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Physiological determinants of climbing-specific finger endurance and sport rock climbing performance

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Abstract

The aim of the study was to examine several physiological responses to a climbing-specific task to identify determinants of endurance in sport rock climbing. Finger strength and endurance of intermediate rock climbers ($n = 11$) and non-climbers ($n = 9$) were compared using climbing-specific apparatus. After maximum voluntary contraction (MVC) trials, two isometric endurance tests were performed at 40% ($s = 2.5\%$) MVC until volitional exhaustion (continuous contractions and intermittent contractions of 10 s, with 3 s rest between contractions). Changes in muscle blood oxygenation and muscle blood volume were recorded in the flexor digitorum superficialis using near infra-red spectroscopy. Statistical significance was set at $P < 0.05$. Climbers had a higher mean MVC (climbers: 485 N, $s = 65$; non-climbers 375 N, $s = 91$) ($P = 0.009$). The group mean endurance test times were similar. The force–time integral, used as a measure of climbing-specific endurance, was greater for climbers in the intermittent test (climbers: 51,769 N · s, $s = 12{,}229$; non-climbers: 35,325 N · s, $s = 9724$) but not in the continuous test (climbers: 21,043 N · s, $s = 4474$; non-climbers: 15,816 N · s, $s = 6263$). Recovery of forearm oxygenation during rest phases (intermittent test) explained 41.1% of the variability in the force–time integral. Change in total haemoglobin was significantly greater in non-climbers (continuous test) than climbers ($P = 0.023$ – 40% test timepoint, $P = 0.014$ – 60% test timepoint). Pressor responses were similar between groups and not related to the force–time integral for either test. We conclude that muscle re-oxygenation during rest phases is a predictor of endurance performance.

Keywords: *Forearm endurance, isometric exercise, muscle oxygenation, pressor response, rock climbing*

Introduction

Rock climbing has developed into a mainstream competitive sport (Oviglia, 2006). This growth is evidenced by the rapid increase in the number and size of indoor climbing walls, and recorded climbs in the various disciplines of climbing. The focus of the new disciplines of sport climbing and bouldering are the gymnastic, athletic, and competitive aspects of climbing and movement on rock (Jones, 1991).

The standard of climbing of the world's leading athletes has risen steadily in the past few decades as new training methods and improved facilities have been developed (Goddard & Neumann, 1993) such that the basic biomechanical demands of elite rock climbing have changed and continue to do so. Today's hardest climbs feature angles up to and greater than 45° beyond vertical (Goddard & Neumann, 1993). On such overhanging terrain, the legs cannot support much of the body mass in the vertical direction; they can only push the body along the plane of the overhanging surface. As the angle increases, the forces exerted increasingly shift to the smaller muscles of the upper limbs. Noé, Quiane, and Martin (2001) observed an increased reliance on upper limb support from 43% to 62% of total body weight when the wall angle was changed from vertical to 10° overhanging. Climbers have recognized that finger strength is a central component of climbing performance and this is the focus of rock climbers' training regimes (Goddard & Neumann, 1993; Hurni, 2003; Jones, 1991; Morstad, 2000; Sagar, 2001).

In climbing, the fingers produce tension on a hold to support a proportion of the body weight. The isometric contraction of the finger flexors of each hand is interrupted intermittently when reaching towards the next hold. Some studies have suggested

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that finger strength is a determinant of performance (Bollen & Cutts, 1993; Grant, Hynes, Whitaker, & Aitchison, 1996). However, differences in methods between studies have resulted in conflicting conclusions (Watts, Newbury, & Sulentic, 1996).

Bouts of sport climbing last for several minutes with sustained periods of intermittent isometric contraction in the finger flexors (Schadle-Schardt, 1998). Studies have demonstrated increased finger endurance in trained climbers (Ferguson & Brown, 1997) and forearm fatigue is associated with falls in climbing and is identified by climbers as a key performance variable. Watts and Drobish (1998) demonstrated that lactate production is related to climbing angle. This finding is supported by Mermier, Robergs, McMinn, and Heward (1997), who observed that lactate production is related to climbing difficulty. Several physiological variables could influence endurance performance during intermittent isometric actions. Increasing central arterial blood pressure has been shown to improve force production during isometric hand contraction (Wright, McCloskey, & Fitzpatrick, 2000). We hypothesized that a greater pressor response during a climbing-specific finger endurance task would improve endurance performance. Other adaptations promoting increased intramuscular blood flow both during contractions and relaxations (while reaching to the next hold) could also be important determinants of performance (Ferguson & Brown, 1997). Enhanced blood flow might result from an increased capillary density, enlargement of capillary cross-sectional area or modifications in dilator function related to endothelial change (Delp, 1995; Sinoway, Mutch, Minotti, & Zelis, 1986; Smolander, 1994; Snell, Martin, Buckey, & Blomqvist, 1987).

Despite the fact that the flexors of the fingers are perceived to have an important role in climbing performance, there is very little information on the finger flexor endurance of climbers in the literature and it appears that no studies have investigated forearm oxygenation in trained climbers during a climbing-specific finger endurance task. We hypothesized that forearm adaptations in climbers distinguish them from non-climbing controls. We predicted that regular participation or training in rock climbing would result in increased finger flexor strength and forearm oxygenation and that these adaptations would promote better performance in a climbing-specific endurance test. It is acknowledged that while differences between trained climbers and non-climbing controls might be attributed to training adaptations, there is the possibility that any differences could have a genetic component.

The aim of this study was to examine several physiological responses to a climbing-specific task to identify adaptations of trained climbers and determinants of endurance performance.

Methods

Participants

Twenty males (mean age 22.5 years, $s = 2.6$) participated in the study, of whom 11 were intermediate rock climbers and 9 were non-hand-trained healthy controls. The researchers tried to recruit participants of similar age and body size. The climbers' self-rated ability (best "on-sight" climbing grade) ranged from F6c to F7c (mean 7a+) on the French scale. On-sight is a term used to describe an ascent of a route at the first attempt with no rests or falls. The climbers (mean age 23.2 years, $s = 3.2$) had a mean climbing experience of 5.3 years ($s = 1.9$). The non-climbers (mean age 21.6 years, $s = 1.3$ years) did not participate in any activities requiring finger or hand strength. The climbers were involved in regular climbing or climbing-specific training activities. The study was approved by the University of Glasgow ethics committee for non-clinical research involving humans. All participants provided informed consent before testing and completed a health and physical activity questionnaire before each test session.

