbing levels. The comparisons between intermediate and advanced climbers (p = 0.057, d = 0.56) and between intermediate and elite climbers (p = 0.083, d = 0.69) showed medium effect sizes but did not reach significance.

When evaluating the half-crimp position, intermediate climbers overestimated their strength in the dominant hand in comparison to the non-dominant hand by 6.9% on average (t(37) = 3.13, p = 0.0034, d = 0.59, see Figure 3 b).

In the dominant hand, none of the groups analysed significantly over- or underestimated their strength in half-crimp position compared to open hand (see Figure 3 c). However, advanced climbers overestimated their half-crimp strength by 9.8% for the non-dominant hand (t(35) = 2.95, p = 0.0056, d = 0.64). Similarly, intermediate climbers overestimated their strength by 5.6% (t(37) = 1.82, p = 0.077, d = 0.36), and elite climbers overestimated by 6.3% (t(10) = 1.95, p = 0.080, d = 0.77), however, these results were not statistically significant (see Figure 3 d).

The results of the two-way ANOVA indicated that sex did not have a significant effect on the absolute difference across all conditions (see Supplementary Figure 4).

Discussion

This study aimed to evaluate how accurately climbers of different climbing levels can assess their finger strength. We hypothesized that climbers of higher climbing levels would demonstrate a more accurate self-assessment of their finger strength. To compare across the three climbing levels, a one-way ANOVA was performed. The group differences resulting from the ANOVA did not consistently show significant findings across the four conditions, indicating that self-assessment may not be influenced by skill level. Similarly, non-significant group differences were observed when further stratifying by sex, and moreover, no significant effect of sex was detected. Given the non-significant influence of sex, further examination in this regard was not pursued. However, it is also possible that the small number of female participants limited the ability to detect a difference.

Our hypothesis that more skilled climbers can better self-assess their finger strength was only partially confirmed regarding the difference between the dominant and non-dominant hand in the open finger position: Intermediate and advanced climbers overestimated their strength in the dominant hand compared to the non-dominant hand, whereas the difference between estimation and measurement was not significant for the elite climbers (see Figure 3). Although the absolute error between estimation and measurement was significant, post-hoc analyses did not reveal statistically significant pairwise differences. Trends suggested that elite climbers may develop a more accurate self-assessment compared to intermediate and advanced climbers, as indicated by medium effect sizes. In the half-crimp position, intermediate climbers did also overestimate their strength of the dominant hand, yet the absolute error did not differ significantly. Given the significant difference in absolute error for the open hand position, it is possible that a similar pattern could emerge for the half-crimp position with a larger sample size of elite climbers. Thus, we conclude that higher skilled climbers tend to estimate their finger strength better with respect to the difference between dominant and non-dominant hand. This ability may

