Journal of Applied Biomechanics, 2011, 27, 40-46

Measuring Lifting Forces in Rock Climbing: Effect of Hold Size and Fingertip Structure

Roger Bourne, Mark Halaki, Benedicte Vanwanseele, and Jillian Clarke

This study investigates the hypothesis that shallow edge lifting force in high-level rock climbers is more strongly related to fingertip soft tissue anatomy than to absolute strength or strength to body mass ratio. Fifteen experienced climbers performed repeated maximal single hand lifting exercises on rectangular sandstone edges of depth 2.8, 4.3, 5.8, 7.3, and 12.5 mm while standing on a force measurement platform. Fingertip soft tissue dimensions were assessed by ultrasound imaging. Shallow edge (2.8 and 4.3 mm) lifting force, in newtons or body mass normalized, was uncorrelated with deep edge (12.5 mm) lifting force ($r < .1$). There was a positive correlation ($r = .65$, $p < .05$) between lifting force in newtons at 2.8 mm edge depth and tip of bone to tip of finger pulp measurement ($r < .37$ at other edge depths). The results confirm the common perception that maximum lifting force on a deep edge ("strength") does not predict maximum force production on very shallow edges. It is suggested that increased fingertip pulp dimension or plasticity may enable increased deformation of the fingertip, increasing the skin to rock contact area on very shallow edges, and thus increase the limit of force production. The study also confirmed previous assumptions of left/right force symmetry in climbers.

Keywords: rock climbing, crimp grip, performance, soft tissue, pulp, force symmetry

Following the rise in popularity of recreational and competition rock climbing over the last two decades there has been a proliferation of literature describing investigations of the determinants of climbing performance (Grant et al. 1996; Sheel 2004; Watts 2004; MacLeod et al. 2007) and injury (Cole 1994; Schoffl et al. 2003; Josephsen et al. 2007; Schoffl and Schoffl 2007; Vigouroux et al. 2008). A specific complex body movement (the "rock-over") can predict general climbing ability level; however, it is not accurate within a specific ability level (Brent et al. 2009). Among climbers of a wide ability range, the most significant determinant of performance appears to be training, rather than any anthropometric factor. However, among elite climbers determinants of performance remain unclear (Sheel 2004; Watts 2004), although performance does correlate significantly with several forearm strength measures (Schweizer and Furrer 2007).

Climbers of similar overall ability (based on maximum red point grade for example) often perceive different personal abilities to perform specific body movements. However, studies relating performance to specific body movements, or specific handgrips, to training or innate anthropometric factors are lacking. The current study specifically investigates the "crimp" grip which is the most common grip used on the sharp-edged shallow holds frequently found on difficult climbs. The crimp grip involves bearing most of the lifting or pulling load on the fingertips, which are typically placed side by side with the fingers touching, the distal interphalangeal (DIP) joints hyperextended, and the proximal interphalangeal (PIP) joints flexed about 90°. The term "closed crimp" is sometimes used to describe the use of the thumb to press on the tip of the index finger to stabilize the grip although the thumb itself does not grip the rock. On downward sloping and rounded edge holds most climbers use the "open hand" grip (DIP and PIP joints flexed about 20°) in preference to the crimp. The open handgrip has been demonstrated to involve lower tendon and pulley loads than the crimp grip (Schweizer 2001; Quaine et al. 2003; Vigouroux et al. 2006; Moor et al. 2009).

Extreme loads applied during crimping sometimes result in finger injuries—most commonly partial or complete tears or avulsions of the A2 or A3 pulleys (Schoffl et al. 2003; Josephsen et al. 2007; Schoffl and Schoffl 2007). Despite the extreme pressures developed (estimated at 1000 kPa (Cole 1994)) major injuries to the skin and pulp of the fingertip are rare—presumably because, most often, lack of friction causes the grip to fail before mechanical failure of the skin or pulp. Although fingertip abrasions and palmar skin flaps are common, these are considered minor injuries by most climbers, as

---

Roger Bourne *(Corresponding Author)* is with Medical Radiation Sciences, Faculty of Health Sciences, University of Sydney, Sydney, Australia. Mark Halaki is with Exercise and Sport Science, Faculty of Health Sciences, University of Sydney, Sydney, Australia. Benedicte Vanwanseele is with Exercise and Sport Science, Faculty of Health Sciences, University of Sydney, Sydney, Australia. Jillian Clarke is with Medical Radiation Sciences, Faculty of Health Sciences, University of Sydney, Sydney, Australia.

they do not prevent climbing for a significant time period compared with tendon and pulley injuries.

