TRAINABLE PHYSICAL VARIABLES AS DETERMINANTS OF ROCK CLIMBING PERFORMANCE

by

Shannon M. Kiehl

An Abstract
of a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Nutrition and Kinesiology University of Central Missouri

December, 2016
Rock climbing causes a variety of physiological changes over time, as observed in elite climbers. The purpose of this study was to determine which trainable physical variables were the strongest predictors of rock climbing performance. Male (n = 22) and female (n = 3) rock climbers (18-23 yrs) underwent assessments for sixteen variables: climbing volume, body fat percentage (BF%), handgrip and pincer strength and endurance, upper-body strength and endurance and power, lower-body strength and power, balance, hip flexibility, core endurance, and maximum oxygen consumption (VO₂max). A scored performance climb was used to measure climbing ability. Upper-body endurance, BF%, climbing volume, core endurance, and VO₂max all significantly (p < 0.05) correlated with climbing performance. A backward stepwise regression analysis explained 85.1% of the variance seen in climbing performance. From strongest to weakest, the following physical variables can predict rock climbing performance: upper-body power, handgrip strength, balance, pincer strength, BF%, and pincer endurance.
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ACKNOWLEDGMENTS

I would like to thank my thesis committee for their help and guidance. I owe a great deal of gratitude to my mentor and advisor, Dr. Steve Burns. He has pushed me to grow academically and professionally, and I am a better person because of his continuous support. I am extremely grateful to Dr. Jennifer Case, Dr. Swarna Mandali and Dr. Wooyoung Lee for providing their expertise and helping me further develop my thesis. I especially want to thank Dr. Scott Strohmeyer for always taking the time to help me, whether it was on my thesis or in the classroom.

Appreciation and thanks shall not go unmentioned to all those who participated in the study and those who helped with data collection. I am especially grateful to my brother, Paul Kiehl, for helping me recruit individuals and for always giving me a helping hand or word of encouragement.

Lastly, I want to dedicate this work in loving memory of Mary Brinkley.
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CHAPTER 1
NATURE AND SCOPE OF THE STUDY

The foundation for this study was inspired by personal experience with rock climbing and the lack of research regarding variables that determine proficient rock climbing performance. Numerous studies have evaluated the anthropometric, physiological, and psychological differences not only between rock climbers and non-climbers, but between advanced and beginner climbers as well (Baláš, Pecha, Martin, & Cochrane, 2012; Grant, Hynes, Whittaker, & Aitchson, 1996; Mitchell, Bowhay, & Pitts, 2011; Wong & Ng, 2009). Although elite climbers tend to share similar anthropometric characteristics, training-induced physiological changes seem to be the most important factors in rock climbing ability (Tomaszewski, Gajewski, & Lewandowska, 2011).

The suggested optimal athletic profile for a rock climber includes: small stature, low percent body fat (BF%), high upper-body (UB) strength to weight (STW) ratios, high dynamic and isometric muscular endurance, UB power, and moderate aerobic power (Watts, 2004). It is well documented that elite climbers outperform non-climbers and lower-level climbers in strength and endurance of the UB, but less information is available for other aspects, such as flexibility, balance, and lower-body (LB) strength (Tomaszewski et al., 2011; Watts, 2004). Furthermore, only a few studies have explored to what extent each factor affects climbing performance, and the variables observed varied from study to study.

Mermier, Janot, Parker & Swan (2000) found trainable factors accounted for the majority of variance in rock climbing performance (58.9%) versus anthropometrics (0.3%) and flexibility (1.8%). Forearm endurance and BF% were included in the training component, but pincer strength, grip endurance, and LB power output were not. Psychological factors and climbing-
specific balance were possible suggestions for the 34% of unexplained variance. In one study, hand-arm strength and endurance, in combination with high climbing volume, years of experience, and low BF%, explained 97% of the variance in rock climbing performance (Baláš et al., 2012). However, factors such as flexibility and LB contribution were not considered in the analysis. Nachbauer, Fetz, & Burtscher (1987) found hip and back flexibility accounted for 16.1% of the variance - a large difference from the 1.8% found by Mermier et al. (2000). Aside from Nachbauer et al. (1987) finding that balance determined 7.4% of climbing performance, there is no further research on climbing-specific balance. There is currently no research on core strength and endurance in rock climbers (Phillips, Sassaman, & Smoliga, 2012). By assessing a number of variables that had not been previously compared with one another, the goal of this study was to further identify the roles of different physical factors in climbing performance.

Need for the study

Rock climbing is a popular sport enjoyed worldwide. Various types of rock climbing and recent advancements in gear give almost every demographic – including persons with disabilities and/or impairments - access to this activity. If anthropometrics is not a limiting factor, individuals can be encouraged their rock climbing performance may be enhanced through physical training. By assessing a wide range of factors, competitive climbers may be able to utilize the knowledge found to improve their current training programs or reconsider overlooked areas of training.

Statement of the problem

This study was focused on trainable physical factors in rock climbing individuals over a wide range of skill levels. Research from this topic may better explain to what extent various physical attributes contribute to climbing performance.
Purpose of the study

The purpose of this study was to determine which trainable aspects of rock climbing are
the strongest predictors of climbing performance.

Research question

The research question used for this study was:

Of the physical factors assessed, which variables are most significant to rock climbing
performance?

Hypotheses

Hypothesis #1

Handgrip and pinch endurance and strength, UB endurance, core endurance, and BF%
will have a strong correlation ($r = \geq 0.9$) with rock climbing performance.

Hypothesis #2

Hip flexion and abduction flexibility, UB power and strength, balance and climbing
volume per week will have a low-moderate correlation ($r = 0.5$-$0.89$) with rock climbing
performance.

Hypothesis #3

LB power and strength and VO$_2$max will not have a statistically significant correlation
with rock climbing performance.

Hypothesis #4

Handgrip strength will be the strongest predictor of rock climbing ability.

Assumptions

The assumptions of this study were:

1) All subjects were healthy enough to partake in the physical assessments; and
2) Subjects answered all questions honestly and gave forth their best effort.

**Delimitations**

The delimitations of this study were:

1) Male (ages 18-45) and female (ages 18-55) rock climbers were recruited from the University of Central Missouri’s (UCM) indoor rock climbing facility;

2) Subjects had more than 5 previous climbs and completed the screening climb (~5.6 Yosemite Decimal System); and

3) Subjects were deemed ready for activity by completing a PAR-Q.

**Limitations**

The limitations of this study were:

1) Control over a subject’s training regimen and/or diet;

2) The effort given forth by each subject during testing; and

3) Subjects were a convenience sample from the UCM campus.

**Definitions**

For the purpose of this study, terms were defined as follows:

**Active start**: Starting a route with feet on the climbing foot-holds (Draper, Brent, Hodgson, & Blackwell, 2009).

**Ape index**: The ratio of arm span to body height (Tomaszewski et al., 2011).

**Belay**: The act of holding and managing the climbing rope to which a climber is attached (Phillips et al., 2012).

**Belayer**: The one who belays.

**Belay device**: Climbing rope is run through this metal device - attached to the belayer’s harness - to hold climbers and stop falls through the use of friction.
**Bouldering**: The simplest form of rock climbing. Routes are generally < 25 ft high; therefore, the only equipment needed is a crash mat and spotter (Phillips et al., 2012).

**Climbing volume**: Vertical distance climbed (in meters).

**Crimp**: A hold that consists of a small edge that fits the fingertips (Phillips et al., 2012).

**Dyno**: Abbreviation for dynamic movement. A jumping maneuver that requires the climber to produce enough vertical momentum come off the wall and reach the next hold (Phillips et al., 2012).

**Heel hook**: A maneuver in which the heel is hooked against a ledge or corner; the hamstring muscles pull the climber closer to the wall (Phillips et al., 2012).

**On-sight**: Successfully completing a climb without advice or prior knowledge of the climb (Phillips et al., 2012).

**Pinch grip**: Any hold having two opposing sides which requires the climber to pinch it with the thumb on one side and fingers on the opposite side (Phillips et al., 2012).

**Pocket**: A hold resembling a pocket that fits 2-3 fingers inside of it (Phillips et al., 2012).

**Quickdraw**: Two carabiners connected by a sewn loop of webbing (Phillips et al., 2012).

**Route**: The path a climber takes to complete a climb (Phillips et al., 2012).

**Slack**: Non-taut portion of the rope (Phillips et al., 2012).

**Sport climbing**: A climber places quickdraws into secured bolts and clips the climbing rope in as he or she ascends (Phillips et al., 2012).

**Top-rope climbing**: Climbing is done by running a rope through anchors at the top of a route. A climber is on one end and a belayer controls the slack with a belay device on the other end (Phillips et al., 2012).
**Trainable physical variables**: Any aspect of rock climbing that could be modified through a training regimen (Mitchell et al., 2011).

**Yosemite decimal system (YDS)**: Commonly used in North America, YDS is a number scale ranking the difficulty of rock climbing routes. The range falls from beginner (5.6) to elite (5.15) (Hurni, 2003).
CHAPTER 2
LITERATURE REVIEW

The purpose of this study was to determine which trainable physical variables were the strongest predictors of proficient rock climbing performance. This literature review covers anthropometric, physiological, and psychological factors previously published with regards to rock climbing. The review is divided into the following seven sub-sections: 1) rock climbing background, 2) anthropometric, physiological, and psychological factors, 3) climbing performance, experience, and body fat percentage, 4) aerobic and anaerobic contributions, 5) upper-body components (UB), 6) lower-body (LB) components, and 7) stability and flexibility.

Rock climbing background

Beginning in the 1800’s, rock climbing was originally used by mountaineers as a form of alpine training. Through the development of new types of gear and techniques, rock climbing evolved into a recreational activity. The sport has shown remarkable growth in the past 30 years; in addition to rock climbing gyms, numerous universities and community centers have added rock climbing walls. Several types of climbing competitions, including an annual international World Cup started in 1988, have further expanded the sport (Macdonald & Callender, 2011; Sheel, 2004; Tomaszewski et al., 2011; Watts, 2004).

Bouldering is the most basic form of rock climbing. Because routes are typically less than 25 feet high, only a crash pad (similar to a gymnastics mat) and spotter are needed. Bouldering is generally seen as a training tool to improve strength, endurance, and climbing skill, but many individuals consider it a sport as well. Top-rope climbing, where a rope is run through anchors at the top of a route, is a safe and stress-free option for beginners. One end of the rope is tied to the
climber; the other end is attached to a belayer via a belay device. Given the belayer is continually taking up slack, a climber rarely falls more than a few feet (Phillips et al., 2012).

