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Reliability and Validity of Functional Grip Strength Measures Across Holds and Body Positions in Climbers: Associations With Skill and Climbing Performance

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ABSTRACT

Purpose: In climbing, exceptional levels of fingertip strength across different holds and body positions are considered essential for performance. There is no commonly agreed upon way to measure such "grip strength variability." Furthermore, the accurate and reliable monitoring of strength is necessary to achieve safe, progressive improvement in strength. Therefore, this study aimed to develop reliability and criterion validity for assessment of grip strength across multiple holds and body positions. **Methods:** Twenty-two advanced toelite climbers (age = 28.5 ± 8.6 years) performed maximal voluntary isometric contractions on two occasions (for test-retest reliability). Conditions included two hold types (edge and sloper) tested in two postures (elbow flexion [90°] and self-preferred). Climbing performance was determined on two "difficulty" routes (difficulty increases with each hold): one route composed of only edges and another only of slopers. **Results:** Test-retest reliability was high (ICC between 0.94–0.99). Significant positive correlations were observed for the forces produced on the sloper test and climbing distance on the sloper route ($r = 0.512, p < .05$), and for the forces produced on the edge test and climbing distance on the edge route ($\rho = 0.579$, $p < .01$). **Conclusion:** These findings support reliability and validity of the method used to measure grip strength variability with different holds and body positions and suggest that improving strength across different grasping types supports adaptive climbing performance.

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Climbing specific strength; elite climbing; functional movement variability; performance monitoring; reliability and validity of grip strength test

Traditionally, the emphasis of accurate and reliable monitoring of strength has been to support safe, progressive improvement (Backe et al., 2009; Phillips et al., 2012). In climbing, where fingertip strength is considered one of the key-determinants of performance (Vigouroux & Quaine, 2006), different grasping techniques are important because some hold types only allow friction to be applied by the fingertips, while others require use of the entire hand and different orientations (Orth et al., 2018). There is evidence to suggest strength related adaptations are specific to the grasping technique (Amca et al., 2012; Carroll et al., 2001). Elite climbers exhibit activity specific adaptation in muscles that cross the wrist and finger joints, favoring isometric strength, endurance, and recovery (Schreiber et al., 2015; Vigouroux & Quaine, 2006), and climbers with high ability levels are better able to generate friction as the available grip surface area is reduced (Fuss et al., 2013). In sum, performance in climbing is partly explained in terms of the climbers ability to exert high forces across various holds, body positions and surface characteristics, hereafter referred to as grip strength variability (Orth et al., 2016).

While it is unequivocal that exceptional levels of fingertip strength are essential for performance at the elite level (Vigouroux & Quaine, 2006), there is little evidence on: (a) how important producing forces across holds and body positions is for explaining ability level, and; (b) how the ability to exert high forces across different holds, body positions and grip techniques might underpin climbing performance, and/or injury prevention (Davids et al., 2003). Nonetheless, studies have identified links between monotonous exercise (exercise that does not sufficiently vary) and overuse injuries, (Jayanthi et al., 2015) slower skill learning (Orth et al., 2018), and athlete drop-out (DiFiori et al., 2014). Furthermore, a lack of "functional movement variability" (a motor learning principle defined as the ability to vary movement patterns to maintain or enhance performance under changing constraints) has been associated with injury/disease and loss of adaptability (Hamill et al., 2012; Pollard et al., 2015; Stergiou & Decker, 2011). It is increasingly recognized that enhancing functional movement variability plays a key role in addressing aforementioned problems associated with monotonous exercise (Wormhoudt et al., 2017). By increasing functional movement variability through training under a diversity of task and environmental constraints, athletes enhance their capability to successfully manage variation in performance and training conditions (Brocken et al., 2020; Seifert et al., 2016; Wilson et al., 2017).

Developing fingertip strength over a variety of holds and body positions may help prevent further injuries, improve the capability to safely adapt to variation in route design, and increase overall movement opportunities/degeneracy available during training (Amca et al., 2012; Orth et al., 2016; Phillips et al., 2012). Indeed, in the process of rehabilitation after a pulley injury, many physiotherapists prescribe behavior change that involves either learning to use a greater variety of grasping types or climbing on routes made up of different types of holds (i.e., a mixture of slopers, edges, pockets, etc.). It is

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probable/likely that increasing grip strength variability can yield a range of benefits without negatively effecting the climber.

A first step toward verifying the importance of grip strength variability is to show that hand and fingertip strength across multiple holds and body positions is associated with climbing performance on particular route types (i.e., the ability to climb as high as possible on a route made up of the associated grip types) (Draper et al., 2011). To date, there are no readily available, validated instruments to assess grip strength variability for climbers. In physiotherapy practice, the most common way to assess grip strength is using handgrip dynamometry. However, this method lacks specificity (Watts et al., 2008), which has led several studies to develop custom-made, climbing specific devices to assess fingertip strength (Baláš et al., 2014; Michailov et al., 2018). These devices are generally reliable and suitable for assessing fingertip strength, and have revealed that fingertip strength on edges plays an important role in understanding climbing performance (Deyhle et al., 2015) and ability level (Laffaye et al., 2016).