In general, small light climbers are perceived to perform relatively better than larger heavier climbers when the most difficult part of a climb involves crimping on very small hand holds where the depth of the hold is smaller than the size of the fingertip. We speculated that in developing pulling force on a shallow edge a large fleshy fingertip, as might be typical of a heavy climber, would tend to deform and roll off the edge, whereas the soft tissue of a small bony finger, as might be typical of a small light climber, would be stabilized by the proximity of rigid bone. Deformation of the fingertip pulp under pressure has been demonstrated (in nonclimbing tasks) to be highly dependent on fingertip shape (Serina et al. 1997); however, there have been no reports of the skin and pulp biomechanics associated with the crimp grip applied to edges of different depth. External examination of climbers' fingers shows a wide range of shapes, but does not reveal the position of the bone relative to the skin surface.

The current study investigates the hypothesis that fingertip pulp dimensions, rather than maximum lifting force ("strength") or body mass normalized lifting force ("strength to mass ratio"), is a significant determinant of a climber's ability to generate force on very small edge holds.

Methods

Subjects

This study was conducted with institutional ethics approval (University of Sydney No. 08–2008/11188) and written informed consent from all subjects. Fifteen subjects (11 male, 4 female) were recruited by word of mouth and advertising in a local indoor climbing gym (Age 36.5 ± 9.4 (mean ± *SD*); Weight 62.7 ± 6.5 kg; Height 174.8 ± 6.8 cm). To ensure similar levels of physiological and anatomical adaptation to the measurement task, and to minimize risk of injury, only experienced regular climbers were recruited. All subjects had been climbing for at least 5 years—regularly in the month previous to the measurement. Each climber completed a questionnaire detailing recent climbing activity, maximum recent climbing difficulty grade, dominant hand, and injury history. Recent maximum difficulty grade attempted ("red point") ranged from Australian 22–31 (Yosemite decimal equivalent: 5.11a–5.14a.) with mean and *SD* 26.8 ± 2.7.

Apparatus

The test apparatus had two major parts: 1) a variable depth rock edge mounted on a rigid horizontal platform above the subject and 2) a force platform with associated measurement electronics on which the subject stood to perform the tests. The rock edge was a square cut sandstone block (Triassic argillaceous quartz. Bulk density: 2.27 tons/m^3. Compressive strength: 57 MPa dry. Dimensions: 300 × 100 × 30 mm. Supplier: Gosford Quarries, Sydney) with texture similar to the rock on which the subjects climbed regularly. The stone block was clamped flat onto the top of a rigid purpose-built shelf 2.3 m above floor level. The depth of the edge to be gripped was adjusted by clamping an appropriate selection of acrylic sheets to the face of a square timber block clamped to the top of the rock (Figure 1). To prevent subjects moving their center of gravity under the shelf and thus "leaning" into the edge to increase friction, a vertical timber sheet was fixed parallel to the wall and directly below the edge. The subject stood on a 500 × 200 × 50 mm wooden block placed with the long edge 200 m farther from the wall than the rock edge above. The subject's body position during measurement was thus similar to a familiar climbing position. A force platform (KIAG SWISS 9261A, Kistler Instrumente AG, Winterthur, Switzerland) was used to measure lifting force. The vertical force signal was recorded at a sample rate of 200 Hz using a 16-channel A-D converter (MP150, Biopac Systems Inc, Santa Barbara CA, USA) and AcqKnowledge software (Version 3.7.3 Biopac Systems Inc, Santa Barbara, CA, USA). We did not test two hands simultaneously pulling on the same edge for several reasons: 1) this body position is relatively uncommon in climbing; 2) a two hand grip would increase the possibility of soft tissue injury as many subjects would be likely to lift their full body weight and thus be in a relatively unstable hanging position; 3) lifting of full body weight would preclude maximum force measurement; 4) the single hand test permits investigation of left/right force symmetry and doubles the number of force measurements available for analysis.