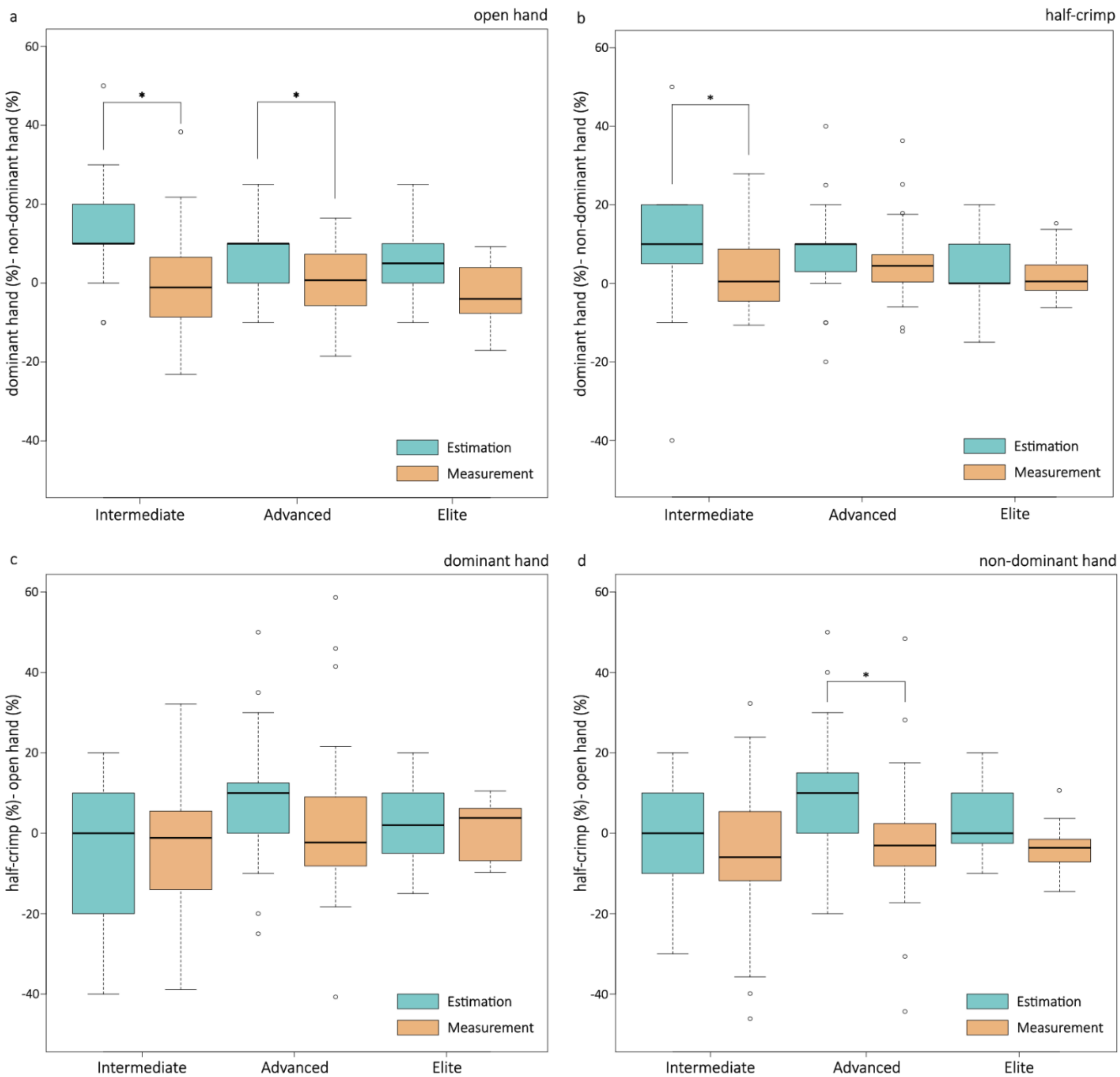

Figure 3 Comparison of self-estimated and measured force values for (a) the difference between dominant and non-dominant hand in open finger position, (b) the difference between dominant and non-dominant hand in the half-crimp finger position, (c) the difference between half-crimp and open finger position for the dominant hand and (d) the difference between half-crimp and open finger position for the non-dominant hand.

* indicates a significant difference between estimated and measured force values

stem from their extensive experience and training, which over time has led to a comprehensive understanding of their own strength. Furthermore, elite climbers train with a coach who gives them detailed feedback on their strengths and weaknesses, which can also contribute to a better understanding of their own abilities. Elite athletes frequently engage in performance analyses, which can also include force measurements. These measurements have the potential to (positively) influence self-assessment. In the case of the elite climbers in this study, their coach assured that he has not conducted any force measurements with his athletes in the last 10 months, but they used a Tindeq sensor (Progressor 300 rechargeable, BLIMS AS, Norway) to control finger forces during the training. Therefore, it remains plausible that pre-existing knowledge from previous measurements could have influenced the climbers' self-assessment.