Sport and traditional climbing are the two main types of lead climbing, meaning there are no top anchors. Sport climbing requires climbers to place quickdraws into permanent preplaced bolts while ascending. Once the top carabineer of the quickdraw is connected, the climber clips the rope into the bottom carabineer, creating a new anchor (Phillips et al., 2012). Indoor sport climbing has been shown to be reasonably safe when compared to other popular sports, such as basketball, soccer and sailing. The injury rate is low, injury severity is minimal, and fatalities are rare (Schöffl, Morrison, Schwarz, Schöffl, & Küpper, 2010). Traditional climbing is considered more dangerous because climbers must create their own anchors by placing gear into cracks and other features as they ascend (Phillips et al., 2012). Though various types of climbing exist, it was the rapid rise of sport climbing competitions that caused scientific research to focus primarily on factors determining successful performance (Philippe, Wegst, & Müller, 2012; Phillips et al., 2012).

### Anthropometric, physiological, and psychological factors

An array of studies has compared anthropometric, physiological, and psychological differences not only between climbers and non-climbers, but also within the climbing population itself. Psychological state and trait attributes (Feher, Meyers, & Skelly, 1998), BF% (Baláš et al., 2012; Mitchell et al., 2011; Romero et al., 2009), hand-arm strength and endurance (HASE) (Baláš et al., 2012; Mermier et al., 2000), flexibility (Baláš et al., 2012; Mermier et al., 2000), and balance (Schweizer, Bircher, Kaelin, & Ochsner, 2005) are among some of the variables studied.
A “sport-specific somatic build” is considered to be essential for top performance in many sports; indeed, certain anthropometric traits are believed to be crucial when identifying talent (Aitken & Jenkins, 1998; Reilly, Secher, Snell, & Williams, 1990). Though the best climbers are likely to be shorter in stature and lower in body mass (Watts, 2004), there is no significant difference when compared to non-climbers (Grant et al., 1996; Tomaszewski et al., 2011). Research regarding the advantage of limb length has been inconclusive. One study found no difference between climbers and non-climbers (Grant et al., 1996), yet another study found climbers had significantly greater leg length, arm length, arm span, and ape index (Tomaszewski et al., 2011). However, ape index is the only anthropometric factor that nearly correlates with climbing ability ($r = -0.397; p < 0.083$) (Tomaszewski et al., 2011; Watts, Martin, & Durtschi, 1993).

Despite similar anthropometrics among advanced climbers, they are not necessary to achieve climbing excellence. Training-specific adaptations (i.e., physiological factors) seem to provide a more important contribution to climbing ability (Tomaszewski et al., 2011). For example, body mass index (BMI) is comparable between climbers and non-climbers, but the proportion of fat and fat-free mass is frequently not (Grant et al., 1996; Philippe et al., 2012; Watts, Joubert, Lish, Mast, & Wilkins, 2003). Tomaszewski et al. (2011) found no significant relationship between self-reported climbing rating and the somatic indices researched, but there was a significant correlation with BF% ($r = -0.614; p < 0.01$). Grant et al. (1996) compared anthropometric and physiological variables between non-climbers, recreational and elite climbers. Age, height, body mass, BMI, arm and leg length were not significantly different across the three groups. It was hand strength and forearm endurance that clearly marked the elite group from the other two. Philippe et al. (2012) found strength - not BMI – was more influential
in finger flexor strength to weight (STW) ratios, supporting anthropometrics play only a small role in climbing ability.

Furthermore, a multiple regression analysis of physiological and anthropometric traits found only BF% and grip strength, both trainable variables, were significant predictors of climbing ability (Watts et al., 1993). A study by Mermier et al. (2000) grouped several variables into three components: training, anthropometrics, and flexibility. The training component (defined as any variable deemed to be trainable) was found to be the only significant predictor of climbing performance when compared to anthropometrics and flexibility (58.9% of variance seen in climbing performance versus 0.3% and 1.8%, respectively). A more recent study by Baláš et al. (2012) found body composition, climbing volume, and years of experience were closely related to HASE. When analyzed through a similar multiple regression analysis as Mermier et al. (2000), the variables studied accounted for 97% of the variance observed in rock climbing performance.

The physical discrepancies between males and females highlight the importance of training versus anthropometrics. Females tend to have a higher BF% and shorter time to failure for grip strength; males have greater arm span, ape index, and hand strength (Baláš et al., 2012; Mitchell et al., 2011). Regardless, one study found both genders had strong negative correlations between their climbing time and pinch/crimp/handgrip STW ratios; additionally, climb times were similar among the groups (Mitchell et al., 2011). Another study observed strong correlations for both genders between climbing performance and climbing experience, BF% and strength tests. The differences between men and women tended to become less pronounced as performance levels increase (Baláš et al., 2012).
The psychological aspect of rock climbing is beyond the scope of this study, but worth noting. Anxiety felt during climbing places tremendous stress on cognitive processing and emotional control; effective anxiety management is therefore seen as a necessity for successful climbing (Hodgson et al., 2008). The emotional state of climbers affects their anxiety levels, which in turns affects their physical state. Generally, as a climb becomes more difficult, self-confidence decreases, and cognitive anxiety increases (Hodgson et al., 2008). However, as climbers develop their climbing ability, their cognitive anxiety levels drop sharply (Feher et al., 1998; Hodgson et al., 2008). Learning from experience, climbers are mentally able to analyze and strategize the best way to complete a route based on their ability, climbing style, and body type (Pezzulo, Barca, Bocconi, & Borghi, 2010). The role of psychobiological status on climbing performance needs further research, but it is clear rock climbing requires more than just physical strength (Hodgson et al., 2008; Mermier et al., 2000).

Throughout the literature, climbing-specific training is recommended to improve climbing performance (Baláš et al., 2012; Grant et al., 1996; Mermier et al., 2000; Watts, 2004). Undoubtedly, there is a strong connection between high climbing performance and high training volume (Baláš et al., 2012; Mermier et al., 2000). Trainable characteristics can be deemed as any aspect of rock climbing which could be modified through a training regimen (Mitchell et al., 2011).

Climbing performance, experience, and body fat percentage

An individual’s climbing rating often indicates his or her training level (Mermier et al., 2000). The beneficial physiological changes, which occur through climbing-specific training, are most commonly seen in high-level climbers (climbing 5.11 or higher on the Yosemite Decimal System). The Yosemite Decimal System (YDS) is the most frequently used rating system in
North America. All rope-climbing routes start with a “5” and a decimal signifying the level of difficulty. The rankings range from recreational (5.4-5.6) to professional (5.14-5.15) (Hurni, 2003; Watts, 2004). Even a self-reported climbing rating is an accurate and reliable reflection of a subject’s actual climbing ability (Dickson et al., 2011).

Although traditional resistance and aerobic conditioning are recommended for rock climbers, climbing itself is an indispensable part of training due to the specific nature of the sport (Phillips et al., 2012). An individual’s climbing experience and volume lays the foundation for physical adaptations to occur over time. On average, it takes three years to consistently lead climb a 5.10-5.14 route; some studies found the highest difficulty levels (5.12-5.14 YDS) were accomplished after 7-14 years of climbing (Baláš et al., 2012; Romero et al., 2009; Tomaszewski et al., 2011). Conceivably more important than years of experience would be climbing volume per week. Volume is best measured in vertical meters climbed versus hours trained, the basis being beginner climbers may spend more hours training but have fewer meters climbed. Elite male climbers average more meters per week (582 m) than novice climbers (94 m); furthermore, grip strength, BF%, and UB endurance are directly correlated with meters climbed (Baláš et al., 2012). However, hours of training per week was not significant enough to be included in the training component of the PCA analysis performed by Mermier et al. (2000).

A study by Baláš et al. (2012) used a structural equation modeling approach to link the observed variables with climbing performance. Although the path coefficients for climbing experience ($\gamma(1,1) = 0.02$) and volume (meters per week) ($\gamma(1,1) = 0.07$) were not significant with climbing performance, they were with HASE ($\gamma(1,1) = 0.25$ and 0.55, respectively); HASE was directly linked with performance ($\gamma(1,1) = 1.11$). When independently assessed, all these variables explained approximately 85% of climbing ability. Yet, when the manifest factor
(HASE) was used as a mediator between performance and exogenous factors (experience, volume, BF%), 97% of the variance could be explained. Simply said, experience and volume indirectly affect climbing performance by creating the physiological changes that do have direct effect.

The influence of body composition on climbing ability continues to be debated. Considering climbers often exhibit lower body fat levels than non-climbers, body fat percentage may be assumed necessary for climbing well (Booth et al., 1999; España-Romero et al, 2009; Watts, 2004). One study found BF% and grip STW ratios were the only significant predictors of climbing performance (Watts et al., 1993). While a handful of studies found no noticeable difference in BF% between climbers and non-climbers, a few still observed a significant correlation between low BF% and climbing performance (Cutts & Bollen, 1993; Grant et al., 1996; Grant et al., 2001; Tomaszewski et al., 2011). Body fat levels for climbers range from 5%-15% throughout the literature (Grant et al., 1996; Watts, Joubert, Lish, Mast, & Wilkins, 2003). These varied results may be attributed to the different ways body composition is measured. Different methods make it difficult to make direct comparisons between studies (Tomaszewski et al., 2011). Mermier et al. (2000) used a three-site skin-fold method (Jackson and Pollock method), while Grant et al. (1996) used a four-site method (Durnin method). Even though both methods underestimated BF%, Durnin’s equation is the most accurate skin-fold method to estimate BF% in elite sport climbers (Peterson, Czerwinski, & Siervogel, 2003; Romero et al., 2009). In light of the mixed literature, it would be suggested low BF% is advantageous, but not essential, for elite-level climbing (Tomaszewski et al., 2011). Findings by Baláš et al. (2012) encourage this claim; BF% is directly related to climbing performance, but HASE has a stronger relationship.
Aerobic and anaerobic contributions

Traditional, sport and top-rope climbing often rely on a blend of aerobic and anaerobic power. Typically, a route includes reoccurring high-intensity sections succeeded by easier portions that give the climber a chance to aerobically recover before the next section. Type of climbing, route difficulty and length of the route all determine to what extent each energy system is used (Phillips et al., 2012). Aerobic metabolism is necessary because rope-climb durations last 2-7 minutes on averages; climbing provides recovery and continued muscle contractions following spurts of high-intensity movement (Phillips et al., 2012). Oxygen consumption (VO₂) is concomitant with climbing pace (Booth, Marino, Hill, & Gwinn, 1999). Higher-level climbers (5.10-5.12YDS) average 32.95 mL O₂·kg⁻¹·min⁻¹ at 8.9 m/min⁻¹, 36.2 at 9.9 m/min⁻¹, and 42.2 at 12.4 m/min⁻¹ (Watts, Clure, Hill, Humphreys, & Lish, 1995). VO₂ also increases with climbing intensity; 20.7 mL O₂·kg⁻¹·min⁻¹ for easy routes (5.6 YDS), 21.9 for moderate (5.9 YDS), and 24.9 for difficult (5.11YDS) (Mermier, Robergs, McMinn, & Heyward, 1997; Sheel, Seddon, Knight, McKenzie, & Warburton, 2003). Additionally, those with higher climbing capabilities tend to have higher peak oxygen consumptions (VO₂max) in both running and climbing than lower-level climbers (Billat, Palleja, Charlaix, Rizzardo, & Janel, 1995; Watts & Drobish, 1998).