Measurement Protocol

Measurements were performed in an air-conditioned room at 25 °C and approximately 65% relative humidity. Each subject warmed up for ten minutes using a rubber squeeze ring and performing chin-ups on a climbers' hang board. To ensure all subjects had a similar arm position during measurement, wood blocks were added to the platform so that the subject's wrist crease was at the same level as the rock edge when one arm was extended fully above the head. The subject stood on the platform with body centerline directly below the edge to be gripped (Figure 1). The subject was asked to pull down, using a crimp grip, with the maximum effort he or she would be prepared to use in a climbing environment. There was no restriction placed on use of a "closed crimp" (thumb wrapped over the top of index finger). No subject used the thumb as an additional finger on the hold and there was no opposing surface available for the thumb to be used in a "pinch" grip. Lifting force was calculated as the difference between the force measured while the subject was standing relaxed and while pulling down on the edge.

Figure 2 summarizes the structure of the experimental design. All lifting forces were measured separately for the left and right hands using edge depths of 7.3, 5.8, 4.3 and 2.8 mm in a random order, and with a rest of 1–2 min during changes of edge depth. Each subject completed this protocol two times with approximately 30 min of rest

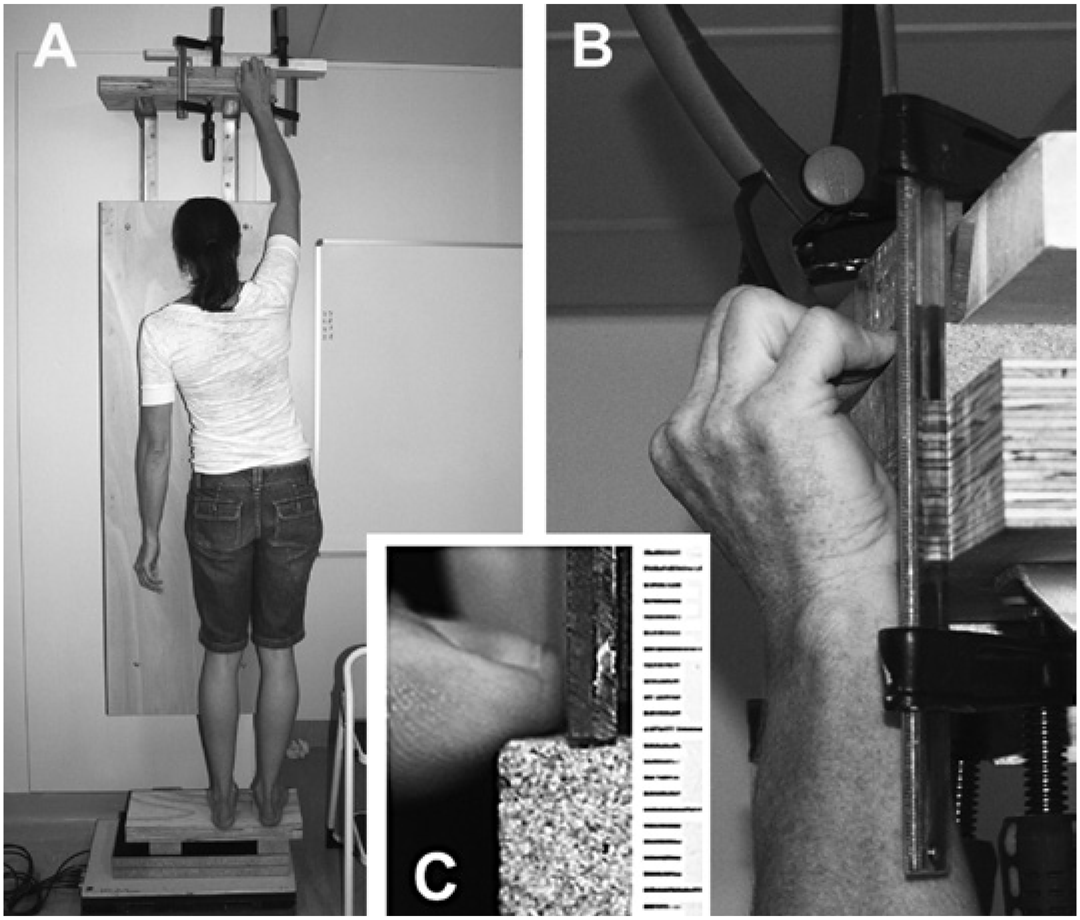

Figure 1 — Adjustable depth rock edge apparatus. A square cut sandstone tile is clamped to a rigid horizontal shelf mounted 2.3 m above floor level. The depth of the edge to be gripped can be varied from 12.5 to 2.8 mm by clamping a series of acrylic sheets to the wood block on top of the sandstone tile. A timber "stand off" sheet is fixed below the shelf to prevent the subject leaning under the shelf. A) Subject standing on the force platform and holding the rock edge in the measurement position. B) Typical crimp grip hand position during maximum force measurement. C) Illustration of typical deformation of a fingertip when crimping the 4.3 mm deep edge. Some clamps have been removed for clarity in images B and C (scale in mm).

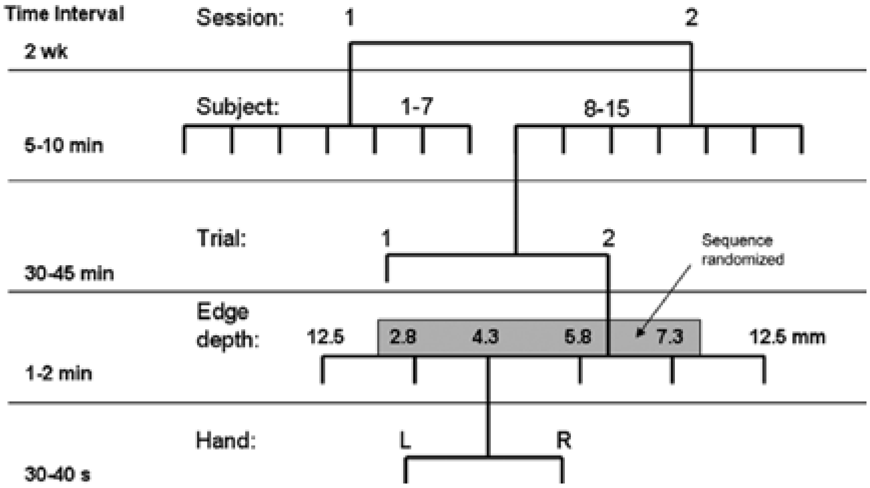

Figure 2 — Summary of experimental structure. Number of force measurements = 15 × 2 × 6 × 2 = 360.