Although some devices were equipped to assess multiple grip types, the reported studies are limited in the range of grip types tested. Furthermore, there are discrepancies in the literature concerning body positions used for climbing specific grip strength testing. For example, some studies use overhead position with involvement of body mass (and without constrained elbow) to increase ecological validity, as this position relates more closely to a real climbing setting (Baláš et al., 2014; Bergua et al., 2020; Feldmann et al., 2020; Giles et al., 2019, 2021; Watts et al., 2008). Other studies use a flexed position with constrained elbow to test the fingers in isolation (Levernier & Laffaye, 2021; Saeterbakken et al., 2020). Importantly Michailov et al., 2018), compared fingertip strength in both positions, that is with and without constrained elbow, which resulted in greater criterion validity for the condition without constrained elbow. Considering the discrepancies in the literature concerning this methodological issue we decided to test fingertip strength in both positions, that is with and without constrained elbow.

Another limitation to existing studies is that they only assess strength on edges and thus only a limited number of grasping actions have been studied (typically the crimp). Since climbers can encounter a huge variety of hold types during their climbing practice (e.g., smooth surfaces, pockets, small and large edges, etc), other grasping techniques, also likely to be very important for performance, should be investigated (Amca et al., 2012; Seifert et al., 2013). Besides, variation in wall slope or the orientation of the hold may require additional variation in hand orientations and ways of organizing the body (Orth et al., 2018), and it is expected that, in order to improve performance over time, elite climbers are, in some manner, able to master all these different grip types (Phillips et al., 2012).

Because of the novel character of this approach and related instrumentation, the objectives of this study are to develop reliability and criterion validity for assessment of grip strength variability with different holds and body positions. We will establish criterion validity by exploring whether maximal isometric fingertip strength measured on two very different hold types (edges and slopers) and positions (with and without constrained elbow) supports self-reported ability level and performance on climbing routes made up of the same hold types as those tested for strength. We hypothesize that more skilled climbers show higher levels of maximal voluntary force for both the crimp and slope grip, and that individuals who are stronger with a particular hold type also perform better on routes composed of the hold grip type.

Materials and methods

Participants

In this study, 22 experienced sport climbers (M_{age} = 28.5 ± 8.6 years, M_{weight} = 71.9 ± 7.3 kg, M_{height} = 180.5 ± 6.5 cm) were recruited using skill-based inclusion criteria (detailed below). The number of participants was based on a power analysis for correlation (α = .05, one-tailed, effect size = .5, β = .8, required sample size = 21). Participants reported their personal best redpoint (i.e., highest difficulty of a route which a climber can climb after the route has been previously rehearsed, Sanchez et al., 2012) and their best personal on-sight (i.e., highest difficulty of a route that a climber can climb without previous knowledge of or practice on the route) expressed on the French-rating-scale-of-difficulty (F-RSD), which was already known to participants. The best redpoint and on-sight were reported based on the hardest route or boulder participants climbed within the past 12 months, which have previously proven to be a valid measure for climbing ability (Draper et al., 2011). The reported climbing levels were transferred to the International Rock Climbing Research Association (IRCRA) scale for analysis (Draper et al., 2015). Minimum inclusion criteria was a climbing ability level of 15 at the IRCRA scale for females and 18 for males, which corresponds to an experience level of advanced and higher. Mean reported climbing ability levels corresponded to M = 19.7 ± 0.5 on-sight and M = 21.6 ± 0.5 redpoint. A total of 22 advanced to high elite climbers responded to flyers seeking participants. Of these, two did not participate in the climbing task due to time constraints. In addition, the analysis of one participant was excluded from the climbing task due to slippage which resulted in a very early fall in one of the two on-sighted routes. This resulted in 22 participants in the test-retest fingertip strength protocol and 19 in the climbing performance protocol. The research project was approved by the institution's ethics committee (Scientific and Ethical Review Board, Vrije Universiteit Amsterdam, reference: VCWE-2018-080) and all participants provided written informed consent before testing.

Equipment and apparatus

To assess hand and fingertip strength across different holds and body positions commonly used in climbing a customized grip strength dynamometer (called the "meta-grip") was developed (Figure 1). From an applied perspective, the design philosophy aimed to allow monitoring and implementation of training interventions that are based on motor learning principles (i.e., functional variability) in a range of contexts (such as

