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Hanging ability in climbing: an approach by finger hangs on adjusted depth edges in advanced and elite sport climbers

Pedro Bergua[a], Jesús Montero-Marin[b], Alejandro Gomez-Bruton[c,d,e,f] and José Antonio Casajús[c,e,f,g]

[a]Post-doctoral researcher in Sport Sciences, University of Zaragoza, Zaragoza, Spain; [b]Primary Care Prevention and Health Promotion Research Network (RedIAPP), Zaragoza, Spain; [c]GENUD (Growth, Exercise, Nutrition and Development) Research group, Zaragoza, Spain; [d]Universidad Isabel I, Burgos, Spain; [e]Centro de Investigación Biomédica en Red de Fisiopatología de la Obesidad y Nutrición (CIBERobn); [f]Instituto de Salud Carlos III, EXERNET (Exercise and health research network), Madrid, Spain; [g]Faculty of Health Sciences, Department of Physiatry and Nursing, University of Zaragoza, Zaragoza, Spain

ABSTRACT
Hanging ability on small depth edges is one of the most limiting factors in climbing. The aim of this study was to assess the reliability and validity of a hanging ability indicator measured on an adjusted depth edge. Forty voluntary sport climbers (34 men) were divided into an advanced group (AG; n = 22) and an elite group (EG; n = 18). Climbers performed three sustained finger tests following a test–retest design: (a) maximum hanging time on a 14-mm edge depth (MHT_14), (b) minimum edge depth in which climbers could hang for 40 s exactly (MED_40) and (c) maximum added weight test on the MED_40 edge depth (MAW_5). EG performed better than AG in all tests. The regression analyses showed that the MHT_14 test and MAW_5 test explained a 35% and 69% of the climbing sport level in AG and EG, respectively. All the tests were reliable (ICC3,1 values ranging from 0.89 to 1.00). The MAW_5 and MHT_14 tests demonstrated to be valid and reliable hanging ability indicators for EG and AG, respectively. The measurement of hanging ability on adjusted depth edges might be a key factor in elite climbers, but not necessary in lower level climbers.

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KEYWORDS
Finger strength; finger endurance; dead hang; edge depth; sport climbing

1. Introduction

One of the main limiting factors of climbing performance is the inability to maintain the fingers-hold contact (Deyhle et al., 2015; Morrison & Schoffl, 2007; Schweizer & Furrer, 2007; Watts, Newbury, & Sulentic, 1996). That ability depends on the maximal specific finger strength-to-weight ratio (Baláš, Mrskoč, Panáčková, & Draper, 2014; Baláš, Strejcová, Malý, Malá, & Martin, 2009; Wall, Starek, Fleck, & Byrnes, 2004; Watts, 2004) and maximal specific finger endurance (Fryer et al., 2015; MacLeod et al., 2007), although ultimately both are conditioned by factors related to the friction coefficient between fingers and holds (Amca, Vigouroux, Aritan, & Berton, 2012). In

CONTACT Pedro Bergua p_bergua@hotmail.com Gómez. C/Julio Alejandro Castro Cardús, nº 8, 1º A. 22005. Huesca. Spain

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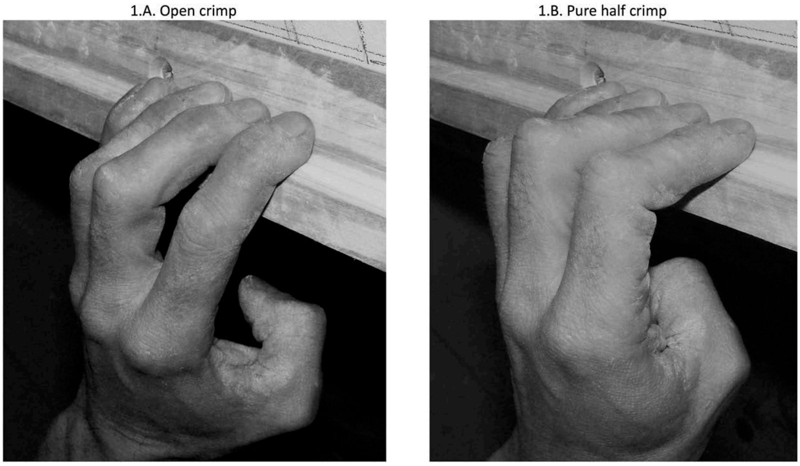

Figure 1. Example of an open crimp grip and a pure half crimp grip.

climbing, the harder sections of the routes are usually composed by the smaller size holds (Bourne, Halaki, Vanwanseele, & Clarke, 2011). From these small size holds, the called "edge" (example in Figure 1) is the more traditionally hold type used in research for assessing specific finger strength and endurance (Baláš et al., 2016; López Rivera & González-Badillo, 2012; MacLeod et al., 2007).