between the two groups of measurements. Subjects were permitted to use chalk as desired and to brush the rock with a toothbrush, as is common practice in climbing.

Maximum single arm lifting force using the crimp grip was measured with the edge depth adjusted to 12.5 mm immediately before and after each of the above two measurement trials. This depth was chosen, as it was comfortable for subjects to apply maximum force in the crimp position.

Ultrasound

Ultrasound images of un-deformed fingertips were acquired with the subject's hand immersed in a water bath at room temperature. To avoid any possible softening of the skin due to immersion in the water bath subjects were scanned either 30 min before the force measurement session or after. Images were acquired with an ATL HDI 5000 ultrasound scanner (Phillips Medical Systems, Australia). A 5–10 MHz, 38 mm linear array transducer was used to obtain real time images. A typical sagittal fingertip image is shown in Figure 3. Still images were captured for the index, middle, and ring fingers of each subject's dominant hand. Images of the nondominant hand were also obtained for two subjects and confirmed absence of significant left/right asymmetry in pulp dimensions. Anatomical measurements were obtained from paper prints of the images and referenced to the scale markers on each image.

Fingertip Pressure

Skin contact area for one subject was estimated by painting the subject's fingertips with a whiteboard marker before the subject applied a maximum force crimp grip at each of the edge depths. Contact area was measured from a photograph of the deposited area of color marker on the rock surface. Soft tissue compressive force was calculated by dividing maximum lifting force (separate measurement for same subject) by contact area.

Statistical Analysis

A 3-factor repeated-measures ANOVA was conducted in STATISTICA (StatSoft Pacific, Melbourne) to compare the dominant and nondominant sides, the two trials for each subject, and edge depth. Pearson's correlation was used to investigate the relationships between the variables with correlation strengths defined as "Weak" for $0.1 < r < .3$, "Medium" $0.3 < r < .5$ and "Strong" $0.5 < r < 1.0$ (Cohen 1988). Only strong correlations ($r > .5$) are discussed in this paper.