Despite increased VO₂ during challenging climbs, values are still lower than those typically found while running or cycling (Watts, 2004). Trained male climbers have been observed with VO₂maxes at 45 mL O₂·kg⁻¹·min⁻¹ during cycling and 55 mL O₂·kg⁻¹·min⁻¹ during running, but generally around 20-45 mL O₂·kg⁻¹·min⁻¹ with vigorous indoor climbing (Bertuzzi, Franchini, Kokubun, & Kiss, 2007; Booth et al., 1999; Magalhaes et al., 2007; Phillips et al., 2012). Subjects in a study by Watts and Drobish (1998) averaged a VO₂max of 55 mL O₂·kg⁻¹·min⁻¹ while running, but a rather stable VO₂ of 30 mL O₂·kg⁻¹·min⁻¹ while climbing; thus,
climbing required 60% less aerobic power than running. Other studies noted average and peak VO₂ values were 33-50% of an individual’s running VO₂ max (Billat et al., 1995; Wilkins, Watts, & Wilcox, 1996). Although these ranges fall below average VO₂ maxes for endurance athletes (65-80+ mL O₂·kg⁻¹·min⁻¹), the values still correspond with aerobic fitness levels required for rapid recovery following high intensity effort (Watts, 2004). Lower oxygen consumption may be due to the smaller muscle mass of the main muscles utilized while climbing (Phillips et al., 2012). Overall aerobic capacity is not likely a limiting factor, but rather the upper-extremities’ VO₂ uptake (Philippe et al., 2012; Phillips et al., 2012).

Disproportionate heart rate (HR)/VO₂ ratios and blood lactate (BL) concentrations above threshold level have been observed in climbing, indicating an anaerobic component (Mermier et al., 1997). Anaerobic power is predominantly needed in climbs less than 2 minutes (i.e., bouldering) and for high-intensity movements, as experienced multiple times during a rope-climb (Phillips et al., 2012). A study by Mermier et al. (1997) found VO₂ levels were fairly stable between easy, moderate, and hard climbs (20, 22, and 25 mL O₂·kg⁻¹·min⁻¹, respectively), but the HR was disproportionately higher (145, 155, and 163 bpm, respectively). Other studies have shown a similarly high HR while climbing (Billat et al., 1995; Watts, Drobish, & Ringheim, 1992). This is partly due to 37% of climb time involving intermittent isometric muscular contractions and the dependence on arms as the major muscle group (Billat et al., 1995). Heart rate rises disproportionately to VO₂ during isometric contractions, no matter the activity (Mermier et al., 1997). The fact that arms are normally positioned above the level of the heart while climbing may also influence HR (Mermier et al., 1997). Astrand, Guharay, and Wahren (1968) found blood pressure, BL, and HR for carpenters was significantly higher when nailing overhead versus nailing at waist level.
A rise in BL concentration further indicates the role of glycolysis in climbing (Mermier et al., 1997). Blood lactate concentrations are significantly correlated with route distance ($r = 0.41$, $p < 0.05$) (Watts, Newbury, & Sulentic, 1996). One study found BL rose as route difficulty increased; BL increased from 1.28 mmol/L at rest to 1.64 for easy (5.6YDS), 2.40 for moderate (5.9YDS), and 3.20 for difficult (5.11YDS) (Mermier et al., 1997). Climbing angles past 90° (i.e. overhangs) further increase route difficulty and, therefore, BL levels; 5.9 mmol/L at 102° has been observed. This increased BL concentration strongly correlates with decreased handgrip force ($r = 0.96$) (Watts & Drobish, 1998). However, another study found BL correlated with decreased handgrip endurance ($r = 0.76$), but not handgrip strength ($r = 0.56$) (Watts et al., 1996). As mentioned by Phillips et al. (2012), lactate concentrations reach 3-10 mmol/L while climbing, which is still noticeably lower than levels produced during cycling or running (Bertuzzi et al., 2007). As with VO$_2$, the smaller muscle mass of the UB would limit lactate production (Mermier et al., 1997).

**Upper-body components**

Finger-flexor strength and endurance are significant factors in climbing performance; finger and UB flexor strength explained 14.2% of the variance in one study (España-Romero et al., 2009; MacLeod et al, 2007; Nachbauer et al., 1987; Philippe et al., 2012). Finger and wrist flexors are extensively used because various grips are required for handling small holds and diverse rock features. Demands placed on the hands change as climbing position changes. One study found forces at the hand were 5-6 kg when all four limbs had contact with the wall, but increased to 9-10 kg when a hand was released (Quaine & Martin, 1999; Quaine, Martin, & Blanchi, 1997). Flexor muscles have to produce enough force to overcome gravity while maintaining hold-specific muscular endurance (Phillips et al., 2012; Watts, 2004). Climbers are
able to meet such demands by faster re-oxygenation of finger flexors (MacLeod et al., 2007). In a study by Philippe et al. (2012) study, there was no difference in rate of de-saturation between climbers and non-climber or gender for both intermittent and continuous isometric finger-flexor endurance tests. However, re-oxygenation was significantly faster during the rest phases of the intermittent test in climbers than non-climbers ($p = 0.013$); there was no difference by gender. Enhanced neuromuscular activity and increased fingertip pulp dimension, which improves friction with the climbing surface, may also play a role in climbing ability (Bourne, Halaki, Vanwanseele, & Clarke, 2011; Phillips et al., 2012).

Grip strength relative to body mass is a strong predictor of climbing ability (Baláš et al., 2012; Macleod et al., 2007; Watts, 2004). It was the only other factor, along with BF%, to significantly predict climbing performance in one study (Watts et al., 1993). Absolute and relative hand and pincer strengths are higher in climbers than non-climbers, and in males than females (Cutts & Bollen, 1993; Watts, 2004). Females should particularly take note of relative handgrip strength because it accounts for 50% of their performance, unlike 30% for males (Baláš et al., 2012). Indeed, an extremely strong correlation was found between best on-sight climbing performances and grip STW ratios ($r^2 = 0.946, p < 0.001$) for females (Philippe et al., 2012). Relative grip strength varies largely at lower-levels of climbing, but the gap narrows with increased performance, especially in men. It seems a high grip STW ratio is needed for elite-level climbing, but simply having high relative grip strength does not necessarily equate to higher climbing ability (Baláš et al., 2012). Relative crimp and pincer strength also generally have a positive impact on climbing. One study found grip and pincer strength are strongest in elite climbers when compared with lower-level and non-climbers. No difference was found in crimp strength, but many subjects found the method used to be painful, which could have
skewed the results (Grant et al., 1996). Although one study did not find pincer strength important (Mermier et al., 2000), another noted hand, crimp, and pinch STW ratios significantly correlated with decreased climb times in both genders (Mitchell et al., 2011).

Despite one study finding grip endurance not important (Mermier et al., 2000), another found grip endurance as the strongest predictor of HASE and, therefore, overall performance (Baláš et al., 2012). Climbers have longer times to failure for continuous and intermittent isometric endurance tests than non-climbers for both hand and pincer grips, and there is a significant gender difference (Cutts & Bollens, 1993; Philippe et al., 2012). Interestingly, finger flexor endurance seems to be more negatively impacted by climbing than strength. A study by Watts et al. (1996) found hand strength and endurance decreased with climb duration ($r = 0.70$ for both), but strength only dropped 22% from pre-climb levels versus a 57% drop in endurance; hand strength also recovered faster. When measured with a climbing-specific device, climbing until failure does not affect finger curl strength (Watts, Jensen, Moss, & Wagonsonomer, 2003).

Due to the effect grip strength had on climb time, it was further suggested that UB pulling strength be investigated (Mitchell et al., 2011). Pulling muscles, such as the elbow and shoulder extensors, are primarily used while climbing; UB and LB extensor strength accounted for 15.2% of variance in one study (Nachbauer et al., 1987; Phillips et al., 2012). Mermier et al. (2000) found isokinetic shoulder extension strength to be an important part of the training component that explained variance in rock climbing ability. Overhead sports tend to develop a shoulder strength imbalance in comparison to non-athletes. Rock climbing, in particular, uses internal rotators and elbow extensors when lifting oneself over a ledge (Phillips et al., 2012). A study by Wong and Ng (2009) found conventional and functional work ratios of internal and external shoulder rotators for climbers differ from non-climbers. Conventional ratios for
eccentric external and internal rotation (ecc ER:IR) and concentric external and internal rotation (con ER:IR) were roughly 1:1 in non-climbers – signifying external and internal rotators contributed equally. The conventional ratios fell below 1 for climbers, implying the internal rotators had a higher work output than external rotators. The functional ratios (ecc ER: con IR and con ER: ecc IR) also fell below 1 for climbers, further indicating internal rotators had stronger concentric and eccentric contractions than external rotators. This training-induced imbalance is likely caused by the internal rotators’ repeated use during the pull-up phase while climbing. The concentric power of the internal rotators is shown to be a major contributor in other overhead sports such as tennis, volleyball and swimming, reaffirming its importance in sport climbing (Bak & Magnusson, 1997; Ellenbecker, 1991; Ellenbecker, 1992; Ellenbecker & Mattalino, 1997; Wong & Ng, 2009). Although UB power output was not found to be a significant predictor of rock climbing performance in one study (Mermier et al., 2000), research still suggests it is a key feature of elite climbers (Watts, 2004) and is important for such movements as the dyno (Phillips et al., 2012). A dyno is an explosive, jumping maneuver that requires the climber to produce enough vertical momentum to come off the wall and reach the next hold (Phillips et al., 2012).

