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Original Article

Intra and Inter-Session Reliability of Movement Velocity During Pull-Ups Performed at Small Climbing Holds

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Abstract

Objectives: The synergy between arm and shoulder muscles, along with isometric finger flexor strength, are crucial for climbing proficiency. However, tests often assess these factors separately rather than in a unified action. This study aimed to determine the intra- and inter-session reliability of the mean propulsive velocity (MPV) during pull-ups on a large hold and on small climbing edges. **Methods**: Ten male climbers (self-reported maximal grade 6b-8b on French scale) participated in two identical sessions. During each session, participants performed two blocks of two pull-ups on a large hold and on four small climbing edges (25, 20, 15, and 10mm) in randomized order. The MPV was recorded using a linear position transducer. **Results**: The MPV during climbing pull-ups at 20mm (0.75±0.16 m/s), 15mm (0.73±0.16 m/s), and 10mm (0.52±0.15 m/s) was reduced compared to a pull-up on a large hold (0.84±0.16m/s). Intraclass correlation coefficients (ICCs) were good-to-excellent across hold sizes for intra-session (ICC 0.84-0.99) and inter-session (ICC 0.73-0.96) measurements. **Conclusions**: The results suggest that the MPV assessed during climbing-specific pull-ups on small holds provides valuable insights into finger, elbow and shoulder muscle force capacities in a unified action. This test could be considered a sport-specific test for monitoring performance in climbers.

Keywords: Field Testing, Finger Force, Grip Depth, Rock Climbing, Upper-Limb Test

Introduction

Over the past five decades, the sportivization of rock climbing has increased the number of practitioners in indoor and outdoor climbing disciplines, intensifying the competitiveness of indoor contests and augmenting the difficulty of outdoor routes[1]. The inclusion of climbing as an Olympic sport in Tokyo 2020 has further accelerated this trend. In this context of heightened demands, precise training monitoring and prescription have become even more critical, allowing professional rock climbers to excel in competitions and take on challenging projects at the limits of human climbing performance.

High performance in rock climbing encompasses a combination of highly technical, psychological, and physical abilities[2–6]. Climbing requires generating external force to move the body against gravity by pulling from diverse holds on the wall, demanding significant neuromuscular capabilities in the upper limb muscles[3,7–9]. However, challenging climbing situations often require to produce upper limb force by pulling from minuscule holds, which requires robust isometric finger flexor strength to effectively transfer the neuromuscular capabilities from the larger elbow flexor and shoulder extensor muscles to the wall[3,9–11]. Hence, the synergy between proximal arm and shoulder muscles power and isometric fingers flexors strength stands out as a crucial physical determinant of climbing proficiency[12]. Several reliable tests have been proposed to characterize the mechanical capabilities of the upper limb neuromuscular system during a pull-up movement. These

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include the one-repetition maximum test[13], a force-velocity profile assessment[7], or a power arm jump test executed from large holds[8]. Assessing finger flexors maximum strength commonly involves bilateral[13,14] or unilateral[11] hanging from fingerboard small holds with the maximum load participants can hold for a predetermined time (3-5") with straight arms.

While these tests are reliable[7,11,13,14] and discriminate climbers of different level and discipline[8,11], they usually examine proximal arm muscles force production and isometric fingers flexors strength separately, rather than in a unified action. Tests whose output is influenced by both proximal arm muscles force and isometric fingers flexors strength are scarce and often involve only isometric maximal contractions, like a 90° elbow flexion isometric pull from a 23mm edge[15,16]. Few studies have examined force application capacities of climbers holding small size holds during dynamic actions and showed that maximal force developed decreased with the hold size[17,18], highlighting how hold size influences climbers' ability to transfer upper limb force production to the wall. However, the necessity for specially designed force plates mounted on a hangboard to obtain these measures poses a significant problem, as it restricts the accessibility and utilization of such measures among practitioners. Furthermore, the reliability of the test, a key aspect of any assessment used to monitor changes in performance (due to training and/or fatigue) was not reported.