The terms holding ability and hanging ability have both been used in the literature. Holding ability is the capacity to hold something or someone but does not necessarily imply that the climber is sustaining his/her own body weight (BW). Therefore, although a heavier climber might be able to hold a barbell for longer time, that does not imply that the climber will perform better when climbing. Consequently, the term hanging ability, in which the climber is hanging from something, will be used in this study, as this term does imply that the climber is hanging and therefore the climber's weight is accounted for. The majority of studies have assessed hanging ability, defined as the capability to hang from edges of different widths until volitional exhaustion or for a certain amount of time (normally edges size range between 6 and 40 mm of depth) (Baláš, MrskoČ, et al., 2014; Baláš, Pecha, Martin, & Cochrane, 2012; López Rivera, 2014; Medernach, Kleinöder, et al., 2015b). The only study that has worked with smaller edges found that maximum lifting force on deep edges did not predict maximum force production on very shallow edges (Bourne et al., 2011).

On the other hand, it has been suggested that high relative grip strength is necessary for climbing at a higher level of difficulty, but high relative grip strength does not necessarily correspond to higher climbing performance, which could be related to the edge size in which the grip strength has been measured (Baláš et al., 2012). The use of edges that involve more than one phalanx to assess maximal finger strength could be less specific than the use of smaller edges (less of a half distal phalange), especially in the highest sport level climbers (Ozimek, Staszkiewicz, Rokowski, & Stanula, 2016). This could be due to the lower proportional recruitment achieved from the flexor digitorum profundus (FDP) (Schweizer & Hudek, 2011; Vigouroux, Quaine, Labarre-Vila, &

Moutet, 2006), which is considered the most important muscle in climbing performance (Philippe, Wegst, Muller, Raschner, & Burtscher, 2012). So far, measures of maximal finger strength would be only explaining a part of the total hanging ability due to a lack of specificity, because they would not use a similar muscle recruitment to that reached during real actions (Watts et al., 2008). This effect might be more pronounced when using very small edges, as demonstrated by the greater association observed between climbing performance and the ability to apply force to very small edges (7.8 mm, r = 0.71; 12.5 mm, r = 0.45) (Bourne et al., 2011). Therefore, the majority of studies would have been assessing the muscle factor of which the gripping capacity depends on, ignoring the influence of the anthropometric characteristics of the skin to hold on to smaller edge depths, and the muscle recruitment reached during real actions.

In relation to the reliability of the measures, lower values have been observed in finger endurance tests measured with dead hangs using edge depths between 6 and 14 mm in low-level sport climbers (López Rivera, 2014), which might be attributed to their smaller ability to apply strength in a stable manner at higher intensities (Limonta et al., 2016), due to the lower finger strength in this group (Baláš et al., 2012). Regarding edge size, 14 mm edges have proved more reliable than less depth edges when performing hanging tests (López Rivera, 2014). Nonetheless, assessing maximal strength of both high-level and low-level climbers with a dead hang from the same size edge could be dangerous due to the high overloads needed to evoke fatigue in the high-level climbers. An example of the previous was shown in the study developed by Lopez Rivera et al. (López Rivera & González-Badillo, 2012) in which 65 kg overloads had to be applied in high-level sport climbers when assessing maximal strength while holding on 15 mm edges.