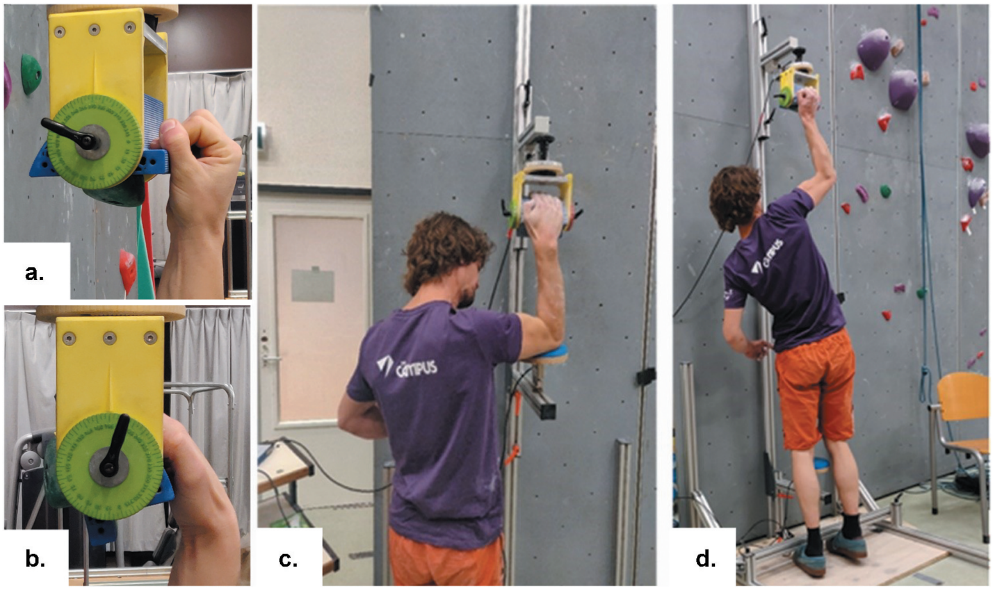

Figure 1. Assessing peak force producing capabilities using different grip types, i.e. at the fingertips using an edge (a) and hand using a slope (b), and using different positions, i.e. either elbow isolated (c) or free, open chain (d) positions. Note the bar at the feet in (d) which was useful for participants who were able to pull more than their body mass.

coaching, physical therapy, performance testing, sport science, etc.). The instrument was 3D-printed with polyamide 12 and contained multiple hold types, to allow assessment of fingertip strength across a range of different hold types commonly used in climbing. In this study the small edge (20 mm deep, 2.5 mm radius) and sloper hold (70 mm deep, 106.39 mm radius) were used. Small pyramids were printed on the surface of the holds to increase friction. Both holds are described in more detail in Figure 2. The instrument was attached onto a climbing wall such that the height and distance from the wall could be adjusted based on the standing height and forearm length of the participants. Dimensions were recorded for replication during the retest phase for each participant. In the constrained condition, participants were instructed to always apply at least 3 kg onto an elbow plate to avoid any compensatory behavior (see Figure 1(c)). Participants received concurrent feedback on whether this requirement was met (Figure 3).

Fingertip force applied onto the meta-grip was obtained by a single point load cell (Mettler-Toledo MT1241-250 kg). Due to its off-center load compensation, the MT1241 measures

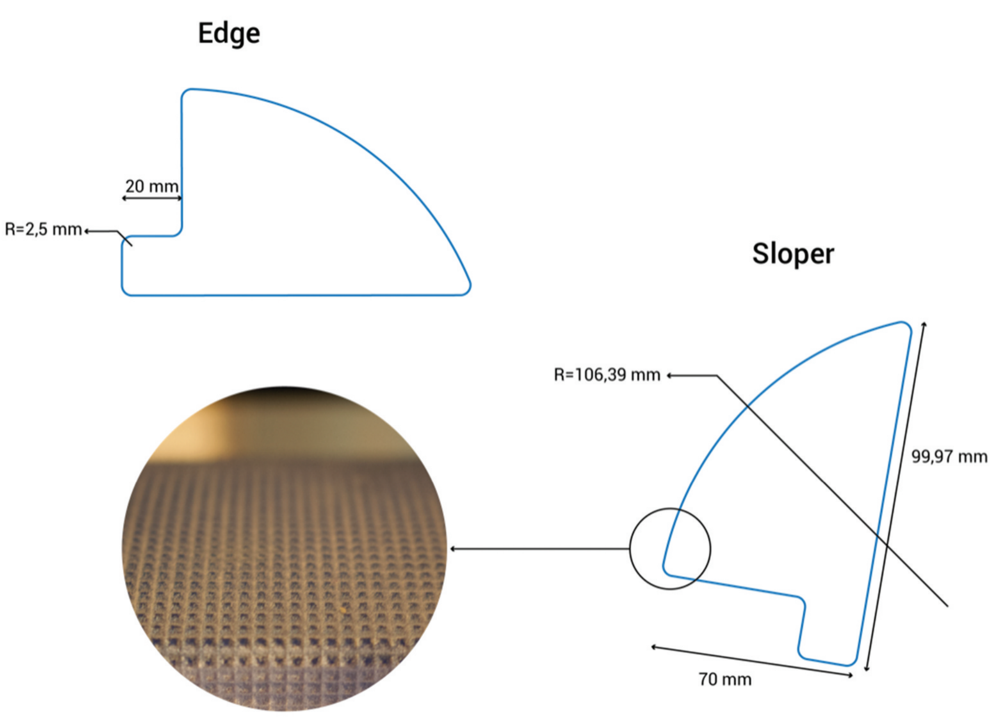

Figure 2. Specifications of the used holds, that is the edge on the left and the sloper on the right. The zoomed in area shows the small pyramids added to the surface to increase friction.

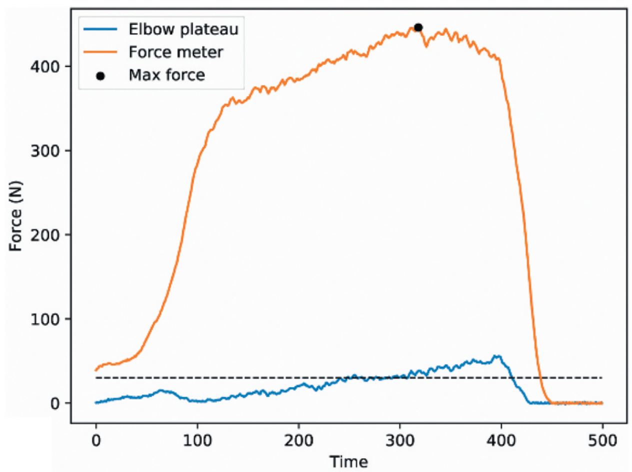

Figure 3. Example time-series data of the vertical forces produced on the meta-grip. Peak force was the max of the moment force produced, noting that this information was available online to the participant during each trial.

force regardless of load application point. A S-beam load cell (AE sensors STS-250 kg) was also attached onto the elbow plate, to control for any additional forces originating at the shoulder. Both systems sampled at 1000 Hz with a National Instruments CompactDAQ system (NI 9218).