An alternative to indirectly measure force production is through the recording of lifting velocity during multi-joint resisted movements like a barbell squat or a bench press[19–21]. Lifting velocity can be precisely and reliably measured during multi-joint resisted movements using commercial linear position transducers or even smartphone apps[22,23], allowing for the description of mechanical capabilities of the neuromuscular system, which has been extensively used in the context of resistance training prescription and monitoring[24]. Due to Newton's second law, acceleration of a mass equals the ratio between the external force applied and the mass to be displaced ($a=F/m$). Therefore, during a pulling movement, the force exerted by the proximal arm and shoulder muscles and the body mass would determine the lifting velocity of the movement[7]. However when a climber faces a lead or boulder climbing route, factors like the depth of the holds where hands have to pull to move the body mass could influence the external force applied[17,18] and, therefore, the lifting velocity despite a constant body mass. Consequently, we propose that measuring lifting velocity during climbing-specific pull-ups performed on small holds (25-20-15-10mm) would serve as an index of both, elbow and shoulder muscles potential to vertically propel the body, and also the ability of the finger flexors to transfer the force from the larger elbow and shoulder muscles to the hold. However, although vertical pulling from small edges would increase specificity regarding typical climbing movements[12], the reliability of this test has not yet been determined.

The aim of the present study was to describe the effect of grip depth (large hold, 25, 20, 15 and 10mm) on the mean propulsive velocity (MPV) attained during a pull-up, and determine the intra-session and inter-session reliability of MPV at each hold. The large hold was used as the easiest condition and served as a reference for the maximum neuromuscular capabilities in a vertical pulling action[17]. We hypothesize that, despite the same absolute load (body weight) during the climbing-specific pull-ups, the absolute MPV would progressively decrease due to changes in the lever and force arm that occurs with the reduction in the depth of the climbing hold, which ultimately would reduce applied force. However, the reliability of the MPV would remain stable across different grip conditions.

Material and Methods

Study design

Ten subjects visited the laboratory on three occasions to determine the intra-session and inter-session reliability of the MPV attained during pull-ups executed over five different grip conditions: a large hold and four small climbing edges with progressively decreasing depth (25, 20, 15, and 10mm). The initial laboratory visit served as a familiarization session, allowing subjects to practice the procedures to be performed in the subsequent experimental sessions (i.e., pull-ups with different grip conditions). At least 48h after the familiarization session, subjects performed the first experimental session (S1).

The S1 started with a standardized warm-up encompassing joint mobility drills, low-intensity resistance training exercises, and brief (3-5 seconds) body weight bilateral dead hangs at each edge depth tested. Following the warm-up, subjects performed two pull-ups for each grip condition (large hold, 25, 20, 15 and 10mm) in random order, with a 3-minute rest interval between grip conditions. After the completion of the pull-ups on each grip condition (Block 1), the measurement was repeated in the same order (Block 2) to assess intra-session reliability. Five to seven days after S1, an experimental session (S2) consisting on one block of measurements was conducted to evaluate inter-session reliability with the first block of the S1. The warm-up and the order of grip conditions in S2 was identical to S1.

Subjects

Ten healthy men from a local mountaineering club participated in the study (mean±SD: age 28±7.9 years; height 1.75±0.05 m, body mass 68.3±7.5 kg; self-reported max red-point grade climbed during last year 6b to 8b on the French scale). Climbing experience was of 4.3±3.2 years (2 to 5 days of training per week including at least one resistance training session containing pull-ups) and their competitive level ranged from intermediate to elite according to IRCRA scale[25]. None of the participants reported any orthopaedic or neuromuscular injuries in the year preceding the study that could have affected their pull-up performance. Subjects were instructed to abstain from consuming beverages containing caffeine or alcohol, as well as refraining from engaging in any form of physical exercise 24 hours before each testing session.