Results

Fingertip Structure

Fingertip anatomy as measured by ultrasound (Figure 3) is summarized for the 15 subjects in Table 1. Climbers with large bone-to-tip pulp measurement also had large palmar pulp measurements ($r = .57, p < .05$). Body weight correlated with palmar pulp ($r = .54$, $p < .05$), but not with tip pulp ($r = -.02$). The smallest bone-to-fingertip pulp measurement was found in the sixth heaviest subject (66.5 kg, male).

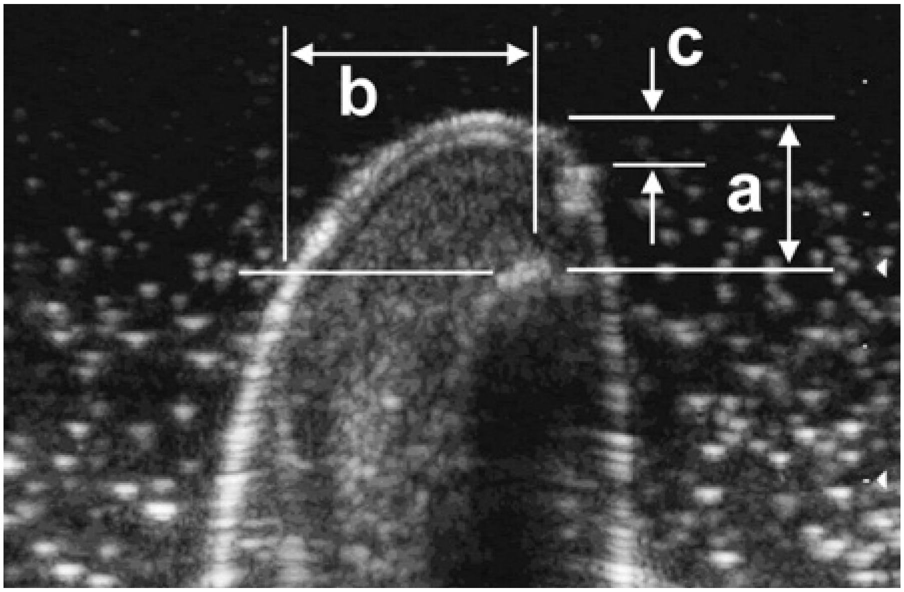

Figure 3 — Typical sagittal ultrasound image of a subject's middle fingertip. Measurements of pulp as indicated. a) Tip of distal phalanx to skin surface at tip of digit. b) Tip of distal phalanx to tip of palmar skin surface of digit. c) Tip of nail to skin surface at tip of digit.

Table 1 Summary of fingertip pulp measurements

	Min	Max	*M*	*SD*
Pulp (bone to tip),[1] mm	4.0	6.3	5.1	0.6
Pulp (bone to palm),[2] mm	7.3	10.8	8.8	1.0
Pulp (nail to tip),[3] mm	0.7	4.6	1.9	1.1

[1] Tip of distal phalanx to skin surface at tip of digit.

[2] Tip of distal phalanx to palmar skin surface of digit.

[3] All subjects had very short nails, as is typical of regular climbers.

Reliability of the Force Measurements

The measurement protocol required subjects to perform a maximal volitional effort that involved a significant level of discomfort. Although this situation is familiar to experienced rock climbers, there is potential for fatigue and psychological factors to cause variability of repeated measurements in identical test conditions. There was no significant difference between the two tests ($F_{(1,14)} < 3.47$, $p > .08$). Furthermore, there was no significant difference between the dominant and nondominant hands ($F_{(1,14)} < .95$, $p > .35$). On the basis of these two observations we used the greater force produced by the dominant hand over the two test measurements for all further analysis.

Correlation of Shallow Edge Lifting Force With Maximum (12.5 mm Edge) Lifting Force

Figure 4 illustrates the mean, standard deviation, and range of lifting forces measured at the five different edge depths. Figure 5 shows the same force data normalized to subject body mass. As expected the lifting force decreased with edge depth ($F_{(4,56)} = 163.6$, $p < .001$). Only the lifting forces measured at 7.3 and 5.8 mm edge depth were correlated with the maximum lifting force (12.5 mm) ($r = .68$, $p < .05$). The lifting forces at 4.3 and 2.8 mm edge depth were not correlated with the maximum lifting force, nor the lifting force at 7.3 or 5.8 mm ($r < .2$), but were correlated with each other ($r = .61$, $p < .05$).