Isometric strength and endurance of UB flexors is the basis for efficient movement in climbing (Phillips et al., 2012). Grant et al. (1996) noted pull-up and bent arm hang tests, which indicate UB strength and endurance, set apart the elite climbers. Elite climbers have stronger forearms and greater forearm (28.3±1.28 vs. 26.02±1.80 cm) and arm (32.7±2.09 vs. 30.9±2.52 cm) circumference than lower-level climbers (Grant et al., 1996, Tomaszewski et al., 2011). The increased circumference is believed to be the result of changes in the forearm and arm muscles’ re-oxygenation rate (Ferguson & Brown, 1997; Philippe et al., 2012). Alomari, Mekary, &
Welsch (2010) found 4 weeks of rhythmic handgrip training lead to substantial blood flow of the forearm. Resistance training (intense intermittent endurance and modest continuous training) has been linked with increased capillary density and capillary-to-fiber ratios (Green, Goreham, Ouyang, Ball-Burnett, & Ranney, 1999; Jensen, Bangsbo, & Hellsten, 2004). Forearms go through similar physical stress when climbing and, therefore, may have similar physiological changes; increased blood flow increases the rate of re-oxygenation and faster re-synthesis of phosphocreatine (Philippe et al., 2012). Shoulder and forearm endurance has been found to be a significant variable in predicting climbing performance (Grant et al., 1996; Mermier et al., 2000; Watts et al., 1993). High UB STW ratio and power output is commonly associated with advanced rock climbers (Watts, 2004). A combination of grip strength, finger hang and bent-arm hang (collectively known as HASE) accounted for 76% of the variation in climbing performance in one study (Balás et al., 2012). Other studies have shown a similar importance of UB strength and endurance (Mermier et al., 2000; Nachbauer, Fetz, & Burtscher, 1987).

*Lower-body components*

Climbing is chiefly considered an UB sport, but LB contributions should not be ignored. Hip flexors are necessary to raise the foot to a stable foothold, while the knee extensors and quadriceps concentrically contract to raise the individual; heel hook maneuvers require strong knee flexors (Phillips et al., 2012). Mermier et al. (2000) found isokinetic knee flexion and extension were important variables in determining climbing performance. Although LB power output was not found to be significant factor (Mermier et al., 2000), some rock climbing movements require the explosive use of the LB. When a hold is out a reach, climbers may perform a maneuver known as a dyno. A powerful tri-extension of the hip, knee and ankle joints must happen simultaneously in order to produce enough leverage to reach a hold (Phillips et al.,
Tomaszewski et al. (2011) found competitive sport climbers had significantly longer legs than non-climbers, which may give some people a mechanical or height advantage. The LB also stabilizes body mass, while the UB adjusts one’s position (Bourdin, Teasdale, & Nougier, 1998). The more efficiently legs move while climbing, the more energy the upper-body may conserve (Watts, 2004).

Stability and flexibility

Research regarding balance and stability is limited. Only one study mentioned balance’s effect (7.4%) on climbing performance (Nachbauer et al., 1987). A study by Zampagni, Brigadori, Schena, Tosi, and Ivanenko (2011) thoroughly examined the control of the center of mass (COM) in elite and non-climbers. High-level climbers demonstrated body movement that optimized energy efficiency and stability while climbing. As noted by Isler (2005), gravity acceleration and far horizontal distance from a vertical wall cause tilting of body weight; this is countered by the grasping force of hands and feet as seen in climbing animals. A reduction in the horizontal distance reduces torque and thereby the muscular force needed for counteracting gravity. Curiously, elite climbers tended to tilt further away from the wall than non-climbers; this could be due to a relatively stronger UB, thus a better ability to oppose gravity (Zampagni et al., 2011). The energy cost of standing straight versus fighting gravity may further explain this tendency. If an individual’s body posture causes their COM to be directed through the ankles, no counterbalancing torque needs to be produced by the calf muscles. However, this position is unstable and requires continuous nervous system control. In fact, the preferred COM position is 4-5cm in front of the ankles. This suggests counterbalancing static tilting torque is more cost-efficient than vertically stabilizing one’s body nearer the rock wall (Gurfinkel, Ivanenko, Levik, & Babakova, 1995). It has been informally proposed that straight arms promote economical
movement by transferring the load from UB to the LB, and the position grants a clearer view for proper footwork (Woodward). Straight arms may conserve energy by relying more on the skeletal system for support than the muscular system. In a bent-arm state, more of the UB must isometrically contract to maintain stability (“Mechanics in Exercise”, 2015). Prolonged isometric contractions reduce local blood flow and can cause muscular fatigue (Ferguson & Brown, 1997). When climbing animals are in a straight-arm state, force produced to overcome gravity is isolated to their hands and feet (Isler, 2005). The same may be true for elite climbers as noted by the importance of handgrip strength and endurance on climbing performance (Baláš et al., 2012; Watts et al., 1993).

Additionally, elite climbers had significantly larger lateral oscillations of their COM than non-climbers (Zampagni et al., 2011). Termed “diagonal gait”, body weight was shifted to the left leg as the right arm reached up and vice versa. When walking, humans tend to move up and down, which allows the mechanical energy of the COM to be conserved and restored with each step; walking flat causes muscles to work less efficiently and waste energy (Cavagna, Willems, & Heglund, 2000; Massad, Lejeune, & Detrembleur, 2007). Climbing in a straight or “ladder-like” manner – comparable to walking flat - may put muscles in a similarly non-ideal condition that wastes energy and stability (Woodward; Zampagni et al., 2011). Non-climbers are often seen taking this “ladder-like” approach, resulting in narrower lateral oscillations. Elite climbers, over time, inherently gain the ability to optimize their body movement by shifting their body mass, translating into better stability and efficiency while climbing (Zampagni et al., 2011).

A seasoned climber pushes with their legs, rather than pull with their arms, to move upward. Proper hip and trunk orientation ensures the body’s position maximizes lower-body power, while minimizing the UB energy needed to stay on the rock wall (Woodward). The core
musculature is described as a “box” with the diaphragm as the top, the pelvic floor and hip girdle as the bottom, gluteals and paraspinals on the back, and abdominals rounding out the front (Richardson, Jull, Hodges, & Hides, 1999). Hodges (2004) is often credited with first suggesting an in-depth definition of lumbopelvic stability (i.e., core stability). He defined it as the “dynamic process of controlling static position in the functional context, but allowing the trunk to move with control in other situations” (Waldhelm & Li, 2012, p. 121). Core strength and endurance in rock climbers has not been scientifically examined, but as with all sports it is believed to play an important role (Phillips et al., 2012). Roetert (2001) explained core stability and balance are beneficial in all sports and activities because the 3-dimensional nature of many movements. A lack of core stability can result in poor technique, which increases an athlete’s chance for injury (Jeffreys, 2002). Core conditioning is likely to improve overall climbing efficiency, especially on overhanging sections (i.e., more than 90° to the ground). In order to keep one’s COM close to the rock, trunk flexion/extension and rotation are constantly utilized. When a climber’s feet lose contact with the rock surface, it greatly increases the workload for the UB; a strong trunk can help a climber regain his or her footing (Phillips et al., 2012).

An individual’s COM is often influenced by feet placement on the wall (Noe, 2006). When traversing rock faces with limited or small foot holds, excellent neuromuscular control is needed to maintain balance and stability (Phillips et al., 2012). This is frequently accomplished via precise movement of the forefoot, which is controlled by way of ankle stability (Schweizer et al., 2005). Effective rock climbing requires the ankles to hold isometric contractions in various positions (Schweizer et al., 2005). In a study comparing soccer players to rock climbers, Schweizer et al. (2005) showed soccer players had a slightly higher absolute strength in ankle extension. The repetitive movement of ankle extensors while kicking can explain the difference.
On the other hand, rock climbers performed significantly better in a one-leg standing stabilometry test (an indication of functional stability); absolute and relative ankle flexion strength were also higher. Ankle movements tend to be slower, more isometric, and more controlled in climbing, resulting in a higher degree of stability and strength than soccer players. Although balance training in climbers has not been researched, focus on ankle strength and endurance is recommended (Phillips et al., 2012). Suggestions include balancing with heels off of a ledge and the foot isometrically held at different ranges of plantar flexion; the medial and lateral portions of the feet should be trained as well. To mimic the irregularity of a rock face, balancing should be practiced on a variety of surfaces, such as foam mats, rocks, wood pegs, etc. (Phillips et al., 2012).

Advanced rock climbers have been recognized for their increased hip flexibility, but its impact on climbing is still debated (Draper & Hodgson, 2008). Flexibility can explain 1.8% (Mermier et al, 2000) to 16% (Nachbauer et al., 1987) of the variance seen in climbing performance. The relevance of hip flexion, abduction and external rotation in high-stepping and bridging movements while climbing has been the basis of most flexibility research (Giles, Rhodes, & Tauton, 2006: Phillips et al., 2012; Watts, 2004). A variety of tests have been used, but not every flexibility test is appropriate for assessing climbing flexibility (Draper et al., 2009). The sit-and-reach is normally a reliable measurement of hip flexion, but not for rock climbers (Draper et al., 2009). Similar to findings by Grant et al. (1996) and Draper et al. (2009) found there was a trend for elite climbers to have higher sit-and-reach scores, but the correlation was very poor (r = 0.15). The foot raise, another flexion test that requires foot placement at maximum hip flexion without lateral movement, was originally used by Grant et al. (1996). Draper et al. (2009) noted placement height increased as climbing ability increased, but it was not a
significant correlation ($r = 0.20$). When an adapted version was tested (foot raised laterally), there was a significant correlation ($r = 0.31$) (Draper et al., 2009). Both versions of the foot raise test are a valid measure of a climber’s hip flexion, but the adapted version may be better because it more closely mimics the move made during climbing (Draper et al., 2009).

Several studies have used the leg span test to measure hip abduction (Grant et al., 1996; 2001; Mermier et al., 2000). Grant et al. (1996) found elite male climbers had significantly wider leg spans than recreational and non-climbers, but this was not the case for females (Grant et al., 2001). Furthermore, Mermier et al. (2000) indicated hip abduction was a poor predictor of climbing performance. Only one study used a lateral foot reach test under conditions similar to climbing; in this situation, hip abduction and external rotation were both considered (Draper et al., 2009). Subjects hung onto a rung located centrally above them and had an active start with their left foot; they laterally extended their right foot as far as possible. There was no significant correlation with climbing ability ($r = 0.20$) until height was considered ($r = 0.30$). Although one study noted no significant correlation between leg length and leg span scores (Grant et al., 1996), this climbing-version of the traditional leg span test took into account external rotation. When viewed in the context of climbing-specific movements, it is plausible height and/or leg length may influence the degree of hip flexibility; however, further research is required to understand this connection. At a minimum, both tests are considered reliable measurements of hip abduction and external rotation when using the lateral foot reach test (Draper et al., 2009).