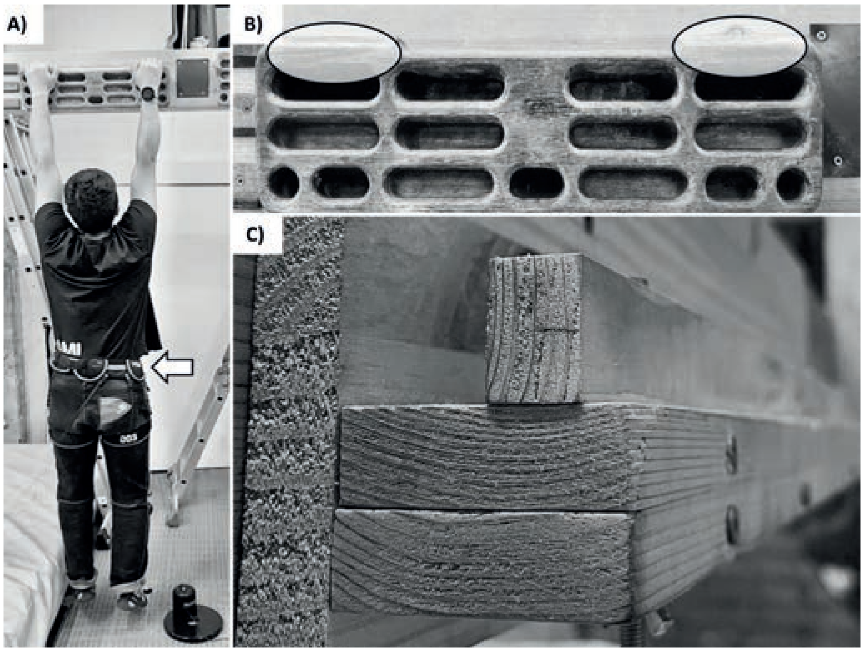

Figure 1. Experimental setup photo. A) Climbers initial position, the white arrow points the attachment of the linear position transducer to the side of the harness. B) Commercial hang-board used for the large hold condition, marked with transparent white circles. C) Custom made hang-board used for manually change between the 25, 20, 15 and 10mm holds conditions.

Procedures

During the pull-up test every subject performed two pull-ups at each grip condition, repeated on two occasions (Block 1 and Block 2) during S1 and only once during S2. Every pull-up started with the climber hanging from the corresponding grip, with the feet hanging in the air and chalked hands positioned around 1.5 times his biacromial breadth (from the little finger) with the elbows fully extended (Figure 1.A) and their preferred grip technique (slope or half-crimp, but not full crimp). After maintaining this position during two seconds, the researcher gave the signal to perform the first pull-up as fast as possible until the chin exceeded the hands. Subjects were instructed to perform a controlled eccentric contraction, stabilize their initial position without leaving the holds (1-2 seconds) and perform the second pull-up.

The large hold was a deep hold larger than the climber's length of the fingers from the metacarpophalangeal joint to the fingertips, requiring a slope grip (Figure 1.B). This grip was used as the grip condition where subjects can exert their maximum pulling force, similar to that attained when doing a pull-up over a traditional gym bar[17]. For the pull-ups on small edges a custom hang-board that allowed to manually modify edge depth was used (Figure 1.C).

The MPV of every pull-up was measured with a linear position transducer (ADR encoder, Toledo, Spain, sampling frequency of 1000 Hz) attached perpendicularly to the side of the harness of the climber (Figure 1.A). The repetition with the highest MPV of the two repetitions performed in each block was used for the posterior analysis.

Statistical Analyses

Statistical analysis of data was performed with SPSS 28 (IBM Corp., Armonk,NY,USA). Values are reported as mean ± SD. Normal distribution was confirmed using the Shapiro-Wilk test. Before conducting reliability testing, pairwise comparisons were performed to assess significant differences between blocks in S1 or between sessions (comparing the block 1 of S1 with the only block measured in S2). The magnitude of the differences between measures and sessions was expressed as a standardized mean difference (Cohen's d effect size; ES). Intra-session (Block 1 and Block 2) and intersession reliability was assessed by the coefficient of variation (CV) and intraclass correlation coefficient (ICC, single measurement, absolute agreement, 2-way-mixed effects model [3, 1]). The ICC was interpreted with values below 0.5, 0.5-0.75, 0.75-0.90, and >0.90 representing, respectively, low, moderate, good, and excellent reliability[26]. Intra-session and inter-session reliability were assessed for the absolute MPV values (m/s). Furthermore, a repeated measures analysis of variance (RM-ANOVA) was used to determine the effect of the grip depth (large hold, 25, 20, 15

Table 1. Absolute and relative mean propulsive velocity (MPV) attained on each hold during both sessions.