Experimental setup

Criterion validity was determined by examining fingertip strength relative to on-sight (first climb) climbing performance on two climbing routes. One route consisted of edges with progressively decreasing edge depth, the other route consisted of slopers with systematically flattening slope. It was estimated that both routes started as 6b and finished as 8b F-RSD. Routes were set up by a professional, international level competition route setter. Due to the increasing difficulty of the holds, participants with higher fingertip strength on a specific hold type were expected to be able to climb higher. Both routes were set on an 8 m high wall with an inclination of 0 degrees, contained 21 handholds and were set up in such a way that the movements required to reach the top were identical between routes (Figure 4). To guarantee safety, climbers were wearing a harness and were secured to a top rope and belayer. Climbing performances were filmed using a rearview camera (Fujifilm FINEPIX XP80).

Procedure

A procedure was developed to assess two types of reliability: intra-session reliability (between trials in one session) and test-retest reliability (between two sessions). Intra-session reliability was determined based on the maximal voluntary isometric contractions performed per hold type and body position during the first testing occasion. To assess test-retest reliability of the fingertip strength assessment, participants were required to visit the lab on two separate days, six to seven days apart. The first occasion consisted of some general questions, fingertip strength assessment and a performance test on the climbing wall and took around two hours. On the second occasion, which lasted 45 minutes to one hour, only the fingertip strength assessment was performed. When entering the research facility for the first time, participants received general instructions and age, climbing level, standing height, body mass, and arm-span were assessed. Participants then proceeded with a standardized warm-up protocol, which consisted of general exercises with a Dyna-Band and a familiarization protocol with the meta-grip. The familiarization protocol consisted of six submaximal contractions with a duration of 10 seconds followed by three seconds of rest, as described by Donath and Wolf (2015), followed by two maximal contractions with two minutes rest in between. After the warm-up, participants received three minutes of rest before proceeding.

Fingertip strength

Participants performed four maximal isometric contractions in every condition. The first two contractions served as a familiarization, following Baláš et al. (2014), the second two were recorded. Tests were performed with the dominant hand and consisted of different combinations of hold types and body position. The following hold and grip types were tested: (1) full crimp grip small edge (a 20 mm depth was used, i.e., this was to ensure only the fingertips were able to exert force Figure 1a), and (2) slope grip (Figure 1b). In the crimp grip conditions, participants were instructed to flex the proximal interphalangeal joint (PIP) and hyperextend the distal interphalangeal joint (DIP) accompanied by their thumb resting on top of the DIP joint of their index finger. In the slope conditions, participants were instructed to use an open grip, with their fingertips touching the end over the sloper hold. These two grip types were tested in the following two body positions: (1) 90/90 elbow ”isolated” position (90/90). The arm was placed on the elbow plate in horizontal position (90 degrees flexion between trunk and arm), with the elbow 90 degrees flexed and the shoulder 45 degrees adducted (Figure 1c). In this way, the elbow was constrained, and the fingers were tested in isolation; and (2) self-preferred 180/0 elbow ”open chain” position (180/0). The shoulder was flexed at 180° and the elbow fully extended (Figure 1d). Once in this position participants could vary their elbow and shoulder angles. This position and instructions aimed to represent a more specific climbing posture, without constrained elbow. Notably, we did not interfere with participant's self-preferred position because doing so can lead to instruction-based interference performance decrements and (potentially) affect the reliability of the test-retest (Wulf, 2008).

Note that in self-preferred conditions a bar was positioned over the feet to keep participants from lifting themselves off the ground. This approach was developed through pilot work and was preferred over adding weights, since it allowed participants to produce force greater than body mass while remaining in complete control of the applied force, and was therefore, considered safer (Figure 1d).

This resulted in four conditions (with two attempts per condition): crimp grip isolated (CI), crimp grip open chain (CO), sloper isolated (SI), and sloper open chain (SO). The order in which the conditions were performed was randomized across the participants. Between every trial, participants rested for two minutes. Participants could use chalk (and did so