Perhaps the best measure of climber flexibility is the foot-loading test; it is significantly related to one’s climbing level ($r = 0.65$) (Draper et al., 2009). Starting from an active position, subjects raised their right foot to a higher hold and transferred their body mass onto that hold. The “loaded” point occurred when the subjects’ hips were above the loaded foot and the majority
of their mass had been shifted to the higher foot hold. The distance between the starting foot hold and the higher foot hold was measured; farther distances equated to higher climbing ability. Because high-stepping and reallocating weight is a trademark skill in rock climbing, many climbing experts agree with the use of this test (Draper et al., 2009). It has been suggested a battery of tests, versus just one, may provide a more comprehensive understanding of climber flexibility (Draper et al., 2009). Further research is needed to identify which flexibility tests are most applicable to rock climbers, which in turn may help determine the role flexibility plays in climbing.

Summary

In conclusion, anthropometric and psychological factors are part of rock climbing, but trainable physical factors appear to have the strongest influence on performance. Rock climbing over time produces numerous physiological changes that distinguish rock climbers from non-climbers; these adaptations appear to be enhanced as climbing ability increases. The following variables explained the majority of the variances observed in rock climbing performance: UB and grip strength and endurance, BF%, and climbing volume. Factors such as overall flexibility, climbing-specific balance, and core endurance are believed to be beneficial to climbing performance, but the research is extremely limited or non-existent.

After review of the current published literature, the first hypothesis of this study is handgrip and pinch endurance and strength, UB endurance, core endurance, and BF% will have a strong correlation with the climbing performance score (CPS); therefore, these factors will be the strongest predictors of CPS. The second hypothesis is hip flexion and abduction, UB power and strength, balance and climbing volume will have a low-moderate correlation with CPS. The third hypothesis is LB power and strength and maximum oxygen uptake will not have a statistically
significant correlation with CPS. The final hypothesis is handgrip strength will be the strongest predictor of CPS.
CHAPTER 3
METHODS

Introduction

The methods described here were designed to determine which trainable physical variables were most significant in determining rock climbing performance. A climbing history questionnaire was utilized. Subjects were assessed on the following physical factors: a performance climb, BF%, handgrip and pinch strength and endurance, UB power and strength and endurance, LB power and strength, VO₂max, core endurance, hip flexion and abduction flexibility, and balance. A Pearson product moment correlation was used to assess relationships between subject characteristics and climbing performance scores (CPS), CPS and physical variables, and among the physical variables themselves. Physical variables were entered into a backward stepwise regression analysis to determine the strength of each variable in predicting the CPS.

Subjects

Male (ages 18-45) and female (ages 18-55) rock climbers were recruited from the University of Central Missouri’s indoor rock climbing facility via a recruitment flyer (see Appendix A). Before participating in the study, subjects completed a health history survey, a climbing history questionnaire and an informed consent form (see Appendices B-D). Subjects demonstrated a readiness by completing a Physical Activity Readiness Questionnaire (PAR-Q), a self-guided health survey used to assess pre-existing medical conditions (Thompson, Gordon, & Pescatello, 2010). A climbing history questionnaire was used to gather information about years of experience, hours climbed per week, types of climbing experienced (i.e., sport, lead, traditional, etc.), self-reported climbing rating and current training regimen.
Subjects were excluded from the study if they had a limited climbing background (< 5 previous climbs) or an unsuccessful completion of the screening climb (~ 5.6 YDS). Exclusions were also based on self-reported pre-existing medical conditions that could have put the subject at risk during testing procedures and/or climbing trials. Considering the maximal effort required for Wingate testing, an age limit was established (<45 yr males, <55 yr females, and all subjects <18 yr were excluded) based on the American College of Sports Medicine’s Guidelines of Exercise Testing and Prescription (Thompson et al., 2010).

Visits

Physical assessments took place over the course of three visits, one at UCM’s rock climbing wall and two in the UCM’s Department of Nutrition and Kinesiology human performance lab. Indoor rock climbing was used because environmental factors are more readily controlled (Mermier et al., 2000). The screening and performance climb were completed during visit one. UB strength and power, BF%, hip flexion and abduction flexibility, VO2max, and balance were assessed during visit two. Tests regarding handgrip and pincer strength and endurance, core endurance, LB strength and power, and UB endurance were completed during visit three. Subjects were asked to continue their current training programs and diet throughout the duration of the study.

Climbing Trials

A USA Climbing level 1 certified competition route setter designed and set both the screening and performance climb routes on ~10 m rock wall. The screening climb was a low-level climb (~5.6 YDS). The performance climb was designed to increase in difficulty with each successive handhold (~5.6 to 5.13 YDS). An experienced route setter climbed the routes to confirm the ratings. Subjects warmed-up with low-intensity aerobic exercises (e.g. beginner-
level bouldering routes) and dynamic movements (e.g. modified or regular push-ups or hand walk-outs) for 5-10 minutes before the screening and performance climb. A successful, single attempt at the screening climb (~5.6 YDS) was required before testing could commence. Using a top-rope climbing system with experienced belayers, subjects were allowed two attempts with unlimited time for the performance climb. The subjects climbed on-sight with no prior practice, knowledge of the route, or verbal encouragement. Subjects were scored in a fashion similar to that used in sport climbing competitions; each subsequent handhold increased in point value by one. The highest CPS achievable was 37; additionally, a subjective point value was given based on how the last hold was handled or “controlled”. A 0.01 was added to the CPS score if the subjects touched but did not grasp the hold before falling. A 0.05 if they were able to grasp the hold but not continue any further. A 0.9 was added if the participants firmly grabbed and tried to move off the hold before falling (Mermier et al., 2000, USA Climbing 2013). The highest score of the two attempts was recorded.

Body fat percentage

BF% was determined using dual energy x-ray absorptiometry (DEXA) (Lunar Prodigy Advance, GE Healthcare, Madison, WI). Subjects were asked to lie still on a full-body scanning table as low x-ray energies were emitted. The procedure was non-invasive, simple and required about ten minutes. The radiation was low, so no shielding of the room or personnel was needed (Center for Disease Control and Prevention, 2007). DEXA is considered to be more accurate than skinfold methods in determining body fat levels of climbers (Romero et al., 2009).

Handgrip strength and endurance

Greater differences are seen in handgrip strength between climbers and non-climbers when grip strength is expressed in relative versus absolute terms (Watts, 2004). The current
study focused on absolute strength because 1) relative grip strength has already been proven to be a predictor of climbing performance and 2) climbers still tend to have stronger absolute strength than non-climbers (Cutts & Bollen, 1993; Watts et al., 1993). A handgrip dynamometer was used to find maximum isometric handgrip strength. The subject stood upright, arm straight and somewhat abducted, with the middle phalanx of the hand in line with the handle. Without the use of additional body movement, the participant quickly squeezed the dynamometer with a maximal voluntary contraction (MVC). There were 3 trials, with 1-minute rests in between, conducted for both hands. The highest values for both hands were averaged together and recorded to the nearest 0.05 kg (Heyward & Gibson, 2014).

The same hand dynamometer was used to determine handgrip endurance. Holding the dynamometer in their hands as previously described for grip strength, subjects squeezed 50% of their MVC until failure. Time was recorded from the point that the value was reached until it was no longer maintained. The researcher watched the dynamometer for the duration of the test. There were 2 trials, with a 2-minute rest in between. The highest times for both hands were averaged together and recorded to the nearest second. Subjects were allowed to chalk their hands for both handgrip tests; climbers often use chalk in order to counteract the reduced friction caused by sweat.

Pincer strength and endurance

Climbers also tend to have stronger absolute pincer strength than non-climbers (Cutts & Bollen, 1993). In keeping with handgrip strength, absolute pincer strength was assessed in the current study instead of relative strength. A pincer dynamometer was used to determine pincer strength. The subject briefly pinched as hard as possible between their thumb and index/middle
digits. There were 3 trials, with 1-minute rests in between conducted for both hands. The highest value for both hands was averaged together and recorded to the nearest 0.01 kg.

Pincer endurance was determined using the same pincer dynamometer. Placing their thumb and index/middle digits on the dynamometer, subjects pinched 50% of their pincer MVC until failure. Time was recorded from the point that the value was reached until it was no longer maintained. The researcher watched the dynamometer for the duration of the test. There were 2 trials, with a 2-minute rest in between. The highest times for each hand were averaged together and recorded to the nearest second. Subjects were allowed to use chalk for both pincer tests.

**Upper-body endurance, strength, and power**

A bent-arm hang test was used to determine UB endurance and is a common test among rock climbers (Baláš et al., 2012). A bent arm was chosen over a full flexion (i.e., lock off strength) or extension position because it has been shown climbers can hold these positions for extended periods of time without the UB fatiguing (Mermier et al., 2000). Stepping blocks were used to position subjects on a pull-up bar in order to reduce additional muscle exertion. Subjects used an overhand grip (chalked up if they desired) slightly wider than shoulder-width apart, with palms facing forward. Once the participant’s elbow joints formed a 90° angle, the steps were removed and timing started. Timing was continued until the angle was no longer sustained. The researcher visually verified when the subject had failed to maintain a 90° angle. Time was recorded to the nearest second.

Upper-body strength was determined through a 1-repetition maximum (1RM) bench press test. Subjects warmed up with 10 repetitions at 50% of their predicted 1RM, 5 repetitions at 75%, and 1 repetition at 90%. Each set was followed by 3 minutes of rest. Subjects then
attempted a 1RM lift; if successful, weight was increased until failure (Hoffman, 2006). The last successful weight lifted was recorded to the nearest 1.0 kg.

Upper-body power was determined by a medicine ball put, also known as a seated medicine ball toss (Miller, 2012). Subjects warmed up for 5 minutes with moderate-intensity aerobic exercise and dynamic movements involving the elbow and shoulder joints. Subjects were allowed numerous practice throws with a lighter medicine ball. Once ready, the subject sat at a 90° angle with their back flush against the chair and the medicine ball held at chest level. Males used 9 kg balls and females used 6 kg balls. Without any extra movement, the subject launched the medicine ball as far as possible at a 45° angle. There were three trials, with 2-minute rests in between. A tape measure running parallel to the subject’s position was used to visually record the farthest distance to the nearest 1.0 cm.