	Session 1		Session 2
	Block 1	Block 2	
Absolute MPV (m/s)			
Large hold	0.84 ± 0.16	0.88 ± 0.19	0.84 ± 0.15
25mm	0.80 ± 0.15	0.79 ± 0.17	0.79 ± 0.15
20mm	0.75 ± 0.16	0.75 ± 0.16	0.73 ± 0.14
15mm	0.73 ± 0.16	0.71 ± 0.16	0.72 ± 0.16
10mm	0.52 ± 0.15	0.56 ± 0.18	0.59 ± 0.16
Relative MPV (%)			
25mm	95.7 ± 9.3	94.2 ± 7.6	93.5 ± 11.4
20mm	89.2 ± 10.0	89.3 ± 9.6	87.5 ± 13.2
15mm	87.1 ± 13.3	85.0 ± 15.2	85.1 ± 12.8
10mm	63.1 ± 16.6	67.0 ± 18.9	70.9 ± 16.1

Table 2. Intra-session and inter-session reliability of mean propulsive velocity (MPV) attained on each hold.

Measure	Intra-Session 1				Inter-Session			
	p	ES	ICC	CV	p	ES	ICC	CV
Absolute MPV								
Large hold	0.29	0.23	0.84 (0.48, 0.96)	9.0	0.85	0.02	0.96 (0.85, 0.99)	4.2
25mm	0.36	0.06	0.99 (0.95, 1)	2.6	0.44	0.10	0.95 (0.81, 0.99)	5.2
20mm	0.82	0.02	0.98 (0.91, 0.99)	3.8	0.53	0.11	0.89 (0.63, 0.97)	7.4
15mm	0.17	0.12	0.97 (0.90, 0.99)	4.2	0.57	0.08	0.93 (0.75, 0.98)	6.9
10mm	0.25	0.21	0.89 (0.63, 0.97)	11.4	0.11	0.45	0.73 (0.22, 0.92)	15.8

and 10mm) on the absolute MPV attained during the pull-ups. For this analysis, the mean of Block 1 and Block 2 of the first session was used. If sphericity was violated (Mauchly's test), degrees of freedom were corrected by Greenhouse–Geisser estimates of sphericity. Bonferroni correction was applied for post hoc analyses to account for multiple comparisons. Effects sizes are presented as partial eta-squared values (η_p^2; small: 0.01; medium: 0.06; large: 0.14) for the main effect of the RM-ANOVAs and as Cohen's d for the paired comparisons (small: 0.2; medium: 0.5; large: ≥0.8). Statistical significance was set at p<0.05.

Results

Table 1 shows the MPV attained in each hold expressed in absolute values and as a percentage of the MPV attained in the large hold condition. The intra- and inter-session reliability of absolute MPV is presented in Table 2. There were no statistically significant differences in the absolute MPV attained in each hold between Block 1 and Block 2 at S1 nor between sessions. The intra-session reliability was between