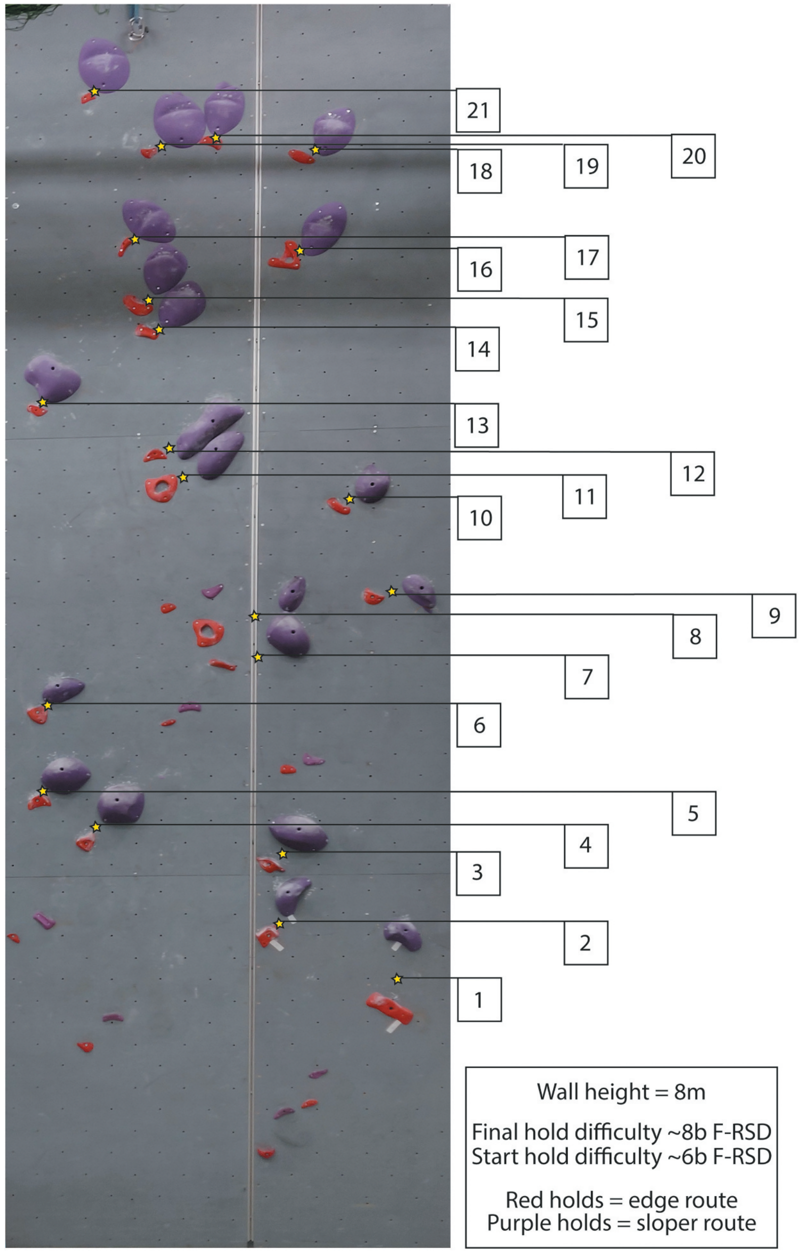

Figure 4. The two climbing routes: the sloper only route (purple) and the edge only route (red). F-RSD = French rating scale of difficulty.

without exception). The grip was cleaned between trials. The warm-up familiarization and fingertip strength protocol were repeated on the second occasion, to determine test-retest reliability.

Climbing performance

On the first testing occasion, after completing the fingertip strength measurements, participants were instructed to climb two routes under on-sight conditions. The order in which the routes were climbed was randomized (coin toss) across participants. Before attempting the first route, participants received two minutes observation time. After completing the preview, participants were asked to put on their climbing shoes, put some magnesium on their hands and attach themselves to the top-rope system. Participants were then allowed to start climbing. The end of an attempt was marked by a fall or completion of the route. Participants were then required to rest until they felt fully recovered (with a minimum of five minutes) before attempting the next route. Considering pilot work, the height of the route, nature of the route (relatively short, starting easy and ending hard, resulting in a relatively short challenging section for every participant, containing around three movements at their absolute maximum) and ability level of participants—five minutes minimum was deemed sufficient (Senna et al., 2016). The climbing performance test was only performed on the first testing occasion.

Data processing

The maximum finger flexor strength was defined as the peak force produced of the moment-to-moment force recorded in the vertical direction during a maximal