Design

The participants undertook three test sessions at least 48 hours apart to ensure adequate recovery. All three sessions were performed at the same time of day (± 1 hour) to limit variations in performance due to diurnal patterns and were completed for each participant within a 3-week period to avoid variations in performance due to training effects. At the first session, after habituation, the participants performed maximal voluntary contraction (MVC) trials and two isometric endurance tests (see below). On the second visit, additional MVC tests and one of the endurance tests were performed. At the third session, the participants performed one endurance test. The participants were asked not to drink alcohol the night before testing and to abstain from eating in the hour preceding testing. They were also asked not to train heavily the day before testing.

Climbing-specific apparatus and positioning of the participant

Finger strength and endurance were measured using apparatus developed at the University of Glasgow (Grant *et al.*, 1996) (Figure 1A). It was designed to be rock climbing specific, simulating as closely as possible the mechanical conditions experienced on a

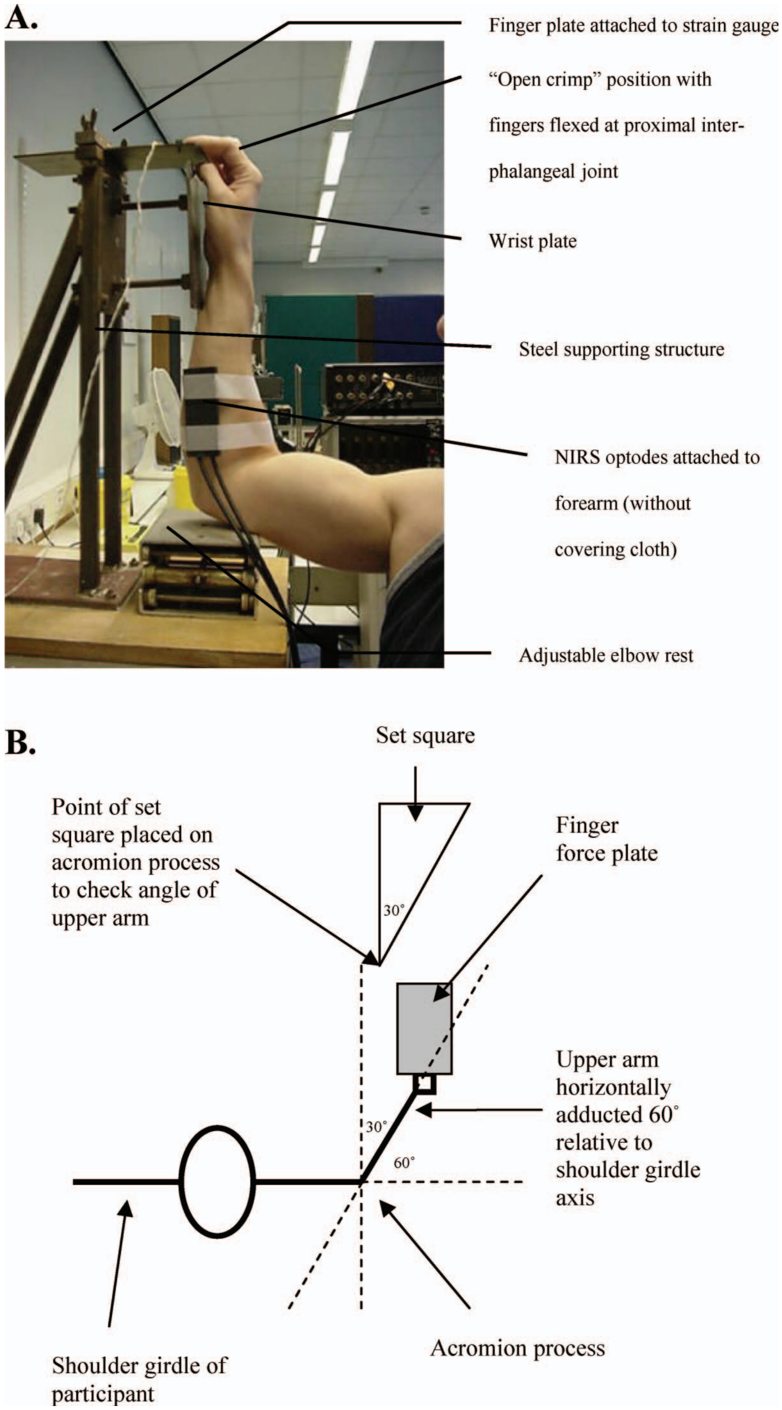

Figure 1. Test apparatus. (A) Finger testing apparatus and arm positioning. (B) Schematic representation of positioning of the participant (transverse plane).

rock face. Force produced from the fingers is determined by the extent of distortion in the finger plate. The plate is attached to a strain gauge (581 DNH Peekel, Rotterdam, Netherlands) and computer via a strain gauge bridge, amplifier, and analog-to-digital converter. The apparatus was calibrated before each test session. During the endurance tests, the participants were given feedback about the force produced and the timing of contractions by a computer monitor and audio speakers. Software was written so that an audio cue "load" or "rest" was given when the contraction time began or ended. "Traffic lights" and a bar display on the monitor assisted the participants to maintain the correct force, showing green for correct force, blue for excessive force, and red for too little force.

The fingers of the right hand were positioned on the plate ensuring maximum contact with the plate surface. The amount of space available for the fingers was limited by a metal "stop" on the plate surface. The participants were instructed to use an "open crimp" position (Goddard & Neumann, 1993) with the fingers flexed at the proximal inter-phalangeal joint. Chalk (magnesium carbonate) was used to promote optimum grip on the plate. The thumb was not allowed to make contact with the plate. The participant's right elbow rested on an adjustable plate to minimize the contribution of the proximal arm, shoulder, and back muscles in pulling during the tests.

The participants were positioned so that the upper arm and forearm formed a 90° angle, and the inferior aspect of the acromion process and the antecubital fossa were level. This was achieved by adjusting the height of the apparatus platform as described in Grant *et al.* (2003). The upper arm was adducted horizontally by 60° relative to the shoulder girdle (transverse plane) for optimum specificity for climbing and comfort (Quaine, Martin, & Blanchi, 1997). The point of a set square was placed on the acromion process. The long side of the set square opposite the hypotenuse was set parallel with the base of the force plate apparatus at right angles to the shoulder girdle. The hypotenuse edge of the set square was placed horizontally from the acromion process and the participant's forearm was pushed against the hypotenuse edge to establish the desired position (Figure 1B).