About the procedure, there is a lack of consensus to asses hanging ability in climbing. Some studies have used specific exercises using two hands (Baláš et al., 2012; López Rivera & González-Badillo, 2012), while others have just used one (Baláš, MrskoČ, et al., 2014; Mladenov, Mihailov, & Schoffl, 2009). Finger strength differences between the dominant and non-dominant hands have been observed to be less than 10% in climbers (Grant, Hynes, Whittaker, & Aitchison, 1996). Therefore, the unilateral assessment, although useful to take into account possible bilateral deficits, seems to be less practical in the diary training than those tests which do not require additional human or material resources, such as the two-hand simultaneously finger hangs, the most accessible exercise for this sort of tests (Medernach, Kleinöder, et al., 2015a).

Consequently, the aim of this study was to evaluate the validity and reliability of a new hanging ability indicator in climbing, measured through a finger hang maximal strength test, by using two hands simultaneously on an adjusted depth edge, according to individual-specific finger strength.

2. Methods

2.1. *Participants*

The inclusion criteria were to have (a) an experience of 3 or more years climbing, (b) a red-point level of 7a+ or more (French scale), (c) a minimum climbing training practice of at least 2 days a week during the past year and (d) absence of finger injuries during the last 6 months. Participants were individually informed about the characteristics and

Table 1. Characteristics of study participants and test conditions.

Variables	Total (*n* = 40)	AG (*n* = 22)	EG (*n* = 18)	*p*
Age (years)[†]	31.05 (5.95)	31.27 (6.15)	30.78 (5.83)	0.797
Sex (% males)[‡]	34 (85.0)	17 (77.3)	17 (94.4)	0.197
BW (kg)[†]	64.42 (7.98)	64.40 (7.81)	64.46 (8.42)	0.981
Height (m)[†]	1.74 (0.08)	1.74 (0.07)	1.73 (0.08)	0.596
BMI (kg/m^2)[†]	21.25 (1.63)	21.11 (1.59)	21.42 (1.71)	0.549
Sport level (IRCRA)[†]	23 (20–25)	21 (20–22)	25 (24–26)	<0.001
Rock climbing experience (days)[a]	1040 (514–1631)	819 (447–1274)	1274 (884–1839)	0.095
Training experience (days)[a]	832 (377–1540)	663 (247–851)	1391 (819–2379)	<0.001
Temperature (°C)[†]	18.78 (4.08)	18.48 (4.13)	19.14 (4.12)	0.619
Humidity (%)[†]	60.48 (6.55)	59.18 (7.79)	62.06 (4.32)	0.149

BW: Body weight; BMI: body mass index; IRCRA: International Rock Climbing Research Association scale. [†]Mean (SD). [‡]Frequency (%). [a]Median (interquartile range). AG: Advanced group; EG: elite group.

risks associated with the study and were given an informed consent to sign. This study followed the declaration of Helsinki 1961 (revision of Fortaleza 2013), and the protocol was approved by the Ethics Committee of Clinical Research from the Government of Aragon (CEICA), Spain (PI13/0091). Finally, 40 sport climbers met all the inclusion criteria and participated voluntarily in the research project. Additionally, 58% of the total sample completed the retest. The participants were divided in two groups for the statistical analysis: advanced group (AG, *n* = 22, 7a+ to 8a red-point level) and elite group (EG, *n* = 18, 8a+ to 8c+ red-point level) (Draper et al., 2011) according to International Rock Climbing Research Association (IRCRA) current classification (Draper et al., 2015). The general characteristics of participants are showed in Table 1.

2.2. *Procedure*

The tests were carried out in 2 separate days at the same time of the day, following a test–retest design with a week in between the tests. The environmental conditions were similar for both groups (Table 1), and test–retest sessions: humidity [test: mean = 61.13% (standard deviation[SD] = 6.72); retest: mean = 60.30% (SD = 6.28); $t = 0.78$, df = 22, $p = 0.441$], temperature [test: mean = 20.24°C (SD = 3.57); retest: mean = 19.74°C (SD = 3.81); $t = 1.71$, df = 22, $p = 0.102$]. Participants were asked to rest and avoid training or climbing the day before the tests. Participants carried out a total of three tests each day: two finger endurance tests and one finger strength test. All tests consisted of finger hangs which were carried out on a wooden edge without a round radius and with adjusted depths between 6 and 40 mm (precision 1 mm). Participants were instructed to hold on with two hands at the same time and the shoulder/elbow angles at 180/0 flexion grade following previous study recommendations (Baláš, Panáčková, Kodejška, Cochrane, & Martin, 2014). They were allowed to use an open crimp grip or a half crimp grip to hold on to the edge (Figure 1), because previous research has demonstrated that these different types of grips do not provide any benefit with respect to muscular fatigue in sport climbing (Quaine & Vigouroux, 2004). The open grip was never used in this study, due to the size of the edges used. Using the thumbs was prohibited to hold on to the edge, so the full crimp was avoided because it entails higher finger stresses than the half crimp and open crimp (Schöffl et al., 2009; Schweizer, 2001).