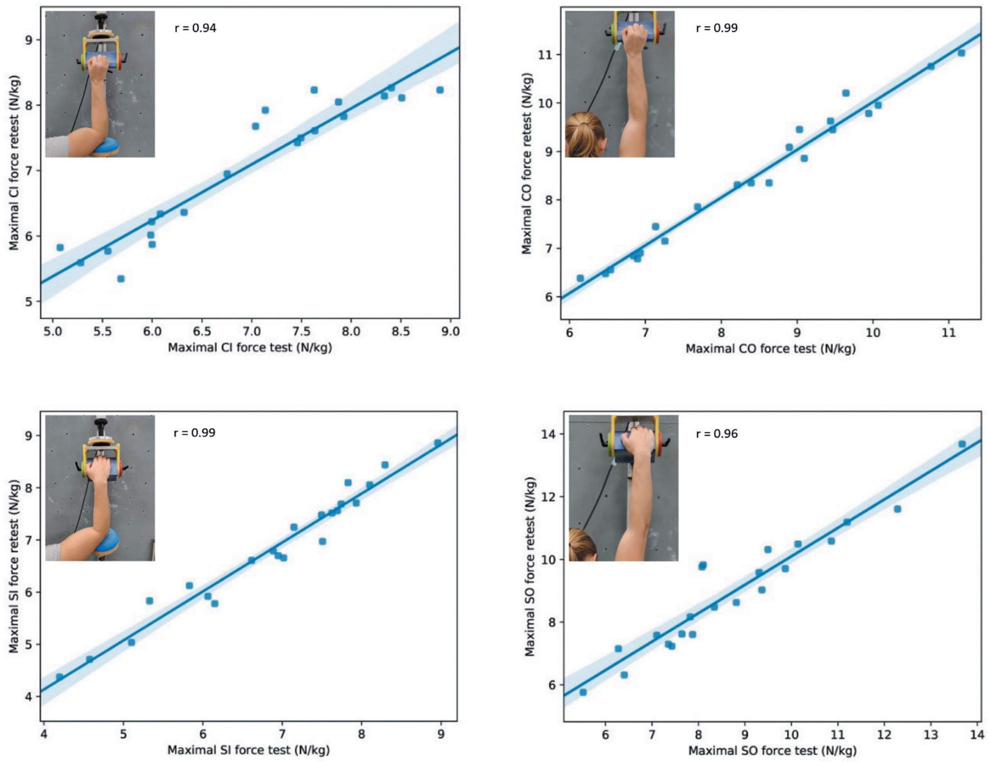

Figure 5. The relationship between the highest obtained MVC during the test and retest, both expressed in N/kg body mass, measured on the crimp grip in isolated position (upper left); crimp grip open chain (upper right); sloper grip in isolated position (lower left), and; sloper grip open chain (lower right). Shaded areas gives the 95% confidence intervals. CI = crimp grip isolated, CO = crimp grip open chain, SI = sloper grip isolated, SO = sloper grip open chain.

voluntary contraction by the finger flexors (recall Figure 3). In climbing, fingertip strength is always related to body mass (since climbers are carrying their body mass on the fingertips). Relative MVC scaled to body mass was calculated using the following equation: relative MVC = MVC/ body mass (Michailov et al., 2018).

Climbing performance was defined by the highest hold reached on the route, hereafter referred to as route score. Scores were assigned according to the IFSC judging system (Hatch & Leonardon, 2018).

Relative MVC was chosen as the main variable for testing the relations between grip strength across holds and body positions and climbing performance because of the relatively short height of each route meaning only a few moves would require near maximal strength (Fuss & Niegl, 2008; Fuss et al., 2013). We also restricted assessment to relative MVC because adding other physically demanding measures (such as endurance tests) would have interfered with data collection without addressing our main research question.

Statistical analysis

The intra-session reliability was determined from the two maximal fingertip strength trials performed in each condition. The highest values of the two trials performed in one condition during the first and second measurement occasions were used to determine test-retest reliability. Both intra-session and test-retest reliability were assessed by computing the intra-class correlation coefficients (ICC) (two-way random with absolute agreement). ICC interpretation statistics follow the guidelines proposed by Koo and Li (2016), that is ICC values below 0.5 indicate poor reliability, values between 0.5 and 0.75 are indicative of moderate reliability, values between 0.75 and 0.9 represent good reliability and ICC values higher than 0.9 are indicative of excellent reliability. Furthermore, the standard error of measurement (SEM) was calculated from the ICC values and the standard deviation (SD) using the following formula: $SEM = SD \times \sqrt{1 - ICC}$. SEM is expressed in absolute number of kilograms loaded onto the meta-grip. Criterion validity was firstly determined by bivariate correlations between the highest recorded MVC for each of the four conditions and self-reported climbing level (on-sight and red-point). Secondly, criterion validity was determined by the bivariate correlations between the highest recorded MVC for fingertip strength measured on the two hold types in the open conditions and route score on the route on edges and the route on slopers. Correlation coefficients were interpret as follows: ±.1 is a weak relationship, ±.3 represents a moderate relationship and ±.5 is a strong relationship (Field, 2009). Significance level was set at $p < .05$.

Results

The used testing protocol was proven to be highly reliable, with intra-session reliability expressed as the ICC for the four conditions: CI: 0.88 (SEM = 5.52 kg), CO: 0.96 (SEM = 3.97 kg), SI: 0.94 (SEM = 4.87 kg), SO: 0.97 (SEM = 4.70 kg), and test-retest expressed as the ICC for the four conditions: CI: 0.94 (SEM = 3.87 kg), CO: 0.99 (SEM = 2.23 kg), SI: 0.99

(SEM = 2.43 kg), SO: 0.96 (SEM = 5.86 kg) (see Table 1 and Figure 5). Raw individual data including body mass and absolute force are given in Supplementary Table 1.

With respect to criterion validity the relationships between self-reported redpoint/on-sight climbing level and absolute/relative MVC on every hold type were explored. This resulted in 16 correlation coefficients, all of which were significant except for the correlation between absolute MVC on crimp grip in isolation (CI) and redpoint climbing level (Table 2, Figure 6). Moderate relationships were found between absolute MVC on CI and on-sight climbing level (r = 0.492, p = .020), relative MVC on CI and redpoint climbing level (r = 0.474, p = .026), and absolute MVC on SO and redpoint climbing level (r = 0.495, p = .019). All the other correlations indicated strong relationships between fingertip strength and climbing performance. There were no systematic differences between isolated and open conditions. In sum, fingertip strength across a range of holds and body positions was significantly related to self-reported redpoint and on-sight climbing level.

To assess the criterion validity, the relationships between fingertip strength measured in the open conditions and route scores on two routes were determined. A significant positive correlation was found between route score on the sloper route and fingertip force measured on the SO condition (r = 0.512, p = .025). Route scores on the edges route also correlated significantly to fingertip force measured on the CO condition (ρ = 0.579, p = .009). No significant correlations were found between fingertip strength measured on the sloper or crimp grip and distance climbed on the route of the opposing hold type (sloper grip—route score edges: ρ = 0.448, p = .054; crimp grip—route score slopers: r = 0.454, p = .051).

Finally, the correlation between the test results of the relative fingertip strength measured on an edge and on a sloper, both in open condition, were analyzed. A significant, strong, positive correlation coefficient of r = 0.727 (p < .001) was found. This corresponds to an explained variance of R^2 = 0.529 indicating 47.1% of the variance between relative fingertip MVC measured on edges and on slopers remains unexplained.