In the comparison between the open hand and half-crimp positions, our hypothesis that more skilled climbers would demonstrate superior self-assessment abilities was not supported. Interestingly when looking at the difference within a group, intermediate climbers demonstrate a more accurate ability to estimate their strength for both the dominant and non-dominant hand whereas advanced climbers tend to overestimate their strength in the half-crimp position for both hands. Elite climbers accurately self-assessed their capabilities, likely due to the factors mentioned earlier. The unexpected result in the self-assessment of strength among advanced climbers may be attributed to their increased participation in discussions with peers. As they spend more time with the climbing training, it seems likely that they are also more involved in climbing-related conversations. In the climbing community, crimp and half-crimp positions are associated with a higher force production compared to the open hand. As previously noted, the half-crimp position is not inherently stronger rather it depends on the hold depth. Hence, it is possible that misinformation is circulating among climbers. Instrumented hangboards, such as those already on the market, can help users to easily quantify their finger forces, thus avoiding false assumptions.

Another explanation for this finding may be that participants were instructed to provide a general self-assessment of their strength rather than specifically for a 23mm deep rung. They were also not allowed to touch the rung before the self-assessment. It is possible that they had a smaller grip in mind when they were trying to assess their strength, which could explain why they rated the half-crimp position as stronger than the open hand. When examining the absolute difference ($\Delta F_{dom}^{halfcrimp,open}$ and $\Delta F_{ndom}^{halfcrimp,open}$), no significant group differences were observed, indicating that the absolute error in self-assessment was not dependent on the skill level. It is possible that in climbing, having an exact understanding of one's own maximal strength in the different finger positions may not be as crucial as skills like knowing the maximal distance of reaching or route reading. Perhaps what matters more is simply knowing whether one can hold on to a hold or not just by visual inspection of the hold shape and selecting the appropriate finger position based on this assessment. Further, it is plausible that other factors like experience with self-assessment tasks, the complexity of the assessment task or limitations of the study design may play a more important role in determining the accuracy of self-estimation regardless of climbing skill level.

One limitation of the study is the likelihood of bias in self-assessment, as many participants tended to estimate differences in 10%-increments, probably due to the inherent challenge of estimating percentages accurately. Therefore, it is likely that the estimated differences are higher than the actual measured differences due to the greater precision of the measurement. Another limitation of this study is the difference in measurement settings between Bern and Zurich. In Bern, the large number of participants and therefore limited time per individual reduced the level of control, particularly during the completion of the questionnaire. However, the force measurements were always supervised by a skilled operator, ensuring their reliability. Still the measurements had to be conducted in quick succession, with limited recovery time between trials, due to the large number of participants. In contrast, the laboratory in Zurich provided a highly controlled environment, with close observation of all procedures and sufficient recovery time between trials. These differences in measurement execution may have introduced slight variations in the results, which should be considered when comparing the elite climbers assessed in Zurich with the other participants measured in Bern. It should also be mentioned that the inter-session reliability of the elite climbers showed very high ICCs, which underpins the reliability of the test procedure and confirm results with a very similar measurement protocol (Baláš, Panáčková, et al., 2014; Levernier & Laffaye, 2021). It could be that elite climbers are more accustomed to achieving their maximal performance on the first attempt, while less experienced climbers may need more attempts. At least we tried to give the participants in Bern a brief opportunity to get used to the rung. However, how many repetitions with sufficient rest time are needed so that the maximal strength no longer changes should be investigated – as, in fact, a measurement protocol including data processing would be desirable in general for best possible comparability of studies.

Another limitation pertains to the exclusion of numerous climbers measured in Bern due to incorrect questionnaire responses. The underlying cause of the issue, whether it due to the complexity of the question or the difficulty of the self-assessment task, remains unclear. Improved supervision during questionnaire completion might have mitigated this issue and reduce the number of exclusions. To address this limitation in future research, it may be beneficial to introduce a preliminary phase where participants touch the rung and conduct a baseline measurement with their left hand in open position to familiarize themselves with the campus board. Following this preliminary phase, participants can proceed with the self-assessment before starting with the actual force measurements.