Before initial tests began, a specific warm-up was completed, which consisted of joint mobility exercises followed by progressive finger hangs until participants felt sufficient activation to do the first test without reaching muscle failure (supplementary Table 1). A pulley system was used to adjust the intensity when it was less than BW. The precision and intensity of the warm-up was controlled with a load cell (UTIL CELL 160) incorporated under the wooden edge. The participants rested 6–8 min after warm-up while their general data were obtained. Recovery time between finger endurance tests ranged from a minimum rest equivalent to 10 times to a maximum of 20 times the effort time performed in the previous test (Clarke, 1962) (e.g. if the effort time performed was 45 s, the recovery time could range from 450 to 900 s). Recovery time between strength test attempts ranged from 2 to 3 min. Participants dried their hands using climbers chalk (magnesium carbonate) before each test. The wooden hold was regularly brushed to provide the same friction conditions for all participants.

2.3. *Measurements*

Participants reported their climbing experience (CEXP) as the time climbing outdoors, and training experience (TEXP) as the time developing specific exercises to improve their climbing ability (indoor climbing, finger hangs, campusing etc.). Both CEXP and TEXP were calculated in days from the number of weekly days of practice and years of experience. BW was measured including the same harness for all participants, their own shoes and minimal clothes (Soehnle, precision 0.1 kg). Height (H) was measured with bare feet (metric tape, precision 0.01 m). Sport level was assessed through the best red-point ascent achieved in the previous 6 months (GRADE). GRADE was converted to the IRCRA scale to enable posterior numerical treatment. Two endurance tests were performed to assess hanging endurance. Edge depth was selected from the results of these tests to perform the hanging ability test. All the tests ended once the contact was lost between the participant and the edge or initial posture was clearly altered (i.e. elbow elevation or back inclination). The description of each test is presented below:

- Endurance test 1. *Maximum hanging time (s) on a 14-mm edge depth (MHT_14).* It consisted of dead hang on a 14-mm edge depth for the maximum possible duration without added weight. We choose a 14-mm depth edge because a previous study reported that it was the most reliable edge depth when compared to other edge depths and performing the same test in different level climbers (López Rivera, 2014).
- Endurance test 2. *Minimum edge depth (mm) in which climbers could hang for 40 s exactly without added weight (MED_40).* To search MED_40 edge depth, we used our observations of a pilot study with 10 elite sport climbers (mean GRADE 8a+/b – French scale). We found that approximately for every 4 s climbers exceeded 40 s on MHT_14, they could make MED_40 on a 1-mm smaller depth edge. If participants hanged 40 s in MHT_14, MED_40 was not performed because that was considered their MED_40 edge. If climbers did not reach 40 s in MHT_14, they performed MED_40 based on prior cited observation. For example, if the value in MHT_14 was 52 or 28 s, the

Table 2. Increments based on participant feelings after each attempt.

Participant feeling after finger hang	Weight increment used
Nearly fell	+3% of previous weight
I could hang for 2 or 3 s more	+6% of previous weight
I could hang for 4 or 5 s more	+10% of previous weight
I had enough margin	+15% of previous weight

MED_40 edge depth was 11 or 17 mm, respectively. Nonetheless, if during the new attempt, the climber performed a time that was not close to 40 s (±4 s), a second attempt was performed adapting the edge depth again. The time limit was standardised to 40 s because no elite climber has performed a finger hang longer than that time in a 6-mm edge in prior research (López Rivera, 2014). Six millimetre was the smallest depth edge that we considered valid to assess hanging ability because below 5.8 mm, this ability seems mostly dependent on the fingertips skin features (Bourne et al., 2011).