The calculated fingertip compressive stress developed by one subject in this study (based on the measurements of contact area) was 1340, 884, 800, 724, and 616 kPa on the 2.8, 4.3, 5.8, 7.3, and 12.5 mm edges respectively.

Correlation of Force With Anthropometric Measurements and Climbing Performance

Climbers with large bone-to-tip pulp measurement tended to generate a higher lifting force in newtons on the 2.8 mm deep edge ($r = .65$, $p < .05$). Lifting force in newtons produced on the 2.8 mm deep edge also correlated with subject height ($r = .71$, $p < .05$) and reach ($r = .81$, $p <$

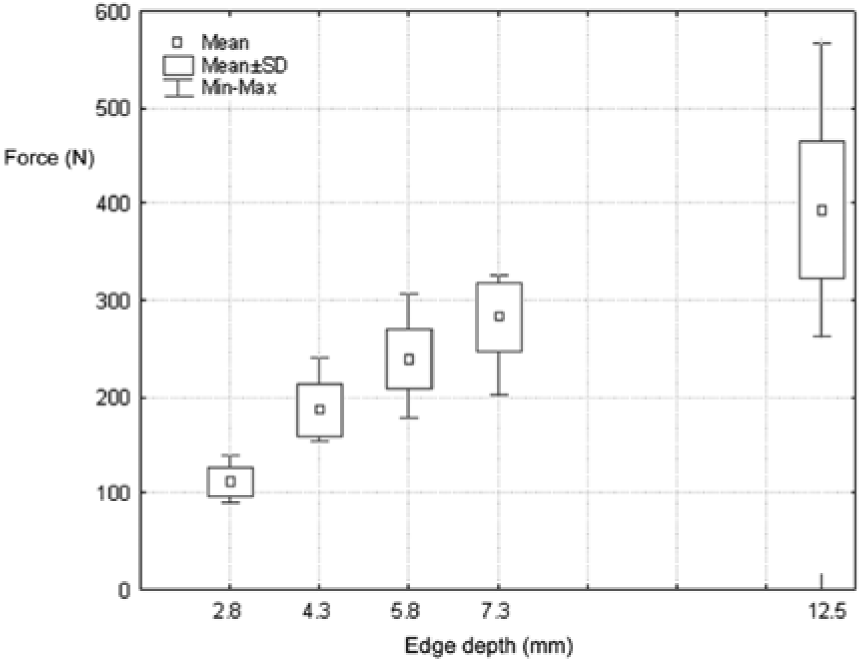

Figure 4 — Mean, standard deviation, and range of lifting force (all 15 subjects) versus edge depth.

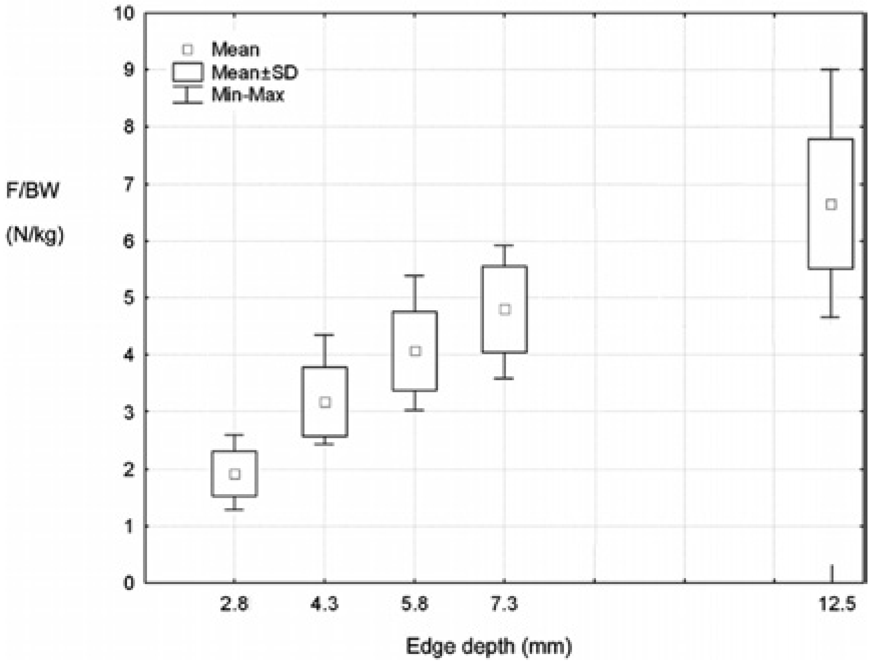

Figure 5 — Mean, standard deviation, and range of body mass–normalized lifting force (all 15 subjects) versus edge depth.