Habituation and warm-up

Before MVC measurements (visit 1), the participants were asked to perform three sub-maximal contractions of 5 s each on the plate with 30 s rest between contractions and 2 min rest before proceeding to MVC measurement. After MVC measurement, the participants were accustomed to the endurance test protocol. Habituation test A consisted of two contractions at 40% of MVC lasting 10 s, with 1 min rest between contractions. Habituation test B consisted of one trial of six contraction/relaxation cycles (10 s contraction, 3 s relaxation). This habituation procedure was repeated as a warm-up at visits 2 and 3.

Test procedure

During visit 1, all participants performed eight MVC attempts with 1 min rest between attempts. Note that 5 min rest was allowed after the third and sixth attempts to prevent accumulation of fatigue. Strong verbal encouragement was given to all participants to optimize the MVC scores (McNair, Depledge, Brettkelly, & Stanley, 1995). If the final attempt produced the highest score, another measurement was taken to ensure a representative value was obtained. On visit 2, the participants undertook another four MVC attempts in an effort to ensure the maximum value attained on visit 1 was representative of the participant's true maximum. Any value higher than that recorded in the first visit was recorded as MVC.

The participants performed the two endurance tests on visits 2 and 3, in randomized order. The endurance contractions were performed at 40% of MVC. The bar on the monitor display flashed red when the force fell 2.5% below this. Each test was ended automatically by the computer when the bar flashed red for longer than 1 s. Verbal encouragement was provided to all participants. In the continuous test, the participants maintained a continuous isometric contraction on the plate at 40% ($s = 2.5\%$) until volitional exhaustion. In the intermittent test, the participants maintained a cycle of continuous isometric contractions at 40% ($s = 2.5\%$) for 10 s, followed by 3-s rest periods until volitional exhaustion. This test was designed to mimic the contraction/relaxation periods identified by Schadle-Schardt (1998) as being typical contraction/relaxation ratios used in sport climbing.

Anthropometry

Body mass was measured using scales (Avery Beam Balance, Birmingham, UK). Stature was measured using a stadiometer (Holtain Ltd, Crymych, UK). Percentage body fat was predicted by taking four skinfold measurements (Holtain skinfold limiting calliper) using the method of Durnin and Womersly (1974). All skinfold measurements were taken from the right side of the body and by the same researcher. Forearm circumference was measured to the nearest 0.5 cm using a measuring tape (Dean, London, UK). Measurements were taken from the widest point of the forearm, near the proximal end.

Blood pressure

Blood pressure measurements were taken using an electronic blood pressure cuff (Colin BP-88/BP-88C Patient Monitor), positioned on the participant's left (resting) arm. All measurements were taken with the participant in the test position to avoid any variations due to body position (Webster, Newham, Petrie, & Lovell, 1984). Resting blood pressure was measured three times at 1-min intervals after 3 min of quiet rest. The third measurement was used as the resting value. The blood pressure apparatus varied in cycling time depending on the participant's blood pressure at the time of cuff inflation. If the participant's blood pressure was high, the cuff took longer to inflate. The machine was cycled continuously until cessation of the test. The last value obtained during the test was used in the analyses. The timing of measurement of this value varied due to differences in blood pressure between participants and length of the test.

Near infra-red spectroscopy

Changes in muscle blood volume and oxygenation were recorded in the flexor digitorum superficialis of the test forearm using near infra-red spectroscopy (NIRS) (NIRO-500 Hamamatsu Photonics K.K., Japan). The flexor digitorum superficialis (FDS) flexes the fingers at the proximal inter-phalangeal joint and was considered the most suitable muscle in which to monitor haematological changes due to simulated climbing. The NIRS optodes were placed 4 cm apart on the anterior forearm surface, over the belly of the flexor digitorum superficialis. The flexor digitorum superficialis was located by palpation and correct placement of the optodes was confirmed by observing the selective response of muscle blood oxygenation and volume to FDS activation. The optodes were positioned and warmed up according to the manufacturer's instructions. The NIRO-500 measures changes in muscle blood oxygenation and volume in the portion of the muscle between the optodes in μM relative to the resting value at the start of the test. Muscle blood oxygenation and volume were sampled at 2 Hz and changes in chromophore concentrations were calculated using software (ON-MAIN Hamamatsu Photonics). All participants had a generally low percentage body fat (mean 13%, $s = 4$). Therefore, we assumed that subcutaneous adipose tissue thickness did not affect the penetration of the infra-red light.

Statistical analysis

Differences between the group means were determined using two-sample *t*-tests with statistical significance set at $P < 0.05$. Data for both groups of participants were pooled to examine physiological responses to the test procedures. The software used was Minitab version 13 by Minitab Inc., PA, USA. Linear regression was used to analyse the relationship of these responses to finger endurance, as measured by the force – time integral from the endurance tests (0.4 * MVC * test time). The force – time integral was chosen as a measure of "climbing-specific" endurance rather than test time alone, as it combines relevant variables and thus provides a representative value. The absolute force produced by the finger flexors and the duration of the climbing bout are both likely to affect the muscular effort expended. If the participant has an advantage in any of these variables, it is likely that endurance capacity will be increased.

Results

The climbers had greater absolute MVC, despite having a lower body mass (Table I). Linear regression revealed a relationship between MVC and climbing performance (climbing grade). MVC explained 49.9% of the variability ($r = 0.706$) in the climbers' climbing grade. Group mean endurance test times were similar. There was a group difference in force–time integral in the intermittent test ($P = 0.001$) (Table I). Multiple regression revealed no relationship between the climbers' force – time integral (both tests) and climbing performance.

Blood pressure

Group mean systolic and diastolic blood pressure increased during the endurance tests (pressor response) ($P = 0.001$), although there were no differences in group mean blood pressure responses (Figure 2). Linear regression was used to analyse the relationship of pressor response and the force – time integral for both tests (pooled data from both

Table I. Anthropometric characteristics, strength and endurance scores for climbers and non-climbers (mean $\pm s$).