- Strength test. Hanging ability in climbing was assessed through a finger strength test, which consisted of the *maximum added weight (kg) to the BW during 5 s on MED_40 (MAW_5)*: The participants performed the first attempt with only their BW on the MED_40 edge. Then, a progressive approximation was made to the target weight based on participant feelings after each attempt (Table 2), using a quickdraw to connect hanging dumbbells to the climbing harness. MAW_5 was ended when climbers reached 5 s hanging. If the participant did not reach the 5 s in an attempt, the test was finished and the final value was calculated taking into account the last increase of weight used and seconds completed in the finger hang. The final value was expressed relative to BW and edge depth as follows:

$$(((\text{Maximum added weight to 5 s in MED\_40} + \text{BW})/\text{BW})/\text{MED\_40}) \times 100$$

2.4. *Statistical analysis*

-All of the variables were described using either mean and SD values or frequencies and percentages. The comparisons between groups were performed using Student's *t*-test, Mann–Whitney's *U* test and chi-squared test, depending on the nature of the variables. The test–retest reliability was assessed using the intra-class correlation coefficient (ICC) – and its 95% CI – with a 58% of the initial sample. ICC was calculated from the following equation: $ICC = MS_S - MS_E/MS_S + (k - 1)MS_E$, where MS_S is the subjects mean square and MS_E is the error mean square, from repeated measures ANOVA, and k is the number of trials – $ICC_{3,1}$ according to the nomenclature of Shrout and Fleiss (1979). We also calculated the standard error of measurement (SEM), as the square root of the mean square error term from the ANOVA, and the minimal difference (MD) needed to be considered real, as follows: $MD = SEM \times 1.96 \times \sqrt{2}$ (Weir, 2005). Cohen's d was used as an effect size (ES) measure. Pearson and partial correlations between all the indicators and sport level were calculated. We used the stepwise method to introduce the indicators (independent variables) into the regression models. Standardised coefficients (beta) were used to assess the individual contribution of the variables in explaining the difficulty level, and the Wald test was used to evaluate its significance. Multiple determination coefficients were calculated to observe the explanatory power of the models, and their significance was assessed by using analysis of variance. The K–S test was used to determine whether the distribution of the residuals met the assumption of normality. Durbin–Watson values were used to rule out autocorrelation problems in the errors. All the performed statistical tests were bilateral (two-tailed), and the significance level was $\alpha < 0.05$. All analyses were performed with IBM SPSS Statistics for Windows, Version 19.0. Armonk, NY: IBM Corp.

3. Results

The characteristics of participants are shown in Table 1. No significant differences were found for anthropometric variables between AG and EG. On the contrary, there were significant differences between groups in sport level and TEXP, favouring EG participants.

As shown in Table 3, the three dead hang variables (MHT_14, MED_40 and MAW_5) showed significant differences between groups, favouring the EG (all $p < 0.001$) with high ESs for all the indicators. Test–retest reliability was high in all cases, both for AG and EG, with MED_40 and MAW_5 showing higher values than MHT_14 in both groups (Table 3).

Pearson's correlations between the indicators (MHT_14, MED_40 and MAW_5) were ≥0.92 ($p < 0.001$) – inverse in the case of MED_40. Table 4 shows the raw relationships and partial correlations between all the indicators and sport level. All the indicators were highly related to the sport level, in both groups. Moreover, partial correlations indicated a significant contribution of each indicator when explaining sport level in the EG but not in the AG.

Table 5 shows the explanatory power of the indicators on sport level by means of regression models. MHT_14 explained a 35% of difficulty level in AG, with an increase of 0.08 IRCRA points for every second increased on the MHT_14. On the other hand, MAW_5 explained a 65% of difficulty level in EG, with an increase of 0.37 IRCRA points for every complete unit increased in MAW_5. An increase in one IRCRA point is equivalent to half an increase in the French scale (i.e. passing from a 7a to a 7a+). (Draper et al., 2015). Finally, MAW_5 showed less error when predicting sport level in EG than MHT_14 did in the AG.

4. Discussion

The major findings of this study were (a) the high associations between all the performed tests and sport level for both groups, (b) the MAW_5 test resulted in a valid and reliable hanging ability indicator for elite climbers, and (c) the MHT_14 test resulted in a valid and reliable hanging ability indicator for advanced climbers.