Understanding how climbers perceive their finger strength is important for launching preventive measures against finger injuries. Identifying areas of misinformation could serve as a first step to develop an effective prevention strategy. Based on our findings, it is important to raise the awareness of climbers regarding the advantages and disadvantages of the half-crimp position, emphasizing its suitable application and instances where an open hand position might be more appropriate. Conducting additional studies to evaluate self-assessment across various rung depths and gaining insights into prevailing knowledge within the climbing community would sharpen possible preventive measures.

Further, this study compared the maximal finger strength among climbers of intermediate, advanced and elite skill levels using different finger positions. For men, significantly varying maximal finger forces were observed across the three climbing levels, with advanced climbers demonstrating higher maximal forces than intermediate climbers, while elite climbers exhibited even higher forces compared to advanced climbers. This positive correlation between finger strength and climbing level is consistent with the results reported in other studies (Baláš et al., 2012; Levernier & Laffaye, 2021; Vereide et al., 2022). In general, we also observed a moderate correlation between climbing level and maximal finger strength for women (see Figure 2), confirming the findings of Baláš et al. (2012). However, there was no significant difference observed between intermediate and advanced climbers when compared to elite female climbers. This unexpected finding may be attributed to the limited number of elite female participants. Unlike in the male group, which compromised professional climbers competing in international competitions, the female elite group lacked such representation.

Further, we confirm for both men and women that the open hand position allows for the generation of higher forces compared to the half-crimp finger position on a relatively deep rung on which the entire distal phalanx could be placed (Schweizer, 2001; Winkler et al., 2023). It should be noted that the depth of the rung is probably decisive in which finger position higher forces can be achieved: Amca et al. (2012) observed higher forces in the half-crimp position compared to the open hand position as the rung became less deep. For advanced climbers performing a finger dead hang on a 21mm deep rung, Ferrer-Uris et al. (2023) found similar maximal loads for the half-crimp and open hand position. Levernier & Laffaye (2021) also report similarly high forces in a half-crimp and half-open position for three different climbing levels – measured on a rung with a depth of 10mm, but in view of the illustrations of their publication, this seems rather too little, since the first phalanx appears to be placed almost entirely on the rung. Winkler et al. (2023) showed that when hanging on an 8mm deep rung (as opposed to hanging on a 23mm deep rung), the half-crimp finger position was stronger relative to the open finger position. Thus, our findings should not be generalized to smaller rungs. Nevertheless, the benefit of utilizing an open hand position on rather deep holds should not only be considered in terms of maximal force but also in terms of reducing the risk for a pulley rupture as ligaments are subject to much higher stress in half-crimp than in open hand position (Vigouroux et al., 2006). We therefore recommend using the open hand position whenever possible; in this way, even higher forces can be achieved on deeper holds.

In our male climbers, the dominant hand was on average only up to 2% stronger than the non-dominant hand for both the open and half-crimp finger positions. This small difference was also observed among female advanced climbers. Our finding that the dominant hand is not significantly stronger in a climbing-specific finger-strength test – and this across different climbing levels – confirms the results of similarly conducted studies (e.g., Levernier & Laffaye, 2021). However, if measurements are taken with a hand dynamometer in a non-climbing-specific way, then the dominant hand was shown to be stronger (e.g., Gürer & Yildiz, 2015).

For female elite climbers no clear trend was observable but caution is advised when interpreting these results due to the very small group size.

Conclusion

In conclusion, our results confirm a positive correlation between finger strength and climbing level. Further, our findings support the use of the open hand instead of the half-crimp position on rungs on which almost the entire distal phalanx can be placed. Given the lack of consistently significant absolute differences between the three climbing groups, it appears that climbing skill levels has no influence on climbers' accuracy in self-estimating their strength. The observed tendency of advanced climbers to misjudge their half-crimp strength relative to the open hand suggests a potential focus for preventive interventions. These false assumptions could be counteracted by measurements of the maximal forces – as is already possible in some climbing gyms with instrumented hangboards for each customer.