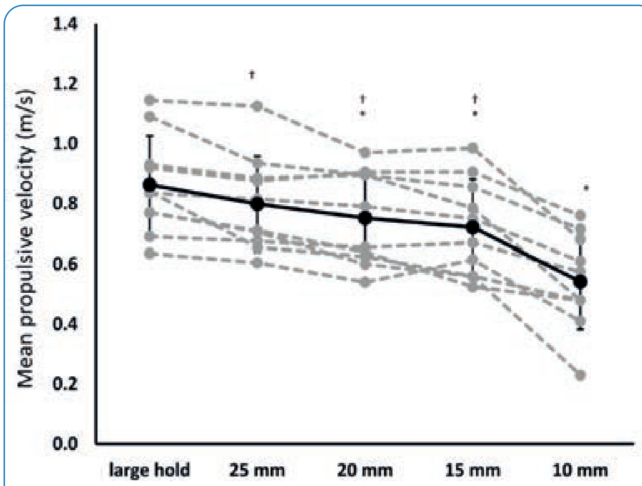

Figure 2. Effect of hold depth on mean propulsive velocity attained during the lifting phase of pull-ups. The individual values (grey lines) and the mean ± SD (black line) is depicted. * Statistically significant difference (P<0.05) from the pull-up on a large hold. † Statistically significant difference (P<0.05) from the pull-up on a 10mm hold.

good and excellent (0.84-0.99), even for the smallest hold (0.89). The inter-session reliability was moderate to excellent (0.73-0.96) with the 10mm hold showing the lower reliability (0.73).

The results reveal a significant main effect of grip depth on the absolute MPV ($F_{1.47,\ 13.26}$= 26.8, p<0.001; η_p^2=0.75) (Figure 2). Compared with the large hold, the MPV decreased when the pull-ups were performed on the 20mm (-12.9%, p=0.012), 15mm (-16.4%, p=0.033) and 10mm (-37.2%, p=0.003) edges but not the 25mm edge (-7.4%, p=0.074). Furthermore, the MPV attained when gripping the 10mm hold was also significantly lower than the MPV attained in the 25mm (-32.1%, p=0.002), 20mm (-27.9%, p=0.003) and 15mm (-24.8%, p=0.004) edges.

Discussion

We determined the effects of the grip depth on the magnitude as well as on the intra- and inter-session reliability of the MPV attained during climbing-specific pull-ups. MPV was measured using a linear position transducer attached to the climber's harness during pull-ups executed gripping a large hold and four progressively decreasing small holds (25, 20, 15 and 10mm). Our results show that MPV decreases with the reduction in hold size, with the large hold and 10mm hold showing the greatest and lowest MPV, respectively. These results suggest that force transmission from elbow and shoulder muscles to the hold is compromised with the reduction in size of the hold. However, both intra-session and inter-session reliability of MPV ranged from good to excellent across all grip conditions.

The reduction in hold depth significantly influenced maximal pulling force capacity indirectly measured through the recording of MPV, a phenomenon previously reported by directly measuring with a force plate the forces exerted by the fingers during an isometric[18] or a dynamic vertical pulling movement[17]. For example, Vigouroux et al.[17] found that maximal applied force during a pull-up was significantly reduced when performed on a 10mm edge compared with all the other holds and when performed at 14, 18, and 22mm edges compared with a large hold, which is in agreement with our findings of decreased MPV with reduced hold depths. This decrease in MPV with reduced hold depth may be associated with changes in the lever and force arm as well as with a reduction in contact area on smaller climbing holds, which ultimately would reduce finger flexors applied force[27]. Therefore, during dynamic actions like pull-ups, this diminished force application from the fingers to the hold hinders the transfer of force from elbow and shoulder muscles to the wall, reducing the MPV of the movement, as evidenced by our findings. However, technical factors could also have contributed for the reduced MPV. For example, as Vigouroux et al.[17] suggested, the risk of losing the grip during a vertical pull-up on smaller holds could involuntarily made climbers to reduce the lifting MPV in order to reduce the swinging and therefore the risk of losing the grip.

One of the novel elements of the present study was the determination of intra-session and inter-session reliability of the MPV attained during climbing-specific pull-ups performed across holds of similar sizes as those encountered in climbing routes. The results show that MPV could be reliably measured during the same session (ICC=0.89-0.99) or at different sessions (ICC=0.73–0.96) at a range of hold sizes from 10mm to 25mm. This denotes an excellent reliability, comparable to established for measuring upper limb neuromuscular capabilities[7,8,12,28] or maximal isometric finger flexor strength separately[11,12,14,15]. Therefore, the results suggest that measuring lifting velocity during climbing-specific pull-ups on small holds (≤20mm) can serve as a reliable index of a climber's maximal neuromuscular capabilities to produce vertical forces against a submaximal specific load (their body weight).