The current study found high correlations between the maximum finger strength (MFS) test and sustained finger endurance tests measured by dead hangs, which is in line with previous research (López Rivera & González-Badillo, 2012), supporting the importance of finger strength as a climbing performance key factor and suggesting that sustained finger endurance is highly dependent on MFS (Stone et al., 2006). It has been reported that the strongest climbers are able to hang more time on the same edge depth, or the same time on a smaller edge depth than weaker climbers. Because of this, we proposed two finger sustained endurance tests to adjust the edge depth to the finger

Table 3. Descriptive data, reliability of the tests and differences between groups.

		Advanced group					Elite group					
		Mn (SD)	ICC (95% CI)	SEM	MD		Mn (SD)	ICC (95% CI)	SEM	MD	*d*	*p*
MHT_14 (s)	Test	29.68 (12.42)	0.89 (0.60–0.97)	2.94	8.15	Test	52.28 (16.13)	0.91 (0.41–0.99)	4.36	12.08	1.66	<0.001
	Retest	33.63 (10.50)				Retest	53.00 (19.45)					
MED_40 (mm)	Test	18.27 (5.83)	1.00 (1.00–1.00)	<0.01	0.01	Test	11.78 (3.56)	0.99 (0.98–1.00)	0.27	0.22	−1.30	<0.001
	Retest	18.00 (5.51)				Retest	12.43 (4.47)					
MAW_5 (*)	Test	7.78 (2.08)	0.99 (0.98–1.00)	0.14	0.39	Test	12.06 (3.70)	0.99 (0.98–1.00)	0.23	0.19	1.48	<0.001
	Retest	7.81 (1.90)				Retest	11.87 (4.05)					

AG: Advanced group; EG: elite group; ICC: intra-class correlation coefficient; 95% CI: 95% confidence interval of the ICC; SEM: standard error of measurement; MD: minimum difference; *d*: Cohen's *d*; *p*: *p*-value for the t-contrast between groups at test; MHT_14: maximum hanging time on 14 mm edge depth using half-crimp technic; MED_40: minimum edge depth for 40 s hanging with the own body weight using half-crimp technic; MAW_5: maximum added weight relative to body weight during 5 s on MED_40. AG: test (n = 22), retest (n = 16). EG: test (n = 18), retest (n = 7). *(((kg + Bw)/Bw)/mm) × 100. Kg: Kilograms added to body weight; Bw: body weight.

Table 4. Relationships between the indicators and sport level.

	r	95% CI	p	$r_{y3.12}$	p
MHT_14					
AG	0.62	0.27–0.83	0.002	0.28	0.224
EG	0.77	0.47–0.91	<0.001	0.56	0.024
MED_40					
AG	−0.57	−0.80 to −0.20	0.006	0.10	0.669
EG	−0.73	−0.89 to −0.40	<0.001	0.69	0.003
MAW_5					
AG	0.58	0.21 0.80	0.005	0.07	0.779
EG	0.84	0.61 0.94	<0.001	0.79	<0.001

AG: Advanced group (n = 22); EG: elite group (n = 18); MHT_14: maximum hanging time on 14 mm edge depth using half-crimp technic; MED_40: minimum edge depth for 40 s hanging with the own body weight using half-crimp technic; MAW_5: maximum added weight relative to body weight during 5 s on MED_40. r = Pearson's correlation coefficients. $r_{y3.12}$ = Partial correlation (including variables 1,2,3). p = p-value.

Table 5. Explanatory power of the indicators on difficulty level according to the group.