Characteristic	Climbers ($n = 11$)	Non-climbers ($n = 9$)	95% CI for difference in group mean
Stature (cm)	175.5 ± 6.7	179.9 ± 5.3	(−1.3, 10.1)
Body mass (kg)	66.4 ± 6.8	75.5 ± 6.3	(2.9, 15.3)*
Percentage body fat	11.3 ± 3.6	14.9 ± 3.0	(0.2, 7.0)*
Forearm circumference (cm)	27.8 ± 1.0	27.6 ± 1.6	(−1.5, 1.2)
Forearm circumference ($cm \cdot kg^{-1}$)	0.4 ± 0.0	0.37 ± 0.0	(0.1, 0.0)*
MVC (N)	485 ± 65	375 ± 91	(187, 32)*
MVC/body mass ($N \cdot kg^{-1}$)	7.4 ± 1.2	5.0 ± 1.2	(3.6, 1.2)*
Intermittent test time (s)	277.7 ± 83.0	251.6 ± 107.2	(−120.6, 68.4)
Continuous test time (s)	110.5 ± 28.1	105.3 ± 29.4	(−33.9, 23.6)
Force – time integral (intermittent test) ($N \cdot s$)	51,769 ± 12,229	35,325 ± 9724	(27,140, 5746)*
Force – time integral (continuous test) ($N \cdot s$)	21,043 ± 4474	15,816 ± 6263	(10,876, −423)

*Significant difference between group means ($P < 0.05$).

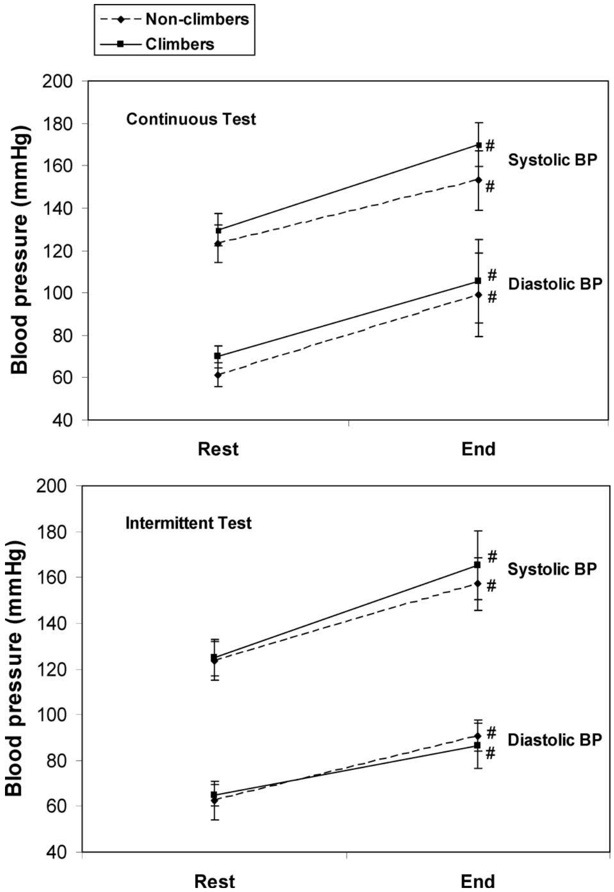

Figure 2. Group mean blood pressure responses for the endurance tests. # Significant difference from rest. - - ♦; - -, non-climbers; —■—, climbers.

groups, $n = 20$). Both systolic and diastolic pressor responses were not related to the force–time integral for both tests (continuous test $P = 0.700$, intermittent test $P = 0.451$).

NIRS analysis (intermittent test)

Muscle blood oxygenation [HbO_2] tended to decrease during contractions and recover (re-oxygenation) during rest phases, creating a pattern of "peaks" and "troughs" (Figure 3). Re-oxygenation (Δ[HbO_2]) during the 3-s rest phases was represented by the difference between [HbO_2] at the start of a rest phase ("trough") and that at the end of a rest phase ("peak"). The medians of the first three rest phases, last three rest phases, and middle three rest phases of the test for each participant were selected for analysis because they gave a representative profile of [HbO_2] changes during the test. Due to the variable test times between participants, the values represent relative rather than absolute time points. Rest phase re-oxygenation was significantly greater in climbers than in non-climbers at the middle of the test ($P = 0.001$) and end of the test ($P = 0.001$) (Figure 4). Multiple regression was used to analyse the relationship between finger flexor re-oxygenation and the force–time integral. There was a significant positive relationship between rest phase re-oxygenation and the force–time integral ($P = 0.005$). Rest phase re-oxygenation explained 41.1% of the variability in the force–time integral. Multiple regression was used to analyse the relationship between pressor response (systolic and diastolic) and rest phase re-oxygenation. No relationships were observed.

NIRS analysis (continuous test)

Analysis of group mean change in muscle blood volume (Δ[HbT]) and Δ[HbO_2] was performed at 20% incremental time points from 0% (test start) to 100% (end point of the test). Change in muscle blood volume increased relative to rest in non-climbers at the 40% to 100% time points ($P = 0.001$), but only at 100% in climbers ($P = 0.001$). Δ[HbT] increased significantly relative to rest in non-climbers at 40%–100% time points (P values < 0.05), but only at 100% in climbers ($P = 0.045$). Δ[HbT] was significantly greater in non-climbers than climbers at 40% ($P = 0.023$) and 60% time points ($P = 0.014$) (Figure 5). Δ[HbO_2] decreased relative to rest and the change was greater in the climbers than in non-climbers, although P values < 0.05 at all points in the test, for both groups (Figure 5). Multiple regression revealed no relationship between Δ[HbT] or Δ[HbO_2] and the force–time integral.

Discussion

Climbing-specific endurance

There were no differences between groups for endurance test times (Table I). This finding is surprising, as Carlson and McGraw (1971) observed lower isometric endurance in individuals with higher MVC. Based on these findings, it might be anticipated that the climbers in the present study would have shorter endurance times as they had much higher MVCs than the non-climbers. Both groups exerted force at 40% MVC but the absolute force of the climbers was greater. Carlson (1969) and Carlson and McGraw (1971) hypothesized that a negative relationship between MVC and isometric endurance can be explained by the fact that blood flow is progressively occluded as force increases. Thus, in a group with a higher absolute force, there would be greater blood flow occlusion and a reduced endurance time. The results from the present study differ from the findings of Ferguson and Brown (1997), who observed greater intermittent isometric forearm endurance times in a trained climbing