.05). There was no correlation with subject height or reach at edge depths larger than 2.8 mm.

Maximum climbing grade correlated with body mass–normalized lifting force on the 7.3 mm (r = .71, p < .05) and 5.8 mm deep edges (r = .57, p < .05). The correlation was weaker at all other edge depths ($r_{(12.5\text{ mm})}$ = .45; $r_{(4.3\text{ mm})}$ = .42; $r_{(2.8\text{ mm})}$ = .27).

Discussion

This is the first reported study of lifting forces generated on shallow edge holds when using the crimp grip, and also the first report of dominant/nondominant arm strength symmetry in climbers. The study is particularly relevant to climbers because the measurement task used has a strong biomechanical similarity to a real climbing situation. The observed good symmetry of dominant/nondominant hand lifting force, although an unsurprising finding in experienced rock climbers, adds quantitative support to previous assumptions of such symmetry (Watts 2004; Schweizer and Furrer 2007).

The lifting force in newtons generated on the shallowest edges (2.8 and 4.3 mm) could not be predicted by maximum lifting force (12.5 mm edge), even after body mass normalization. This finding provides objective support to the common perception among climbers that maximum strength is a poor predictor of performance on climbs where the major difficulty involves extreme crimping on shallow edges.

Our original hypothesis was that climbers with a relatively small volume of fingertip pulp would be able to generate greater lifting force on a shallow edge hold than climbers with a larger volume of pulp due to the expected ability to form a more stable interface between the fingertip and the rock. The finding of strong positive correlation between bone-to-tip pulp dimension and lifting force on the shallowest (2.8 mm) edge suggests the opposite. A possible biomechanical explanation is that a larger volume of pulp permits greater deformation of the fingertip and thus increases the skin to rock contact area resulting in increases in the moment arms of the lifting forces applied by the fingers. This would imply that skin to rock friction and/or soft tissue stress are significant limiting factors in the development of lifting force. If this is the case, then the normal adaptive toughening of fingertip skin due to regular intense climbing may be counterproductive in force production on small edges. Similarly, the perceived performance superiority of women when climbing on small edges may be the result of generally softer and thinner skin (Fruhstorfer et al. 2000). Both these possibilities could be tested in future studies with appropriate equipment. Skin elasticity could be measured as described by Dawes-Higgs et al. (Dawes-Higgs et al. 2004). Adequately precise skin thickness measurements would require a higher resolution ultrasound scanner that that used in our study.

It is noteworthy that although over 360 force measurements were conducted in our study no subject's fingers ever slipped off the test edge. At the same time, there was a remarkable lack of variation in maximum force produced in two separate trials and between the dominant and nondominant hands. It can be concluded that experienced climbers have a well developed tactile sense of the point of slippage or loss of stable contact between fingertips and rock. This sense is most likely related to perception of pressure and shear forces in the fingertips, and microscopic lateral movements of the skin across the rock.

The magnitude of the calculated fingertip pressure stress (1340–616 kPa depending on edge depth. Estimated for one subject only as this measurement was added post data collection and the other subjects were not available for testing) is in agreement with a previous estimate of 1000 kPa (Cole 1994). The wide range of stress across different edge depths suggests that soft tissue pressure stress is not the feedback signal that limits maximum effort. As edge depth decreases the contribution of shear force relative to compression, and consequently the importance of skin friction, would be expected to increase. The decrease in lifting force with decrease of edge depth is consistent with shear and consequent microscopic skin slippage being a major feedback signal that limits effort.

In our study subjects were constrained to a tripedal stance and we measured only the vertical force developed by a single hand. Quaine et al. (1997) demonstrated that the transition from a quadrupedal to a tripedal posture (following removal of one hand from a hold) resulted in a significant change in the contact (lateral or nonvertical) force on the remaining hand. Our experiment differs significantly from that of Quaine et al. in that our subjects stood on a 200 mm wide ledge rather than 15 mm wide foot holds vertically below the handholds. Our subjects could thus stand in balance on the ledge without any need for hand contact to maintain balance but sufficiently close to the vertical plane of the handhold to preclude the application of significant lateral force. The static tripedal stance is typical of the position a climber must maintain when moving one hand between holds.