AG (n = 22)	$R_{y.123}$	$R^2_{y.123}$	$f(df_1/df_2)p^a$	Se	DW	p^b
	0.62	0.35	12.21 (1/20) 0.002	1.26	2.21	0.949
			B (95% CI)	Se	Beta	p^c
Intercept			18.53 (17.06–20.01)	0.71		<0.001
MHT_14			0.08 (0.03–0.12)	0.02	0.62	0.002
EG (n = 18)	$R_{y.123}$	$R^2_{y.123}$	$f(df_1/df_2)p^a$	Se	DW	p^b
	0.84	0.69	38.66 (1/16) <0.001	0.91	1.46	0.897
			B (95% CI)	Se	Beta	p^c
Intercept			20.73 (19.14–22.32)	0.75		<0.001
MAW_5			0.37 (0.24–0.50)	0.06	0.84	<0.001

AG: Advanced group; EG: elite group; MHT_14: maximum hanging time on 14 mm edge depth using half-crimp technic; MAW_5: maximum added weight relative to body weight during 5 s on MED_40. $R_{y.123}$: multiple correlation coefficients. $R^2_{y.123}$: adjusted determination coefficient. $f(df_1/df_2)$: f-value and degrees of freedom. Se: Standard error; DW: Durbin–Watson values; B: regression slope; 95% CI: 95% confidence interval; Beta: standardised slope. [a]p-value associated with the f-contrast. [b]p-value associated with Kolmogorov–Smirnov contrast on residuals. [c]p-value associated with the slope t-contrast.

strength level: (a) the MHT_14 test, to get closer to the target edge depth and (b) the MED_40 test, to standardise the edge depth for every climber. Although the endurance tests aim was to adjust the edge depth, all tests (including the strength test) showed a high significant correlation with climbing performance in both groups, evidencing a similar and sufficient capacity to differentiate climbers of different levels. These findings are in agreement with the traditional relationship found between climbing sport level and MFS, especially when the latter is measured relative to BW (Watts, Martin, & Durtschi, 1993). The association between climbing level and MFS tests relative to BW has traditionally shown to be higher when the level of climbers increases (Baláš, MrskoČ, et al., 2014), but due to the small sample size of our study ‐ and therefore the confidence intervals derived from it ‐ we were unable to confirm that the association between the indicator that took into account climbers BW (i.e. MAW_5 test) and climbing level was significantly different between the EGs and AGs.

The high correlations obtained between tests suggest that all of them are showing indirectly the MFS, probably due to the high intensity of the sustained endurance tests (Stone et al., 2006) (near to 70% MFS, based on endurance times performed) (Rohmert, 1960). Nevertheless, the partial correlations obtained between tests in the EG indicated that each one of them provided additional information to the other tests when predicting climbing performance, which did not happen in the AG. This could be due to the smaller edge depth used by the EG, which could have activated more fibres of the FDPs in the MAW_5 test, because (a) the greater arm length between the line of muscle force application and the point of force application on the fingertip (Schweizer & Hudek, 2011) and (b) the maximal intensity of the test. The FDP has been suggested to be the most important muscle in climbing performance (Philippe et al., 2012), as it generates the greatest proportional force in the flexion of the distal phalanx of the fingers (Vigouroux et al., 2006). Since higher sport level climbers usually climb using smaller holds (i.e. their performance depends more on their hanging ability in smaller depth edges) (Amca et al., 2012), it is possible that the higher sport level climbers could have a greater specialisation of the FDP fibres, which would be in agreement with the functional prevalence of large and less fatigable motor units observed in elite climbers (Limonta et al., 2016). In this exploratory study, we assessed hanging ability on 6 mm depth edges or more, so it always depended more on finger strength and less on the skin characteristics aforementioned (Bourne et al., 2011). However, in general, with smaller edge depths, skin characteristics become more important. As EG climbers were assessed on smaller edges, the skin characteristics component seems to be more important in higher sport level climbers. Therefore, a test such as the MAW_5, a MFS-specific test that involves the FDP muscles and also the mentioned skin component, could be the most specific measure to assess the hanging ability of elite climbers. The partial correlations obtained between all tests for AG indicated that none of the carried out tests added more information about climbing performance than the others, so none of them seemed to be more determinant than the others to predict sport level in this group, which could be due to a very similar muscular implication of these tests for the AG. When comparing results between AG and EG, a higher inter-correlation among predictors was found in AG than in EG, and thus, greater uniqueness of the tests was observed in EG. In fact, in EG, all tests added explanatory power in a significant way regarding climbing performance when controlling the others, suggesting that more than one test would be needed to assess strength/endurance and skin properties in this group of climbers.