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Competing interests

The authors have declared that no competing interests exist.

Data availability statement

All relevant data are within the paper. Researchers interested in raw data should contact the corresponding author.

A Appendix

Table 3
Mean measured force differences [CI 95%] between climbing groups in relation to bodyweight (%)

		Elite-Advanced	Elite-Intermediate	Advanced-Intermediate
Men (n = 85)	**Dominant hand, open**	19.22 [9.87, 28.58]	29.75 [21.79, 37.70]	10.52 [3.91, 17.13]
	Non-dominant hand, open	20.89 [9.90, 31.88]	29.67 [19.92, 39.42]	8.78 [2.07, 15.49]
	Dominant hand, half-crimp	19.13 [9.37, 28.89]	30.82 [21.81, 39.82]	11.69 [5.04, 18.33]
	Non-dominant hand, half-crimp	20.27 [9.00, 31.54]	31.04 [20.51, 41.57]	10.77 [3.48, 18.06]
Women (n = 39)	**Dominant hand, open**	-7.18 [-11.08, -3.28]	7.93 [2.50, 13.37]	15.12 [9.12, 21.11]
	Non-dominant hand, open	-0.30 [-5.15, 4.55]	12.36 [5.65, 19.06]	12.66 [6.34, 18.98]
	Dominant hand, half-crimp	-0.90 [-8.60, 6.80]	13.71 [5.62, 21.79]	14.61 [8.12, 21.10]
	Non-dominant hand, half-crimp	-2.23 [-8.59, 4.12]	11.38 [3.72, 19.04]	13.62 [6.42, 20.82]