It should be noted that the findings of this study cannot be expected to describe lifting force production in all climbers or nonclimbers. We selected experienced subjects that regularly climbed at high difficulty levels on rough sandstone. This group of climbers would be expected to have developed many structural anatomical adaptations to fingertip stress that may not be found in the wider population of climbers and nonclimbers. However, within the group of subjects tested it can reasonably be assumed that levels of soft tissue adaptation were similar and that the observed differences in lifting forces generated were probably attributable to strength and anthropometric features rather than soft tissue adaptation.

An unexpected finding of this study is the positive correlation between lifting force in newtons on the smallest edge and subject height and reach. If this result were simply the result of a mechanical lever advantage (due to arm length and consequently greater flexion of the elbow joint when holding the edge in the crimp position), then the correlation would be expected to be apparent at all edge depths. Further research is required to clarify this relationship.

Acknowledgments

The authors wish to thank Robert Bell for construction of the test apparatus and Jack Bellamy for assistance with measurements.

References

Brent, S., et al. (2009). Development of a performance assessment tool for rock climbers. *European Journal of Sport Science, 9,* 159–167.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. New York: Academic Press.

Cole, A.T. (1994). Finger tip injuries in rock climbers. *British Journal of Sports Medicine, 24,* 14.

Dawes-Higgs, E., et al. (2004). Accuracy and reliability of a dynamic biomechanical skin measurement probe for the analysis of stiffness and viscoelasticity. *Physiological Measurement, 25,* 97–105.

Fruhstorfer, H., et al. (2000). Thickness of the stratum corneum of the volar fingertips. *Clinical Anatomy (New York, N.Y.), 13,* 429–433.

Grant, S., et al. (1996). Anthropometric, strength, endurance and flexibility characteristics of elite and recreational climbers. *Journal of Sports Sciences, 14,* 301–309.

Josephsen, G., et al. (2007). Injuries in bouldering: A prospective study. *Wilderness & Environmental Medicine, 18,* 271–280.

MacLeod, D., et al. (2007). Physiological determinants of climbing-specific finger endurance and sport rock climbing performance. *Journal of Sports Sciences, 25,* 1433–1443.

Moor, B.K., et al. (2009). Friction between finger flexor tendons and the pulley system in the crimp grip position. *Clinical Biomechanics (Bristol, Avon), 24,* 20–25.

Quaine, F., et al. (2003). Effect of simulated rock climbing finger postures on force sharing among the fingers. *Clinical Biomechanics (Bristol, Avon), 18,* 385–388.

Schoffl, V., et al. (2003). Pulley injuries in rock climbers. *Wilderness & Environmental Medicine, 14,* 94–100.

Schoffl, V.R., & Schoffl, I. (2007). Finger pain in rock climbers: reaching the right differential diagnosis and therapy. *Journal of Sports, Medicine, and Physical Fitness, 47,* 70–78.

Schweizer, A. (2001). Biomechanical properties of the crimp grip position in rock climbers. *Journal of Biomechanics, 34,* 217–223.

Schweizer, A., & Furrer, M. (2007). Correlation of forearm strength and sport climbing performance. *Isokinetics and Exercise Science, 15,* 211–216.

Serina, E.R., et al. (1997). Force response of the fingertip pulp to repeated compression—Effects of loading rate, loading angle and anthropometry. *Journal of Biomechanics, 30,* 1035–1040.

Sheel, A.W. (2004). Physiology of sport rock climbing. *British Journal of Sports Medicine, 38,* 355–359.

Vigouroux, L., et al. (2006). Estimation of finger muscle tendon tensions and pulley forces during specific sport-climbing grip techniques. *Journal of Biomechanics, 39,* 2583–2592.

Vigouroux, L., et al. (2008). Middle and ring fingers are more exposed to pulley rupture than index and little during sport-climbing: A biomechanical explanation. *Clinical Biomechanics (Bristol, Avon), 23,* 562–570.

Watts, P. (2004). Physiology of difficult rock climbing. *European Journal of Applied Physiology, 91,* 361–372.