Lower-body strength and power

Lower-body strength was determined through a 1 RM leg press test. Subjects warmed-up with 10 repetitions at 50% of their predicted 1RM, 5 repetitions at 75%, and 1 repetition at 90%. Each set was followed by 3 minutes of rest. Subjects then attempted a 1RM press; if successful, weight was increased until failure. The last successful weight attempted was recorded to the nearest 1.0 kg.

Lower-body power was assessed through the Wingate bike test as explained by Inbar, Bar-Or, and Skinner (1996). Subjects warmed up on a cycle ergometer for 5-10 minutes, alternating between 30 seconds of pedaling and 30 seconds of rest; a 3-5 minute rest followed to reduce any fatigue connected with the warm up. The warm up protocol has been found acceptable for many groups regardless of age, gender or health status (Inbar et al., 1996).
When told to “start”, subjects pedaled as fast as possible for 3-4 seconds to overcome the initial low-resistance and friction of the flywheel. The full resistance load was then applied for exactly 30 seconds. Workload was 0.092 kp/kg BW for males and .075 kp/kg for females (Bar-Or, 1987). Because this was a maximal test, subjects were verbally encouraged to continue pedaling as fast as possible the entire 30 seconds. Two to three minutes of light resistance pedaling constituted the cool down. Because of the test’s high intensity, subjects might have been prone to dizziness and syncope. However, a warm up and cool down possibly helped prevent these symptoms and improve the subjects’ morale. It was reasonably assumed, under these precautions, the Wingate test would be safe to use by a healthy individual (Inbar et al., 1996). Peak power output, mean power output and fatigue index were collected. A correlation was conducted between CPS and the three measurements. Mean power output (in watts) had the highest correlation with CPS ($r = 0.228$) and, therefore, was used to represent LB power in later statistical analyses.

**Hip flexion and abduction flexibility**

Hip flexion flexibility was determined through the foot raise test as used by Grant et al. (1996). Subjects stood 23 cm from a wall, with hands placed on the wall at shoulder height. Without any lateral motion, subjects were asked twice to lift the toe of their right foot as high as possible. Once the spot was marked, the distance was measured from the point on the wall to the ground to the nearest 0.5 cm.

Hip abduction flexibility was determined through a leg span test also mentioned by Grant et al. (1996). Subjects stood with their back straight against a wall. Subjects placed their feet as far apart as possible while maintaining full knee extension. Leg span was measured from left to right medial calcaneus to the nearest 0.5 cm, using a tape measure.
Balance

The Athlete Single Leg Stability test was done on the Biodex Balance System SD at a level 4 to obtain functional ankle stability. Unlike a static force plate, the dynamic tilting platform of the balance system was more likely to stimulate the neuromuscular control aspects of balancing, resulting in a more accurate test. Dynamic balance is the ability to perform a task while maintaining balance or being able to regain balance on an unstable surface (Paillard & Noe, 2006; Winter, Patla, & Frank, 1990). Subjects were barefoot as they stood on the Biodex platform while holding onto the support handles. The testing protocol was explained during this time, and subjects performed a sample trial in order to familiarize themselves with the dynamic balance plate. Once ready, subjects stood on one foot in the center of the platform and let go of the support handles. Three trials of 20 seconds, with a 10-second rest in between each trial, was conducted for each leg; the overall stability index (OSI) score for each leg was averaged together and recorded to the nearest 0.01cm. The score is the distance a subject deviates from the center of pressure (CoP). Higher scores equate to less postural stability (Riemann & Davies, 2013).

Core endurance

Core endurance tests seem to be the most reliable indicator of overall core stability (Waldhelm & Li, 2012). Four different tests were used to measure core endurance as mentioned by Waldhelm and Li (2012). First, a trunk flexor test involved subjects sitting with knees bent, while leaning back at a 30° angle. Second, a trunk extensor test was conducted by having subjects lie prone on a treatment table. After legs were secured, the UB with arms crossed was held horizontal over the edge. Last, a left and right side bridge test required participants to be in a side-lying position by supporting their weight on their feet and one forearm. Each test was timed from the moment stability was reached until failure to maintain the necessary position; all tests
were timed to the nearest second. For the purpose of simplifying later statistical analyses, all 4 measurements were correlated with CPS. There was hardly any correlation with trunk flexion and extension \((r = 0.01 \text{ and } r = 0.10, \text{ respectively})\). Right and left side bridges had stronger correlations with CPS \((r = 0.398 \text{ and } r = 0.381, \text{ respectively})\). The right side bridge test was ultimately used to represent core endurance.

**VO\(_{2\text{max}}\)**

Maximal oxygen consumption was measured on a bike ergometer using a metabolic cart. Subjects warmed up for 2 minutes at 60 watts, maintaining a cadence between 50-60 rpm. During the test, resistance increased by 1 watt every 4 seconds; cadence was maintained between 50-60 rpm. Subjects continued until at least two of the following criteria were met: 1) RER (respiratory exchange ratio) was >1.0, 2) HR was within 5 beats of the age-predicted maximum HR, or 3) an RPE (rating of perceived exertion) of \(\geq 17\) on the Borg Scale (Evans & White, 2009). VO\(_{2\text{max}}\) was recorded to the nearest 0.5 mLO\(_2\)·kg\(^{-1}\)·min\(^{-1}\). Subjects cooled-down until HR fell below 100 bpm.

**Statistical Analysis**

A Pearson product moment correlation was used to assess relationships between subject characteristics and CPS, CPS and physical variables, and among the physical variables themselves. Correlation coefficients \((r)\) 0.9 or higher signified a strong correlation, 0.7-0.89 was moderate, 0.5-0.79 was low, and anything below 0.5 was not statistically significant (Vincent, 2005). A multiple regression analysis determined the significance of subject characteristics (gender, height, weight, age) in predicting CPS. A backward stepwise multiple regression analysis was used to determine the strength of each physical variable in predicting CPS.
Significance for all tests were determined using a two-tailed test with a 95% confidence interval.

Statistical analyses was performed using the statistical software program PASW Statistics 18.
CHAPTER 4
RESULTS

A group of male (n=22) and female (n=3) rock climbers participated in the present study. The mean height for the males was 179.5 ± 5.9 cm, weight 77.7 ± 12.4 kg, and age 20.4 ± 1.4 years. The mean height for the females was 155.1 ± 15.1 cm, weight 56.8 ± 15.0 kg, and age 20.7 ± 1.5 years. The participants had a wide range of climbing background and ability as represented by Table 1.

Table 1
Participants Climbing Background and Ability

<table>
<thead>
<tr>
<th></th>
<th>Beginners (5.7-5.8 YDS)</th>
<th>Intermediate (5.9-5.10 YDS)</th>
<th>Advanced (5.11+ YDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Subjects</td>
<td>6</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Years Climbed (years)</td>
<td>2.22 ± 2.25</td>
<td>1.00 ± 1.61</td>
<td>2.94 ± 1.38</td>
</tr>
<tr>
<td>Volume (yards/week)</td>
<td>222.00 ± 179.00</td>
<td>925.00 ± 571.00</td>
<td>1559.00 ± 1005.00</td>
</tr>
<tr>
<td>Types of Climbing*</td>
<td>2.00 ± 1.00</td>
<td>2.00 ± 1.00</td>
<td>4.00 ± 1.00</td>
</tr>
<tr>
<td>CPS**</td>
<td>20.80 ± 4.40</td>
<td>26.10 ± 2.30</td>
<td>31.0 ± 3.60</td>
</tr>
</tbody>
</table>

Note: Values are Mean ± SD. (*) Types of climbing is the number of different styles of climbing experienced by the subject (i.e., top-roping, sport, ice climbing, etc.). (**) CPS (Climbing Performance Score) is out of 37.

Correlation strength was considered strong ($r = \geq 0.9$), moderate ($r = 0.70-0.89$), low ($r = 0.50-0.79$), or very poor ($r = < 0.50$) based on the correlation coefficient; anything below $p < 0.05$ was not significant (Vincent, 2005). Table 2 identifies the significant correlations found between trainable physical factors and climbing performance scores (CPS). Only climbing
volume, UB endurance and BF% had moderate strength correlations with CPS, all other factors fell below $r = 0.50$. Correlations among the physical variables themselves were also evaluated, as noted in Appendix E. Although height, weight, gender and age did affect some aspects of climbing (i.e. handgrips strength, balance, etc.), the subject characteristics themselves did not correlate with CPS (See Table 3). A multiple regression analysis found the height, weight, gender and age only explained 25.3% of the variance seen in CPS, and this was not significant ($F = 1.693, p = 0.191$).

Table 2

<table>
<thead>
<tr>
<th>Correlation Coefficient with CPS</th>
<th>Significance *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (yards/week)</td>
<td>0.615</td>
</tr>
<tr>
<td>UB Endurance (sec)</td>
<td>0.604</td>
</tr>
<tr>
<td>BF%</td>
<td>-0.604</td>
</tr>
<tr>
<td>Core Endurance (sec)</td>
<td>0.434</td>
</tr>
<tr>
<td>VO$_2$ max (ml/kg/min)</td>
<td>0.451</td>
</tr>
</tbody>
</table>

Note: (*) = $(p < 0.05)$. CPS = climbing performance score. BF% = body fat percentage.
Table 3

Correlations Between Subject Characteristics and CPS/Trainable Physical Variables