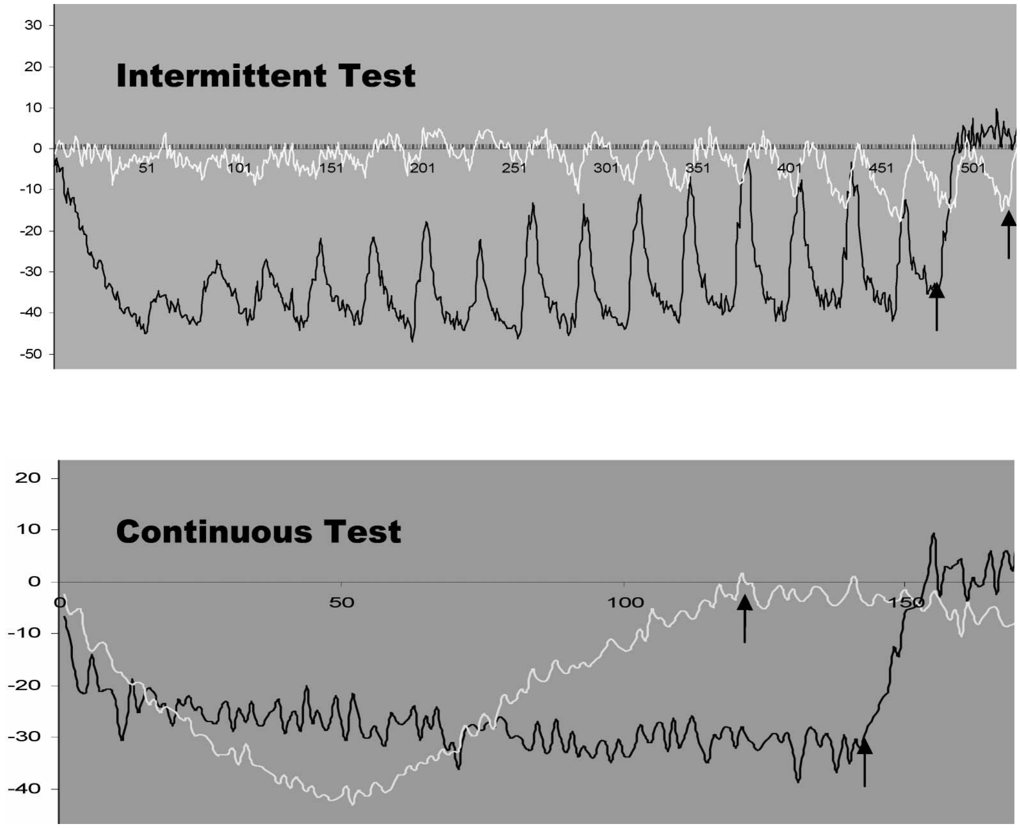

Figure 3. Example of NIRS traces of changes in muscle blood oxygenation [HbO_2] during the endurance tests showing changes in μM relative to rest (set to zero before the start of the test). Black trace = climber, white trace = non climber. y-axis = [HbO_2] μM (zero = resting value), x-axis = time (s). "0" denotes the start of the test. Exercise ceased at 501 s into the intermittent test, and at 154 s into the continuous test.

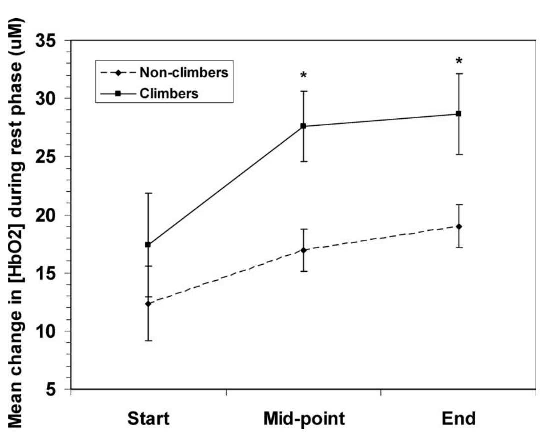

Figure 4. Group mean rest phase re-oxygenation during the intermittent test. The values represent the difference between [HbO_2] at the start of a rest phase ("trough") and end of a rest phase ("peak"). Start = median of Δ[HbO_2] during first three rest phases of the test. Mid-point = median of middle three phases of the test. End = median of final three rest phases of test. * Significant difference between group means ($P < 0.05$). - - ♦ - -, non-climbers; —■—, climbers.

group. Ferguson and Brown also used contractions of 40% MVC but observed similar absolute forces between a group of trained climbers and non-climbing controls. The absence of group differences in MVC observed by Ferguson and Brown might have been attributable to the climbing specificity of the test apparatus. The superior endurance times of climbers observed by Ferguson and Brown could be related both to the absence of group MVC differences and greater vasodilatory capacity in the climbers. We hypothesized that, in the present study, any endurance disadvantage due to superior MVC in the climbers is offset by the increased vasodilatory capacity possessed by the participants. The intermittent test in the present study was designed to simulate closely the contraction patterns experienced during climbing. Ferguson and Brown (1997) used a contraction–relaxation ratio of 5 s to 2 s, and measured endurance times to fatigue of over 12 min in climbers. The test times for the climbers in the present study were generally between 4 and 5 min, similar to the times measured for completion of World Cup competition routes (Schadle-Schardt, 1998). It is therefore conceivable that 40% MVC is representative of the forces required at the fingers in real climbing. However, more research is required to obtain direct evidence of the forces generated in the fingers, as well as realistic contraction–relaxation ratios during different sport climbing types (indoor competitions, outdoor rock climbs).