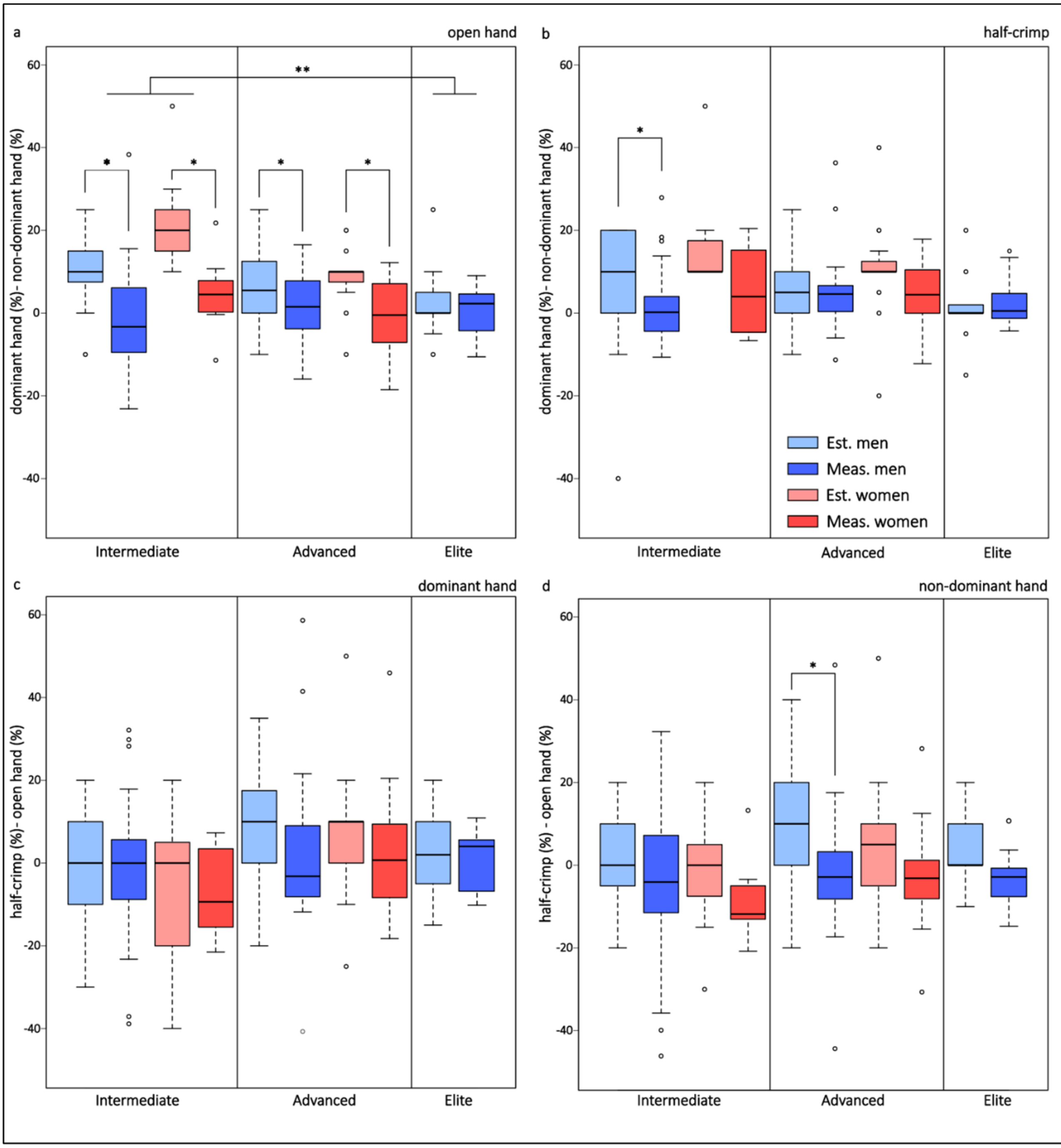

Figure 4 Comparison of self-estimated and measured force values for men and women separately. Due to the small group size (n=2) elite female climbers were not considered.

* indicates a significant difference between estimated and measured force value

** indicates a significant effect for the absolute difference between skill levels

(a) shows the difference between dominant and non-dominant hand in open finger position. Male and female intermediate climbers overestimated their strength in the dominant hand compared to the non-dominant hand by 10.7% ($t(30) = 3.78$, $p < 0.001$, $d = 1.01$) and 18.4% ($t(6) = 3.82$, $p = 0.0087$, $d = 1.54$), respectively. Similarly, male and female advanced climbers overestimated their strength by 5.6% ($t(19) = 2.09$, $p = 0.050$, $d = 0.64$) and 9.3% ($t(15) = 3.41$, $p = 0.0039$, $d = 1.15$), respectively. The two-way ANOVA showed a significant effect of climbing level on the absolute difference $\Delta F^{open}_{dom,ndom}$ ($F(2,79) = 5.98$, $p = 0.0038$), but no significant effect of the sex ($F(1,79) = 0.51$, $p = 0.48$). Post-hoc testing revealed that elite climbers could self-estimate their relative strength better than intermediate climbers ($p = 0.008$). (b) shows the difference between dominant and non-dominant hand in the half-crimp finger position. Male intermediate climbers significantly overestimated their strength in their dominant hand by 5.7% ($t(30) = 2.41$, $p = 0.022$, $d = 0.52$). The two-way ANOVA revealed no significant effect of skill level or sex on the absolute difference. (c) shows the difference between half-crimp and open finger position for the dominant hand. Significant results were not observed for either the t-test or the two-way ANOVA. (d) shows the difference between half-crimp and open finger position for the non-dominant hand. Male advanced climbers overestimated their strength in the half-crimp position compared to the open hand by 11.8% ($t(19) = 3.09$, $p = 0.0061$, $d = 0.75$). The two-way ANOVA showed no significant effect of skill level or sex on the absolute difference.