Dynamic vertical pulling from small holds may be suboptimal to develop upper limb neuromuscular power due to the submaximal MPV developed during the movement compared to using a large hold or a gym bar[17]. However, the test provides reliable insights into isometric finger force production and elbow and shoulder muscles force capacities in a unified action, as frequently encountered in climbing. Therefore, this test could be considered as an ecological sport-specific performance assessment. Furthermore, the present test, despite requiring maximal intention lifting velocity, it is performed against a submaximal load. This may reduce the associated fatigue and the risk of injury compared with tests including isometric maximal voluntary contractions[11,13,14] or dynamic contractions against maximal loads[13]. This fact, together with the ease to measure MPV by using an affordable instrument like a low-cost commercial linear transducer or a smartphone app[22,23,29], allows for daily testing, integrating the test into a climber's training routine. For example, similar to the use of a countermovement jump height to control fatigue derived from high-intensity running sessions[30], the MPV during a simple pull-up against a 20-15mm edge could be used to monitor the fatigue generated by a climbing session on the main muscles involved in climbing (finger flexors and elbow and shoulder muscles).

However, the combined nature of the test (isometric finger flexor action plus a dynamic concentric contraction of the arm muscles) precludes distinguishing the main muscles responsible for a change in MPV during climbing-specific pull-ups performed from a single hold. This problem could be solved by measuring lifting velocity not only from a small hold, but also using an additional gym-bar or a large hold climbing-specific pull-up. In this regard, a larger decrease in MPV during a climbing-specific pull-up on a 20mm edge (e.g., a 20% decrease) compared to the reduction (e.g., a 5% decrease) in MPV during a pull-up performed on a gym bar (or large hold pull-up) would suggest that exercise induced more fatigue in the finger flexors, decreasing their ability to transfer the force from elbow and shoulder muscles to the wall. However, further research is needed to determine the sensitivity to fatigue of combining a maximal intention pull-up performed on a gym-bar and a climbing-specific pull-up on a small edge. This information would be valuable to discern the origin of a reduction in climbing pull-up performance using a unified action.

The present study presents some limitations that warrant acknowledgment. While sample size aligns with previous studies exploring the impact of hold depth on finger flexor force capabilities[17,18], the heterogeneous level of climbers (6b to 8b) could limit the generalization of the data. The reliability of the present test may be reduced with lower ability climbers, potentially limiting its applicability on this population. To address these constraints, future research should focus on evaluating the test's reliability across diverse performance levels among both female and male climbers. Furthermore, investigations about the sensitivity of the test to factors such as training-induced fatigue and chronic training changes in maximal isometric finger flexor strength or the force capacity of elbow and shoulder muscles, would provide valuable insights.

In conclusion, the data illustrates how hold depth influences vertical pull-up performance, with smaller holds impairing MPV. Despite this, the results highlight the reliability of MPV measurements during climbing-specific pull-ups performed on different small holds (25-20-15-10mm). Consequently, measuring MPV during a climbing-specific pull-up performed on a small hold serves as an integrative measurement influenced by both, maximal isometric finger flexor strength and the force capacity of elbow and shoulder muscles, making it a valuable climbing specific test for monitoring training prescription and complement information attained with other tests.

Ethics approval

The study was approved by the research ethics committee of A Coruña-Ferrol (SERGAS 2022-309). The study was performed in accordance with the latest version of the Declaration of Helsinki.

Consent to participate

All participants gave written informed consent for the experimental procedures.

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Authors' contributions

Study design: CSV, DCP; Study conduct: CSV, DCP; data collection: CSV, DCP; Data analysis: CSV, AGR, DCP; Data interpretation: CSV, AGR, DCP; Drafting manuscript: CSV, AGR, DCP. Revising manuscript content and approving final version: all authors included in the manuscript.

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