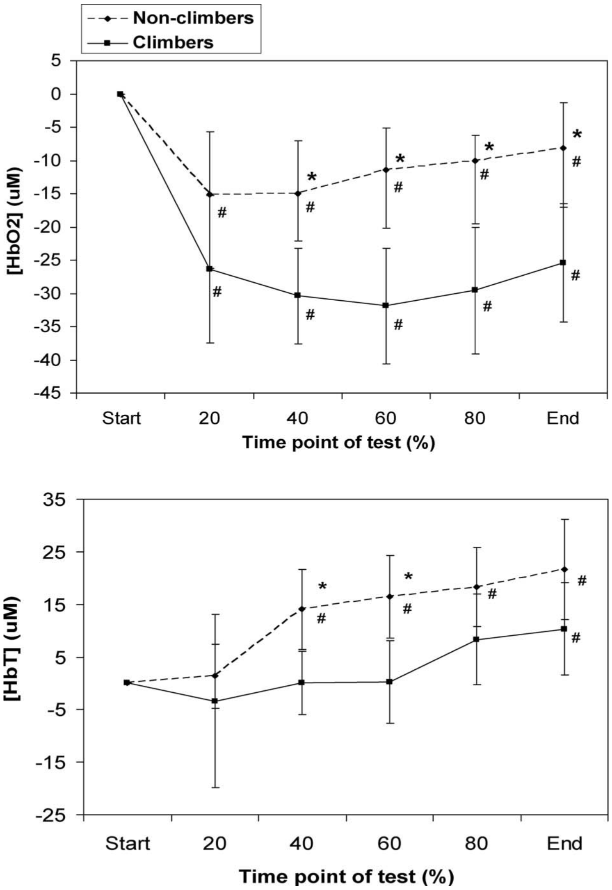

Figure 5. Group mean changes in NIRS variables during the continuous test (HbO_2, HbT) (μM) relative to resting value (rest = zero). * Significant difference between group means ($P < 0.05$). # Significant difference from rest ($P < 0.05$). - - ♦ - -, non-climbers; —■—, climbers.

To make useful comparisons between the groups for climbing-specific endurance, absolute force and endurance time were combined to provide a relevant measure of the muscular effort performed in the test (the force–time integral). There was a group difference in force-time integral, intermittent test: ($P = 0.001$). That this advantage reached significance only in the climbing-specific (intermittent) endurance test underlines the unique physiological demands of this activity. We conclude that climbing-specific endurance is an important characteristic of trained climbers. However, we observed no relationship in the intermittent or the continuous test between the force–time integral and climbing grade. The lack of strength in this relationship, despite the large differences in the force–time integral between groups, might be explained by the small sample in the climbing group ($n = 11$) and narrow variation of climbing ability among the participants. It should also be recognized that endurance is only one of several factors that might contribute, to varying extents, to success in rock climbing. Other factors that influence performance include route-finding skills, movement ability, finger strength and strength in several body areas, flexibility, and psychological factors.

Determinants of the force–time integral

Both systolic and diastolic blood pressure rose during the endurance tests, as anticipated for isometric exercise (Jones & Round, 1990). Increasing central arterial blood pressure has been shown to enhance force production during isometric muscle activity (Wright *et al.*, 2000). It was hypothesized that an increased pressor response would confer a performance advantage in the endurance tests by opposing occlusion caused by the muscular activity and thus permit increased intramuscular blood flow. There were no group differences in pressor response (Continuous test: $P = 0.207$ systolic, $P = 0.857$ diastolic. Intermittent test: $P = 0.326$ systolic, $P = 0.172$ diastolic). As there were no relationships between pressor response and the force–time integral, it is suggested from these data that an increased pressor response does not confer an advantage in climbing-specific endurance. Wright *et al.* (2000) also demonstrated that the positive effect on abductor pollicis force production from increasing blood pressure could be removed by elevating the hand. It is plausible that a similar effect could have occurred in the present study, and could also occur in climbing (where the arms are often extended above the head).

Several studies have observed that training with fatiguing ischaemic muscle actions results in attenuation of the pressor response. Such adaptations are thought to be due to changes in the sensitivity of the peripheral chemoreceptors and mechanoreceptors and the central command component of the cardiovascular response. Ferguson and Brown (1997) observed an attenuated blood pressure response in trained climbers during isometric hand-grip exercise compared with non-climbers. The magnitude of the pressor response varies with exercise intensity and duration (Kahn, Favriou, Jouanin, & Grucza, 2000). The pressor response to isometric exercise is affected by a central command component (MacDougall *et al.*, 1992) related to the effort produced by the individual, and by a peripheral component related to the build up of metabolites in the exercising muscle and to muscle mechanoreceptors. Considerable verbal encouragement was given to all participants to ensure maximum effort. However, it is plausible that the climbers, being more accustomed to producing maximum efforts of a similar type, were able to produce a greater effort and thus exhibit a larger central command-mediated pressor response. Furthermore, the higher forces produced by the climbers (due to the higher MVC) could have accounted for the trend for a large pressor response in the climbers, via a peripheral response to greater activation of chemoreceptors and mechanoreceptors within the exercising muscles. The larger change in forearm oxygenation in climbers during the endurance tests supports the hypothesis that a larger metaboreflex could have occurred. The larger forces produced by the climbers compared with the non-climbers in the present study could account for the contrast with the findings of Ferguson and Brown (1997), as the forces produced in that study were similar between climbers and non-climbers.

Near infra-red spectroscopy

After completing the endurance tests, the participants commented on having a painful burning "pump" in the forearm muscles and the forearm was visibly larger and firm to the touch. This is consistent with the type of forearm fatigue experienced in rock climbing (Goddard & Neumann, 1993). During the intermittent test, NIRS-determined muscle blood oxygenation [HbO_2] fell rapidly from the resting value and followed a pattern of "peaks" and "troughs", corresponding to the relaxations and contractions respectively (Figure 3). We hypothesized that the ability to restore muscle oxygenation during the rest phases would be an important predictor of climbing-specific endurance performance. There were reoxygenation group differences ($P = 0.001$) at the middle and end of the test (Figure 4). There was a positive relationship between rest phase $\Delta[HbO_2]$ and climbing-specific endurance (force–time integral) ($R^2 = 41.1\%$). Thus we conclude from these results that muscle re-oxygenation during rest phases is an important determinant of climbing-specific endurance. We hypothesized that forearm re-oxygenation during the rest phases would be directly related to the magnitude of the pressor response, via an opposition of the mechanical vasoconstriction caused by high intramuscular pressure (Asmussen, 1981). Although there was a weak positive relationship, it was not significant ($P = 0.273$ and $P = 0.162$ at 50% and 100% time points respectively). Thus, we conclude from these results that forearm oxygenation is not dependent on the pressor response in a climbing-specific endurance test. Factors influencing forearm re-oxygenation during rest phases could include muscle capillary density, vasodilatory capacity (Ferguson & Brown, 1997), and muscle fibre relaxation times (Jones & Round, 1990). Training regimes promoting angiogenesis in the forearm muscles could be an important component of training for elite rock climbing.