<table>
<thead>
<tr>
<th></th>
<th>Gender+</th>
<th>Height</th>
<th>Weight</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPS</td>
<td>-0.294</td>
<td>0.246</td>
<td>-0.153</td>
<td>0.273</td>
</tr>
<tr>
<td>Volume (yards/week)</td>
<td>-0.015</td>
<td>0.167</td>
<td>-0.149</td>
<td>0.391</td>
</tr>
<tr>
<td>Handgrip Endurance (sec)</td>
<td>-0.013</td>
<td>0.087</td>
<td>0.171</td>
<td>0.070</td>
</tr>
<tr>
<td>Handgrip Strength (kg)</td>
<td>-0.696**</td>
<td>0.566**</td>
<td>0.416</td>
<td>0.148</td>
</tr>
<tr>
<td>UB Endurance (sec)</td>
<td>-0.550**</td>
<td>0.463*</td>
<td>0.034</td>
<td>0.085</td>
</tr>
<tr>
<td>BF%</td>
<td>0.567**</td>
<td>-0.493*</td>
<td>0.235</td>
<td>-0.144</td>
</tr>
<tr>
<td>Pincer Endurance (sec)</td>
<td>-0.330</td>
<td>0.325</td>
<td>0.156</td>
<td>0.288</td>
</tr>
<tr>
<td>Pincer Strength (kg)</td>
<td>-0.269</td>
<td>0.038</td>
<td>0.315</td>
<td>0.126</td>
</tr>
<tr>
<td>Core Endurance (sec)</td>
<td>-0.174</td>
<td>0.141</td>
<td>-0.118</td>
<td>0.313</td>
</tr>
<tr>
<td>Hip Abduction (cm)</td>
<td>0.055</td>
<td>0.159</td>
<td>-0.017</td>
<td>0.353</td>
</tr>
<tr>
<td>Hip Flexion (cm)</td>
<td>0.229</td>
<td>-0.184</td>
<td>0.075</td>
<td>0.375</td>
</tr>
<tr>
<td>Balance (cm)</td>
<td>-0.243</td>
<td>0.321</td>
<td>0.650**</td>
<td>-0.426*</td>
</tr>
<tr>
<td>UB Strength (kg)</td>
<td>-0.477*</td>
<td>0.526**</td>
<td>0.631**</td>
<td>-0.138</td>
</tr>
<tr>
<td>LB Strength (kg)</td>
<td>-0.597**</td>
<td>0.581**</td>
<td>0.496*</td>
<td>-0.275</td>
</tr>
<tr>
<td>UB Power (cm)</td>
<td>-0.344</td>
<td>0.492*</td>
<td>0.360</td>
<td>-0.041</td>
</tr>
<tr>
<td>LB Power (watts)</td>
<td>-0.571**</td>
<td>0.579**</td>
<td>0.617**</td>
<td>0.041</td>
</tr>
<tr>
<td>VO2max (ml/kg/min)</td>
<td>-0.478*</td>
<td>0.306</td>
<td>-0.005</td>
<td>0.210</td>
</tr>
</tbody>
</table>

Note: (*) = (p < 0.05). (**) = (p < 0.01). (+) = For statistical purposes, males were inputted as “1” and females as “2”. CPS = climbing performance score. BF% = body fat percentage. UB = upper-body. LB = lower body.
A backward stepwise multiple regression analysis was used to determine the strength of each physical variable in predicting CPS. All physical variables were entered into the model; each round, variables were removed if their absence improved the model. Table 4 lists the standardized coefficients (Beta) for each variable in order of strength of prediction, strongest to weakest. Only 6 of the 16 variables were found to be significant. The suggested model accounted for 85.1% of the variance seen in CPS ($F = 16.125, p < 0.01$). The following regression equation was generated: $CPS = 7.289 + 0.058 \text{ (med ball put)} + -0.234 \text{ (handgrip strength)} + -2.432 \text{ (balance)} + 1.433 \text{ (pincer strength)} + -0.260 \text{ (BF\%)} + 0.149 \text{ (pincer endurance)}$. The unstandardized coefficients ($\beta$) used in the equation indicated how much CPS increased with one increase in the physical variable’s unit of measure. The following, in order of strength, were the most significant predictors of climbing performance: UB power ($\text{Beta} = 0.605, p = 0.000$), handgrip strength ($\text{Beta} = 0.585, p = 0.002$), balance ($\text{Beta} = -0.575, p = 0.000$), pincer strength ($\text{Beta} = 0.531, p = 0.001$), BF\% ($\text{Beta} = 0.489, p = 0.001$), and pincer endurance ($\text{Beta} = 0.488, p = 0.000$).
Table 4
Strength of Trainable Physical Factors in Predicting CPS (Strongest to Weakest)

<table>
<thead>
<tr>
<th>Physical Variables</th>
<th>Standardized Coefficients (Beta)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>UB Power</td>
<td>0.605</td>
<td>0.000*</td>
</tr>
<tr>
<td>Handgrip Strength</td>
<td>0.585</td>
<td>0.002*</td>
</tr>
<tr>
<td>Balance</td>
<td>-0.575</td>
<td>0.000*</td>
</tr>
<tr>
<td>Pincer Strength</td>
<td>0.531</td>
<td>0.001*</td>
</tr>
<tr>
<td>BF%</td>
<td>0.489</td>
<td>0.001*</td>
</tr>
<tr>
<td>Pincer Endurance</td>
<td>0.488</td>
<td>0.000*</td>
</tr>
<tr>
<td>LB Power</td>
<td>0.135</td>
<td>0.265</td>
</tr>
<tr>
<td>Climbing Volume</td>
<td>0.115</td>
<td>0.369</td>
</tr>
<tr>
<td>UB Endurance</td>
<td>0.114</td>
<td>0.453</td>
</tr>
<tr>
<td>Core Endurance</td>
<td>0.085</td>
<td>0.451</td>
</tr>
<tr>
<td>Hip Flexion</td>
<td>-0.083</td>
<td>0.460</td>
</tr>
<tr>
<td>VO2max</td>
<td>0.076</td>
<td>0.586</td>
</tr>
<tr>
<td>LB Strength</td>
<td>0.060</td>
<td>0.644</td>
</tr>
<tr>
<td>Hip Abduction</td>
<td>-0.025</td>
<td>0.820</td>
</tr>
<tr>
<td>Handgrip Endurance</td>
<td>-0.025</td>
<td>0.823</td>
</tr>
<tr>
<td>UB Strength</td>
<td>-0.024</td>
<td>0.850</td>
</tr>
</tbody>
</table>

Note: (*) = (p < 0.05). CPS = climbing performance score. BF% = body fat percentage. UB = upper-body. LB = lower body.
Discussion

The purpose of this study was to determine which trainable physical variables were the strongest predictors of proficient rock climbing performance. The four hypotheses for this study were: 1) handgrip and pincer strength and endurance, UB endurance, core endurance, and BF% would have a strong correlation with climbing performance scores (CPS), 2) hip flexion and abduction, UB power and strength, and balance would have a low-moderate correlation with CPS, 3) lower-body (LB) power and strength and VO₂ max would have a poor correlation, and 4) handgrip strength would be the strongest predictor of rock climbing ability.

The main findings of this study found UB endurance, BF%, and climbing volume were moderately correlated with climbing performance scores. All other trainable variables had correlations which fell below \( r = 0.50 \), thereby indicating poor correlation associations with CPS (See Appendix E). Despite core endurance and VO₂ max having weak relationships with CPS, they were still significant. It was correctly hypothesized that handgrip strength, pincer strength and endurance, and BF% would be among the strongest predictors of CPS; however, handgrip endurance, UB endurance, and core endurance were not significant. Balance and UB power were the other two significant predictors (See Table 4). Interestingly, handgrip strength came second to UB power as the strongest predictor of rock climbing ability. In order of strength, the following variables significantly predicted CPS: UB power, handgrip strength, balance, pincer strength, BF%, and pincer endurance. These six variables explained 85.1% of the variance seen in the CPS. Additionally, none of the subjects’ characteristics (i.e. gender, height, age, weight) significantly correlated with or predicted climbing rating (See Table 3).
Despite a minor trend for males to have a higher CPS than females, the correlation was very poor and insignificant. Even though the female sample in this study was small (n = 3), gender differences appear to be inconsequential when determining the effect of anthropometric and trainable physical variables on climbing performance (Mermier et al., 2000). In fact, none of the subjects’ characteristics correlated with CPS (See Table 3). The factors only described 25.3% of the variance seen in CPS, and this was not significant. Height and weight, along with other anthropometric traits, do not correlate with climbing ability; anthropometrics only explained 0.3% of climbing performance in one study (Mermier et al., 2000; Tomaszewski et al., 2011). The exception would be Nachbauer et al. (1987), which found height and body mass explained 9.9% of the variance. However, the current study analyzed a restricted number of variables, which could have exaggerated height and weight’s role in climbing performance. Mermier et al. (2000) also found age had no effect on climbing performance, but most rock climbing studies only assess younger climbers (~20-33 yr). Though not significant, there was a direct correlation between CPS and age. With age comes more potential years of experience, which is linked to higher climbing levels, and older climbers are as prone to risk-taking as younger climbers (Baláš et al., 2012; Llwewlllyn & Sanchez, 2008). Additionally, balance - one of the top three predictors of CPS - and age correlated with one another. Balance increases with age in young adults as the ability to consistently and accurately use visual input is acquired over time (Balogun, Ajayi, & Alawale, 1997). Despite having lower risks for re-injury, climbers over 40 years of age may start to feel the repercussions from years of climbing (Backe, Ericson, Jansan, & Timpka, 2009; Bollen & Wright, 1994). Bollen and Wright (1994) found many of their subjects (20-50 yrs) had bone spurs or “scalloping” in their fingers, but only the older rock climbers (> 40 yrs) had full-blown osteoarthritis in their hands. They complained of stiffness and aching in cold weather,
while the younger participants were asymptomatic. Future research should consider older climbers to better understand the benefit of years of climbing experience in conjunction with the limitations of aging.

Three physical factors had a moderate correlation with CPS: climbing volume, BF% and UB endurance (See Appendix E). In regards to climbing volume, elite climbers completed the most vertical meters per week (e.g., beginner: mean 222 ± 179 m; intermediate: 925 ± 571 m; advanced: 1559 ± 1005 m) (See Table 1). This paralleled findings by Baláš et al. (2012), who noted it held true for both males and females. Though the current results showed climbing volume correlated with CPS, it was not a predictor. It appears the amount of climbing done does not directly affect CPS, but rather the physical aspects of climbing do (i.e. hand-arm strength and endurance). Baláš et al. (2012) found climbing volume correlated with UB endurance, BF%, and relative handgrip strength, but not climbing performance. When hand-arm strength and endurance (HASE) was used as the link between CPS and climbing volume/years of experience/BF%, 97% of the variance in climbing performance was explained. Only BF% correlated with volume in the present study (See Appendix E). Additional studies have confirmed the importance of low BF% in climbing; for example, one study found BF% and high handgrip strength to weight (STW) ratios were the only predictors of performance (Giles et al., 2006; Sheel, 2004; Watts et al., 1993). UB endurance is a distinctive trait among elite climbers, as seen by greater forearm endurance and circumference (Grant et al., 1996). It is well documented these adaptations greatly influence climbing performance (Baláš et al., 2012; Grant et al., 1996: Mermier et al., 2000; Watts et al., 1993).