Discussion

The objectives of this study were to test the reliability and criterion validity of assessing grip strength variability across multiple holds and body positions.

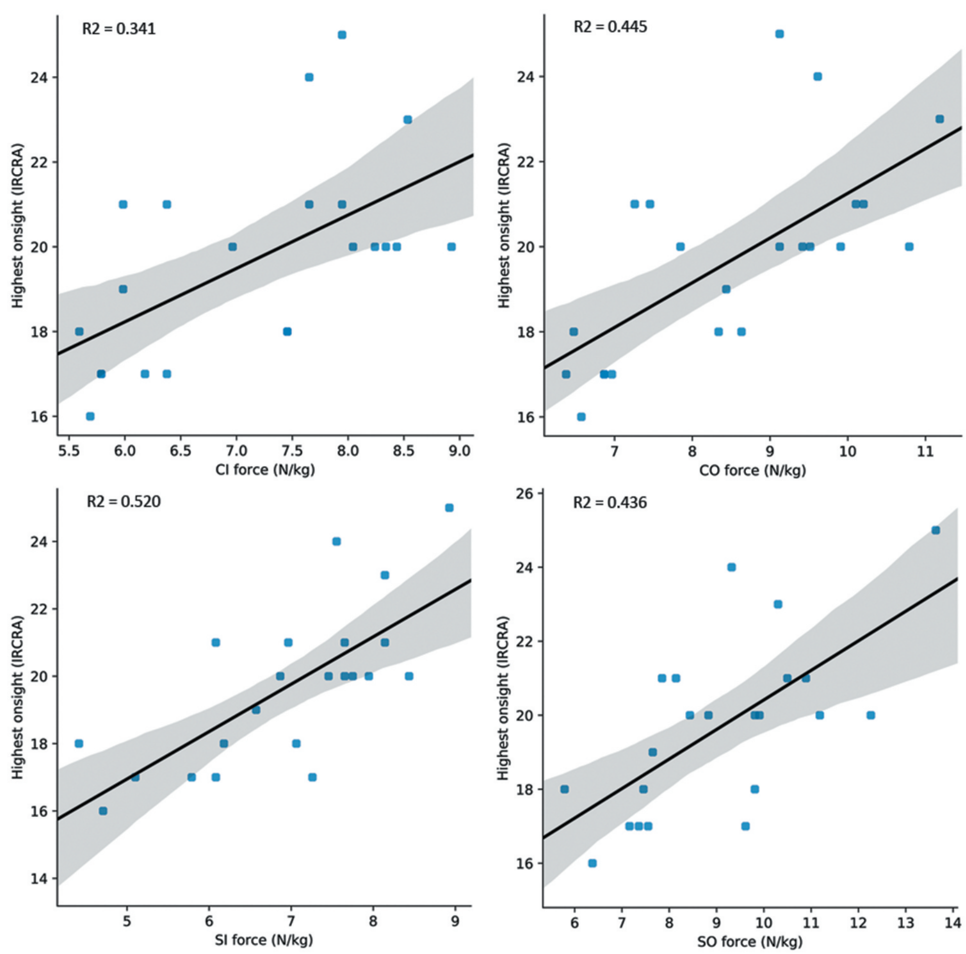

Figure 6. The relationship between highest on-sight level expressed on the IRCRA scale and relative fingertip force, expressed in N/kg body mass, measured on the crimp grip in isolated position (upper left); crimp grip open chain (upper right); sloper grip in isolated position (lower left), and; sloper grip open chain (lower right). Shaded areas gives the 95% confidence intervals. CI = crimp grip isolated, CO = crimp grip open chain, SI = sloper grip isolated, SO = sloper grip open chain.

Table 1. The intra-session and inter-session reliability expressed as the ICC for the four conditions.

	Intra-session	Inter-session
CI	0.88	0.94
CO	0.96	0.99
SI	0.94	0.99
SO	0.97	0.96

CI = crimp grip isolated, CO = crimp grip open chain, SI = sloper grip isolated, SO = sloper grip open chain.

Grip strength can be reliably assessed on a range of holds and body positions

The data showed good to excellent reliability for assessing grip strength on a range of holds and body positions in sub-elite and elite climbers. Both the intra- and the inter-session reliability were good to excellent with all ICC values equal to 0.88 or higher (Table 1). These values are similar in magnitude to reliability values reported previously on other climbing-specific fingertip strength assessment tools (Baláš et al., 2014; Michailov et al., 2018). Since previous measurements were reported on horizontal uniform edges, the current research extends existing work by also including two conditions with a sloper hold (also highly reliable).

Grip strength across holds and body positions is consistent with performance

Criterion validity was tested in two ways. Firstly, by determining whether grip strength across holds and body positions is associated with climbing ability. Secondly, by determining if strength on a specific hold type (edges and slopers) supported climbing performance for their respective hold type (i.e., routes made up exclusively either of edges or slopers).