In the continuous test, the change in muscle blood volume was greater in the non-climbers than the climbers at various time points during the test ($P = 0.023$–40%, $P = 0.014$–60%). Figure 5 suggests greater occlusion of blood flow during contractions at 40% MVC in the climbers. This could be explained by the higher absolute forces exerted by the climbers. The greater occlusion points to improved muscle fibre recruitment during contraction in trained rock climbers, rather than greater muscle mass in the forearms alone. This speculation is supported by the absence of differences in absolute forearm circumference between the groups. However, when forearm circumference is corrected for body mass, the forearm circumference of the climbers was greater ($P = 0.001$) (Table I). Similar endurance tests performed across a range of percentages of MVC could yield further information about the extent of blood flow occlusion during climbing-specific contractions of different intensities.

Finger strength (MVC)

The climbers had greater finger strength than the non-climbers using a climbing-specific protocol ($P = 0.009$) (Table I). This was despite the fact that the non-climbers had a higher mean body mass. These results agree with previous studies that have suggested that climbers have stronger fingers than non-climbers (Bollen & Cutts, 1993; Grant *et al.*, 1996). However, these authors did not report the large differences in MVC scores between the climbers and non-climbers seen in the present study. The smaller differences between the climbers and non-climbers observed by Grant *et al.* (1996) might be attributable to the relatively low climbing standard of the "elite" group. The results of the present study confirm that climbers possess greater finger strength than non-climbers, particularly when a climbing-specific test protocol is used with a highly trained group of individuals. There was a positive relationship between climbing ability (measured by on-sight grade) and MVC, explaining 49.9% of the variability in climbing grade in the climbers. This finding suggests that increased finger strength confers a performance advantage in rock climbing.

This result is perhaps surprising given that sport climbing has an endurance component, as the overall exercise duration is likely to last for more than 4 min (Schadle-Schardt, 1998). However, given that the finger flexors (a small muscle group) must contract isometrically and support large proportions of body weight, and that complete occlusion of blood flow occurs at 45–75% of MVC in isometric exercise (Barnes, 1980; Heyward, 1980; Serfass, Stull, Ben Sera, & Kearney, 1979), it is likely that there is marked occlusion of blood flow to the exercising muscles during many of the moves on a climbing route. Indeed, NIRS data from the present study suggest such occlusion (Figure 5) and de-oxygenation (Figures 3, 5) is greater during contractions in climbers, despite their superior endurance capacity (force – time integral) ($P = 0.001$). The isometric contractions made during moves are interrupted by short periods of rest while reaching to the next hold. Near infra-red spectroscopy-determined forearm [HbO_2] showed considerable recovery towards resting values during these rest periods (Figure 3), even as the participants approached the point of failure in the test. It is possible that finger strength characteristics – specifically coordination and fine control of force production – could frequently be the direct causative factor for failure (falls), rather than muscle fatigue itself. Even long-endurance rock climbs can have forceful individual movements where large forces, muscular fine control, and coordination are required for success. Twitch relaxation time tends to become slowed during isometric fatigue, affecting the frequency at which tetanic fusion occurs. A slowing of motor unit firing rate occurs as a reflex response to the change in relaxation time (Bigland-Ritchie, Dawson, Johansson, & Lippold, 1986), the purpose of which is to maintain muscular fine control (Spurway, 1999). Falls could be caused by loss of fine control and coordination where firing frequencies are high. Greater isometric strength would reduce the requirement for high firing frequencies for a given climbing movement.

Anthropometry

An attempt was made to recruit individuals of similar age, stature, and physical build for comparison of absolute forces recorded for strength and endurance. There were no significant differences between groups for age ($P = 0.144$) and stature ($P = 0.119$) (Table I). However, it was not possible to recruit sufficient individuals of similar body mass. The climbers had lower body mass and percentage body fat than the non-climbers. These results support the findings of Watts and colleagues (Watts, Daggett, Gallagher, & Wilkins, 2000; Watts, Martin, & Durtschi, 1993; Watts *et al.*, 1996) that trained rock climbers tend to have a lower body mass and percentage body fat. It is feasible that a large body mass or any excess body fat would be disadvantageous in elite climbing as body weight must be moved repeatedly against gravity. However, it is well known that climbers have long considered excess body fat to be a disadvantage and many climbers attempt to control it strictly. It is also considered advantageous to avoid hypertrophy training of lower-body muscle groups. Hence, the question remains whether body mass and percentage body fat are important determinants of climbing performance or merely features of climbers' training patterns (Farrington, 1999). It is conceivable that any performance advantage conferred by maintaining low body fat could be offset by an inadequate energy intake to support a rigorous training regime. We hypothesizsed that climbers would possess a greater muscle mass in the forearm due to the requirement for repeated contractions of the finger flexors and other forearm muscles in climbing movements. There were no differences between the groups in absolute forearm circumference ($P = 0.817$), but when related to body mass the climbers' forearm circumference was significantly greater ($P = 0.001$) (Table I). The absence of marked differences in the absolute values could be explained by the difference in body mass between the climbers and non-climbers. This finding is in line with that of Watts, Joubert, Lish, Mast, and Wilkins (2003), who observed similar forearm volumes in competitive climbers and controls, despite the climbers' lower stature and body mass.

Summary

Finger endurance, measured as the force – time integral, was greater for the climbers in the intermittent endurance test ($P = 0.001$). Pressor responses were similar between groups and not related to the force – time integral for either test. There was a positive relationship between change in muscle blood oxygenation during rest phases and the force – time integral ($R^2 = 41.1\%$) in the intermittent test ($P = 0.005$). Thus we conclude from our results that muscle re-oxygenation during rest phases is a good predictor of endurance performance.

References

Asmussen, E. (1981). Similarities and dissimilarities between static and dynamic exercise. *Circulation Research*, *48* (supp. 1), 3 – 10.

Barnes, W. S. (1980). The relationship between maximum isometric strength and intramuscular circulatory occlusion. *Ergonomics*, *23*, 351 – 357.

Bigland-Ritchie, B., Dawson, N. J., Johansson, R. S., & Lippold, O.C. J. (1986). Reflex origin for the slowing of motor neurone firing rates in fatigue of human voluntary contractions. *Journal of Physiology*, *379*, 451 – 459.

Bollen, S. R., & Cutts, A. (1993). Grip strength and endurance in rock climbers. *Proceedings of the Institution of Mechanical Engineers H: Journal of Engineering in Medicine*, *207*, 87 – 92.

Carlson, B. (1969). Level of maximum isometric strength and relative load isometric endurance. *Ergonomics*, *12*, 429 – 435.

Carlson, B., & McGraw, L. (1971). Isometric strength and relative isometric endurance. *Research Quarterly*, *42*, 244 – 250.