The regression analysis suggested a greater specific weight of finger strength for higher level climbers, as reflected the 69% of climbing performance explained by the MAW_5 test in EG, which was almost double of the most explanatory test in AG (i.e. the MHT_14 test). This difference could be due to a greater importance of other factors in climbing performance for the AG group, which were not assessed (e.g. technical, tactical and psychological factors) (Magiera et al., 2013). However, the stepwise regression appeared to be redundant for the EG as only one predictor was selected (probably due to the small sample size and limited statistical power). It therefore seems like more than one test would be needed to assess strength/endurance in this group of climbers, as deduced from the partial correlation results presented above. Nevertheless, using the parameters obtained in the regression could be interesting to test the predictive value and external validity of the models in future research using different samples.

Previous research has also found a 70% of climbing performance explained by a finger hang test, although in this case by an endurance test on a 25-mm edge depth (Baláš et al., 2012). A recent exploratory study obtained a better association with climbing performance with a similar test to the latter, compared with other finger power and strength tests (Vereide, Kalland, Solbraa, Andersen, & Saeterbakken, 2016). These results are in agreement with those in our study, as the MHT_14 test was the one that best predicted climbing performance in the AG climbers (i.e. it seems that at lower climbing levels than the elite, specific sustained endurance tests explain more of the sport level than the maximum strength tests). This fact could be due to the minor importance of the maximum FDP muscles recruitment in this group, as the lower sport level climbers usually climb on greater holds than higher sport level climbers.

The MAW_5 test showed more reliability than MHT_14 in both groups, equally to the MED_40 test. The test that showed to be most sensitive to change and therefore demonstrated the worst ICC was MHT_14, probably because it is an endurance test and is not only dependent of recruitment capacity (maximal strength) but also depends on oxidative capacity and the quantity of available glucolitic substratum (Boushel et al., 1998; Kagaya, 1994). Nonetheless, this does not mean that the MED_40 or MAW_5 does not have discriminative power, as seen in Table 3; differences between participants of the different sport level were significant and showed high ESs. These findings agree with results of similar tests (López Rivera & González-Badillo, 2012), although our results are slightly better, possibly due to the edge depth adjustment to the finger strength level.

In regards to the inclusion of both males and females, previous studies have documented sex differences in isometric endurance tests performed to muscle failure (favouring females). However, possible sex differences disappear or are minimised when the intensities are high (i.e. when the work load is relatively high compared with maximum) (Maughan, Harmon, Leiper, Sale, & Delman, 1986). As the work load of the developed tests in the present study was around or above 70% of the maximal muscle strength (obtained from the reached endurance times) (Rohmert, 1960) (MAW_5 would be 100% of maximal isometric strength, MED_40 would be around 74% and MHT_14 would be between 60% and 90%), it seems unlikely that our results would have been influenced by the inclusion of both males and females.

5. Conclusions

To our knowledge, this was the first study to assess the hanging ability by finger hangs on an adjusted edge depth in sport climbers. Based on our results, we can conclude that all finger strength and endurance performed tests are reliable tests for advanced and elite sport climbers. Nevertheless, the test that showed to be most valid to assess hanging ability seems different according to the climbers' level. In this regard, we suggest that the three developed tests could be performed to assess hanging ability in elite sport climbers, because all of them added unique information regarding performance in this group. The MAW_5 test showed to be the most valid test in elite climbers, probably because of a greater selective recruitment of the FDP or a greater specific weight of the skin characteristics component, which could be more important in these elite level climbers, while the MHT_14 or the same test carried out on a greater depth edge could be better to assess hanging ability in advanced sport climbers.

6. Limitations of the study

It should be recognised that this preliminary study was carried out with a limited number of participants of only two different climbing levels. Future research should use a larger sample, recruiting climbers of different climbing levels, more female subjects and more disciplines of climbing, not just sports climbing (i.e. boulderers), in order to generalise the above suggestions. Further, the dependent variable used in correlation and regression analyses had only six levels, which might be misleading, although their distribution by group and also the distribution of the residuals met the assumption of normality.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Jesús Montero-Marin http://orcid.org/0000-0001-5677-1662
Alejandro Gomez-Bruton http://orcid.org/0000-0002-0520-1640
José Antonio Casajús http://orcid.org/0000-0002-7215-6931

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