Considering the first test of criterion validity, all relative grip strength measures were significantly correlated to self-reported redpoint and on-sight climbing level (ranging from r = 0.58 to 0.72), indicating that climbers of different ability levels can be differentiated across a range of hold types and body positions (Table 2). The values found in this study are in line with previous research showing strong relationships between fingertip strength on edges and climbing ability (Baláš et al., 2014, 2012; MacLeod et al., 2007; Michailov et al., 2018; Philippe et al., 2012; Wall et al., 2004). Our results extend previous research by indicating that higher strength across a range of holds, body positions and grip techniques may be important for higher levels of climbing ability. Notably, the different conditions were also correlated significantly with each other (i.e., with ~53% of the variance explained), indicating that the tests, on the one hand, assess a general ability to produce force at the hands and fingertips. On the other hand, the considerable unexplained variation (~47%) indicates each grip type has unique contributions to understanding expertise. Cadaver studies have shown evidence for a different distribution of forces over tendons in crimp and slope grip (Schweizer & Hudek, 2011). A number of studies compared forces in the flexor digitorum profundus and superficialis tendon (FDP and FDS) in the slope grip and crimp grip. Results suggest that the FDP is the prominent finger flexor on small holds in the crimp grip postion, whereas FDS has a larger contribution to grip strength on large flat holds (slopers; Schweizer & Hudek, 2011; Vigouroux et al., 2006). In sum, these findings provide preliminary support for the notion that increased grip strength variability is important for increased redpoint and on-sight ability level in climbing.

The second test of criterion validity supports the notion that grip strength across multiple holds predicts performance during climbing. We found that maximal force producing capability on edges predicted how high a climber got on the route composed of edges (whereas it did not significantly predict performance on the sloper route). We also found that maximal force producing capability on slopers predicted how high a climber ascended on the route composed only of slopers (whereas it did not significantly predict performance on the edge route). Specifically, significant positive correlations were found between strength measurements and route score on the corresponding hold type and not on the opposing hold type. It could be suggested that congruent correlation coefficients are higher (and are significant) than the incongruent correlation coefficients (which are not significant, even though they are of similar magnitude). These findings provide initial support for criterion validity of the device and suggest that having high levels of fingertip strength on edges may not be necessarily predictive for performance on a sloper route and vice versa.

Table 2. The correlation coefficients (r) between absolute (left) and relative (right) fingertip force and self-reported redpoint and on-sight climbing level.

	Fingertip force		Fingertip force per kg body mass	
	RP	OS	RP	OS
CI	0.400	0.492*	0.474*	0.584*
CO	0.549*	0.616*	0.594*	0.667*
SI	0.535*	0.573*	0.665*	0.721*
SO	0.495*	0.579*	0.562*	0.660*

*p < .05. CI = crimp grip isolated, CO = crimp grip open chain, SI = sloper grip isolated, SO = sloper grip open chain.

Limitations

There are several limitations that might guide future research. In terms of protocol, the procedure to keep participants from lifting themselves off the ground (with a bar over their feet), while it proved safe and reliable, may still be improved. A possibility might be to allow the participants to generate an opposing stopping force with their other arm at a hold positioned at arm span below the dynamometer.

Another point of interest is how grip strength variability might be important in supporting adaptability across a greater range of constraints. For example, a variety of constraints can be manipulated to challenge grip strength limits beyond hold size and type, such as wall angle, hold texture, equipment, or fatigue.

Finally, in this study we were mainly interested in the commonalities and differences between grip strength measured on two distinct hold types: namely edges and slopers. On an edge, different grip types can be performed, namely an open crimp grip and full crimp grip. Because of time and energy level considerations (from the participants perspective), this study tested the full crimp position on edges, so in this way the grip type we tested was most applicable to the climbing performance test. That being said, in the context of grip strength variability it would be interesting to also explore the relationship between climbing performance and grip strength measured on the same edge but across a range of techniques to evaluate an athlete's adaptability (or degeneracy) with respect to a specific edge/hold type.

Implications

To achieve safe, progressive improvement in strength, the accurate and reliable monitoring of strength is necessary (Backe et al., 2009; Vigouroux & Quaine, 2006). Purely from a training and performance perspective the results of this study highlight the potential value of monitoring changes in fingertip strength over different hold types.

Our findings suggest that having a sufficient degree of strength across multiple holds and body positions can be beneficial to performance on routes of varied grip types. High levels of grip strength across multiple holds and body positions could possibly relate to enhanced functional movement variability, supporting the climber's capability to adapt to the variation that is typical of most climbing contexts. For example, since climbing routes often contain different hold types, our study advocates the potential importance of grip strength variability for supporting other indices important to climbing performance such as climbing fluency, efficient exploration, and (being able to more widely) exploit rest points (Orth, Kerr et al., 2017; Orth, van der Kamp et al., 2017; Sanchez et al., 2012; White & Olsen, 2010), and warrants future research.

High levels of maximal producible force by the fingertips is a known aspect of expertise in climbing. Previous research established this using edge hold types (Vigouroux & Quaine, 2006). This study developed a method to reliably measure fingertip strength on multiple holds and body positions requiring different grip types, and hence, this method allows us to combine and compare these measures, potentially allowing a measure for functional variability. In this way, variability would be represented by high levels of grip strength over a range of hold types (e.g., edge, sloper, pinch, one-finger pocket, two-finger pocket, etc.). We extend on existing literature showing that producing high forces on other hold types (in this case a sloper) is also associated with expertise. Furthermore, previous research has not examined relationships between hand strength and performance when climbing without consideration for route design (Orth et al., 2016). This study is unique in that we also tested the relationships between grip strength and climbers' on-sight performance.

In conclusion, this study provides evidence that grip strength across holds and body positions is a key aspect of expertise and performance in climbing. We developed a method to reliably measure fingertip strength on multiple grip types, allowing a measure for variability. These findings allow coaches to track performance of their athletes, and highlight the importance of training grip strength across a variety of holds, body positions, and grip techniques.

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