Delp, M. D. (1995). Effect of exercise training on endothelium-dependent peripheral vascular responses. *Medicine and Science in Sports and Exercise*, *27*, 1152 – 1157.

Durnin, J. V. G. A., & Womersly, J. (1974). Body fat assessed from total body density and its estimation from skinfold thickness: measurements of 481 men and women aged 16 – 72 years. *British Journal of Nutrition*, *34*, 77 – 97.

Farrington, J. (1999). Nutrition. *On the Edge*, *92*, 28 – 29.

Ferguson, R. A., & Brown, M. D. (1997). Arterial blood pressure and forearm vascular conductance responses to sustained and rhythmic isometric exercise and arterial occlusion in trained rock climbers and untrained sedentary subjects. *European Journal of Applied Physiology*, *76*, 174 – 180.

Goddard, D., & Neumann, U. (1993). *Performance rock climbing.* (pp. 33, 39). Leicester, UK: Cordee.

Grant, S., Hynes, V., Whitaker, A., & Aitchison, T. (1996). Anthropometric, strength, endurance and flexibility characteristics of elite and recreational climbers. *Journal of Sports Sciences*, *14*, 301 – 309.

Grant, S., Shields, C., Fitzpatrick, V., Ming Loh, W., Whitaker, A., Watt, I. *et al*. (2003). Climbing-specific finger endurance: A comparison of intermediate rock climbers, rowers and aerobically trained individuals. *Journal of Sports Sciences*, *21*, 621 – 630.

Heyward, V. (1980). Relative endurance of high and low strength women. *Research Quarterly*, *51*, 486 – 493.

Hurni, M. (2003). *Coaching climbing.* Guilford, CT: Globe Pequot Press.

Jones, D. A., & Round, J. M. (1990). *Skeletal muscle in health and disease: A textbook of muscle physiology.* Manchester: Manchester University Press.

Jones, D. B. A. (1991). *The power of climbing.* Leicester, UK: Cordee.

Kahn, J. F., Favriou, F., Jouanin, J. C., & Grucza, R. (2000). Effect of co-contractions on the cardiovascular response to submaximal static handgrip. *European Journal of Applied Physiology*, *83*, 506 – 511.

MacDougall, J. D., McKelvie, D. E., Sale, N., Moroz, D. E., McArtney, N., & Buick, F. (1992). Factors affecting blood pressure during heavy weight lifting and static contractions. *Journal of Applied Physiology*, *73*, 1590 – 1597.

McNair, P. J., Depledge, J., Brettkelly, M., & Stanley, S. N. (1995). Verbal encouragement: Effects on maximal effort voluntary action. *British Journal of Sports Medicine*, *30*, 243 – 245.

Mermier, C. M., Robergs, R. A., McMinn, S. M., & Heward, V. H. (1997). Energy expenditure and physiological responses during indoor rock climbing. *British Journal of Sports Medicine*, *31*, 224 – 228.

Morstad, M. (2000). Training – technique. *On the Edge*, *98*, 70 – 73.

Noé, F., Quiane, F., & Martin, L. (2001). Influence of steep gradient supporting walls in rock climbing: Biomechanical analysis. *Gait and Posture*, *13*, 86 – 94.

Oviglia, M. (2006). Rock festivals. *Up – European Climbing Report*, *3*, 8 – 23.

Quaine, F., Martin, L., & Blanchi, J. P. (1997). The effect of body position and number of supports on wall reaction forces in rock climbing. *Journal of Applied Biomechanics*, *13*, 14 – 23.

Sagar, H. R. (2001). *Climbing your best.* Mechanicsburg, PA: Stackpole Books.

Schadle-Schardt, W. (1998). Die zeitiche gestaltung von belastung und entlastung im wettkampfklettern als element der trainingssteurung. *Leistungssport*, *1/98*, 23 – 28.

Serfass, R. C., Stull, G. A., Ben Sira, D., & Kearney, J. T. (1979). Effects of circulatory occlusion on submaximal isometric endurance. *American Corrective Therapy Journal*, *33*, 147 – 154.

Sinoway, L. I., Mutch, T. I., Minotti, J. R., & Zelis, R. (1986). Enhanced maximal metabolic vasodilatation in the dominant forearms of tennis players. *Journal of Applied Physiology*, *61*, 673 – 678.

Smolander, J. (1994). Capacity for vasodilatation in the forearms of manual and office workers. *European Journal of Applied Physiology*, *69*, 163 – 167.

Snell, P. G., Martin, W. H., Buckey, J. C., & Blomqvist, C. G. (1987). Maximal vascular leg conductance in trained and untrained men. *Journal of Applied Physiology*, *62*, 606 – 661.

Spurway, N. C. (1999). Muscle. In R. J. Maughan (Ed.), *Basic and applied sciences for sports medicine* (pp. 42 – 44). Oxford: Butterworth Heinemann.

Watts, P. B., Daggett, M., Gallagher, P., & Wilkins, B. (2000). Metabolic response during sport rock climbing and effects of active versus passive recovery. *International Journal of Sports Medicine*, *21*, 185 – 190.

Watts, P. B., & Drobish, K. M. (1998). Physiological responses to simulated rock climbing at different angles. *Medicine and Science in Sports and Exercise*, *30*, 1118 – 1122.

Watts, P., Joubert, L. M., Lish, A. K., Mast, J. D., & Wilkins, B. (2003). Anthropometry of young competitive sport rock climbers. *British Journal of Sports Medicine*, *37*, 420 – 424.

Watts, P. B., Martin, D. T., & Durtschi, S. (1993). Anthropometric profiles of elite male and female competitive sport rock climbers. *Journal of Sports Sciences*, *11*, 113 – 117.

Watts, P. B., Newbury, V., & Sulentic, J. (1996). Acute changes in handgrip strength and blood lactate with sustained sport rock climbing. *Journal of Sports Medicine and Physical Fitness*, *36*, 255 – 260.

Webster, J., Newham, D., Petrie, J. C., & Lovell, H. G. (1984). Influence of arm position on measurement of blood pressure. *British Medical Journal*, *288*, 1574 – 1575.

Wright, J. R., McCloskey, D. I., & Fitzpatrick, R. C. (2000). Effects of systemic arterial blood pressure on the contractile force of a human hand muscle. *Journal of Applied Physiology*, *88*, 1390 – 1396.