One of most surprising outcomes of the current study was core endurance’s relationship with CPS. Though the correlation strength was poor, it was still significant (See Appendix E). It
has been speculated that core endurance is beneficial to climbing performance, as in other sports, but it had not been scientifically examined until this time (Phillips et al., 2012; Roetert, 2001). Right and left lateral core endurance correlated stronger with CPS than flexion or extension endurance ($r = 0.398$, $0.380$, $0.014$ and $0.097$, respectively). The movement of the center of mass (COM) while climbing may explain these differences. Due to the nature of climbing, more muscle power is required for movements in the transverse plane than the sagittal plane (Zampagni et al., 2011). Gravity and far horizontal distances from a vertical wall can cause a climber’s COM to become unbalanced, resulting in a fall. Climbers tend to counteract this tilting action by climbing in a straight-arm state and relying on exceptional handgrip strength and endurance. Climbing with straight arms shifts the workload from UB to LB; the UB skeletal structure and hand muscles become the primary forces to maintain stability (Isler, 2005; Zampagni et al., 2011; Woodward). Furthermore, non-climbers often climb in the sagittal plane (i.e. ladder-like climbing), while expert climbers are more in the frontal and transverse planes (i.e. diagonal gait climbing). The larger lateral COM oscillations observed in expert climbers may have the same effect as “bouncing” while walking. Conversely, the limited lateral shifting of the COM by non-climbers may be akin to walking flat, which wastes energy and stability (Cavagna et al., 2000; Massad et al., 2007; Zampagni et al., 2011). Overall, it seems the trunk rotator muscles are needed more than the flexors or extensors. Overhanging sections (i.e. more than 90° to the ground) may be the exception to this rule because the climbing surface is horizontal. Trunk flexion, extension and rotation are all necessary to keep one’s COM consistently close to the wall and to regain footing if one’s foot slips (Phillips et al., 2012).

Even though the relationship was weak, VO$_2$max also significantly correlated with CPS (See Appendix E). Moderate to high aerobic capacity has been suggested as being a key part of
an elite climber’s makeup (Watts, 2004). Those with higher climbing capabilities tend to have a higher VO\(_2\)max in both running and climbing than lower-level climbers (Billat et al., 1995; Watts & Drobish, 1998). Climbing pace and route difficulty causes VO\(_2\) to increase, but climbers still use only a little more than half the oxygen one would use while running or cycling (Booth et al., 1999; Mermier et al., 1997; Watts, 2004; Wilkins et al., 1996). Although a climber’s VO\(_2\)max may fall below an average VO\(_2\)max for an endurance athlete, the values still correspond with aerobic fitness levels required for rapid recovery following high intensity effort (Watts, 2004). Lower oxygen consumption may be due to the smaller muscle mass of the main muscles utilized while climbing (Phillips et al., 2012).

Correlation does not always equal causation. Aside from BF%, none of the other five predicting factors correlated with CPS. The physical factors that significantly explained 85.1% of the variance seen in CPS included UB power, handgrip strength, pincer strength and endurance, BF%, and balance (See Table 4). Upper-body power, as measured by a medicine ball put, was the most significant predictor of CPS. Upper-body power has been suggested as being part of an elite climber’s athletic profile (Watts, 2004). Mermier et al. (2000), using an UB Wingate test, found male and female rock climbers had peak power outputs (6.80 ± 0.85 and 4.80 ± 0.60 W/kg BW, respectively) comparable to freestyle swimmers (4.89 ± 0.59 and 3.65 ± 0.47 W/kg BW), another overhead sport which requires strong UB power (Bak and Magnusson, 1997; Hawley, Maynard, Vickovic, & Handcook, 1992; Mermier et al., 2000). Ironically, UB power was not a strong enough predictor to be included in the statistical analysis by Mermier et al. (2000); this may have been due to the way UB power was tested. The medicine ball put and UB Wingate test are both accurate and reliable measures of power output, but the medicine ball put is more commonly utilized. Not only is the test simple to administer, but the specific movement is also
relatable to a variety of functional tasks performed by athletes (Miller, 2012). The dyno – an explosive move used to reach an otherwise inaccessible hold – uses several of the same muscles used during the medicine ball put: the pectoralis major, anterior deltoid, supra- and infraspinatus, serratus anterior, and triceps (Hislop, Avers, and Brown, 2014; Phillips et al., 2012). The current study had slightly shorter distance scores for the medicine ball put than other sports, such as football, lacrosse or volleyball, but the weight used in the other studies was lighter (Faigenbaum et al., 2006). Interestingly, compared to the results found by one study involving average college-age subjects tossing medicine balls similar in weight as in the current study (6 kg for women and 9 kg for men), male rock climbers ranked in the bottom 10th percentile for distance and females in the bottom 40th percentile (Clemons et al., 2010). The angle at which the participant was sitting (i.e., leaning back 45° or sitting straight up at 90°) may have produced a difference in throwing distance. Although comparing rock climbing to other sports is valuable, future research is desired to create baseline values specific to rock climbers, for both the medicine ball put and UB Wingate test. Additionally, due to the small female sample size used in this study, more research is needed on gender differences.

The second strongest predictor of CPS was absolute handgrip strength. Without a doubt, strong grip strength is needed for climbing and it, along with UB flexor strength, explained 14.2% of the variance seen in one study (España-Romero et al., 2009; MacLeod et al, 2007; Nachbauer et al., 1987; Philippe et al., 2012). Not only does grip strength fatigue at a slower rate than grip endurance while climbing, but it recovers faster (Watts et al., 1996). Because it had already been proven that relative grip strength can predict climbing performance, the current study focused on the effect of absolute grip strength (Baláš et al., 2012; Mermier et al., 2000; Watts et al., 1993). The strength values in the current study were slightly lower than those found
in previous climbing studies, but the wide range of climbing ability assessed likely brought the averages down (Watts, 2004). Handgrip strength is essential in offsetting the pull of gravity; it seems having strong grip strength, regardless of its ratio to body mass, helps with climbing performance (Isler, 2005). Certainly, strength is more important than BMI in finger flexor STW ratios (Philippe et al., 2012).

Although absolute handgrip strength has been used in earlier rock climbing studies, grip strength relative to body mass seems to be the best measure (Baláš et al., 2012; Macleod et al., 2007; Watts, 2004). According to Watts et al. (1993), there is not much difference in absolute handgrip strength between elite, recreational and non-climbers, although other studies would not agree (Cutts & Bollen, 1993; Grant et al., 1996). Advanced climbers’ absolute values rank at the 50th and 75th percentiles of North American aged-matched norms for men and women, respectively. However, when expressed in relative terms, advanced climbers rank at the 80th and 90th percentiles (Watts et al., 1993). High grip STW ratios are associated with increased CPS and faster climb times (Mitchell et al., 2011; Philippe et al., 2012). The use of absolute versus relative strength in the current study’s analysis may explain why grip strength was not the top predictor of CPS. Furthermore, the technique used to measure hand strength has been criticized for not being appropriate for rock climbers. A hand dynamometer is simple and provides instantaneous feedback, but the squeezing motion used lacks application to most of the hand positions required during rock climbing (Baláš et al., 2012; Watts et al., 2008). Except for the pinch grip, other common climbing hand positions (i.e. crimp or pocket) do not involve the thumb and/or palm opposing the fingers in a manner similar to that on the hand dynamometer (Watts, 2004). However, a number of studies have attempted to calculate hand and finger
strength via more specialized equipment, but the results tend to be similar to those found by hand
dynamometers (MacLeod et al., 2007; Philippe et al., 2012; Watts et al., 1996, 2004).

Closely related to handgrip strength is pincer strength and endurance. Grip and pincer
strength correlated with each other in the current study. Along with grip strength, elite climbers
have superior absolute and relative pincer strength compared to recreational or non-climbers;
greater pincer STW ratios equate to quicker route completion times (Cutts & Bollen, 1993; Grant
et al., 1996; Mitchell et al., 2011). The current study focused on absolute pincer strength, which
was higher for males than in previous findings (Grant et al., 1996). In relative terms, both
genders had higher pincer STW ratios (0.16 ± 0.03 and 0.18 ± 0.10 kg/kg BW for men and
women, respectively) than Mermier et al. (2000) (0.14 ± 0.03 and 0.12 ± 0.02 kg/kg BW) or
Grant et al. (1996). Unlike the aforementioned studies, the present study measured pincer
strength with the thumb and two digits (i.e. index and middle finger) versus one, which could
explain the higher values. Absolute pincer strength may be similar to absolute handgrip strength
in that it appears to help with climbing performance, regardless of its ratio to body mass
(Philippe et al., 2012).

Research involving pincer endurance in rock climbers is limited, but one study noted
climbers had a longer time to failure at 50% pincer MVC than non-climbers for both hands
(Cutts & Bollen, 1993). Handgrip endurance has previously been found to be the strongest
indicator of overall climbing performance, but the current study is the first to shed light on the
importance of pincer endurance (Baláš et al., 2012). Rock climbers seek hand positions such that
the force of gravity pulls their hand and/or fingers into the rock. Finger flexors must 1) produce
enough force to overcome the downward pull of gravity, and 2) maintain endurance of the hand
position on the hold (Phillips et al., 2012; Watts, 2004). The hand configuration can no longer be
sustained once the muscles are fatigued, and the climber loses contact with the wall (Watts, 2004). Eccentric and isometric contractions, the primary types used while climbing, produce greater amounts of force than concentric contractions and, therefore, require greater endurance for sustentation. The longer the contraction and the more force produced, the quicker fatigue sets in (Phillips et al., 2012; Plowman & Smith, 2014). Because finger flexor endurance deteriorates at over twice the rate of flexor strength while climbing, finger strength is not given the chance to be fully expended (Watts et al., 1996). This could describe why grip strength recovers faster and is not affected by climbing until failure (Watts et al., 1996; Watts, Jensen, Moss, & Wagonosmer, 2003). By virtue of being a limiting factor in climbing performance, how long a rock climber can sustain a given hand position may be one of the top factors in predicting climbing ability (Balás et al., 2012). Because the majority of climbing grips involve only the fingertips and/or a few fingers, it could explain why pincer strength and endurance were both top predictors of CPS, but not handgrip endurance (Watts, 2004). Future studies are needed to explore the balance between strength and endurance for a variety of handgrips specific to climbing.

Balance was the third strongest predictor of CPS. Several studies have suggested balance is important to rock climbing (Cutts & Bollen, 1993; Mermier et al., 2000), but only one study has proven it partly explains climbing performance (7.4%) (Nachbauer et al., 1987). Movements that promote COM stability are central to efficient climbing, as demonstrated in high-level climbers (Zampagni et al., 2011). Because feet placement on the wall often influences COM, sections with extremely small and/or limited footholds become a challenge (Noe, 2006; Schweizer et al., 2005). Remarkable neuromuscular control is required to maintain stability; this is frequently accomplished via precise movement of the forefoot, which has its genesis in ankle
stability (Schweizer et al., 2005). Compared to soccer players, rock climbers have greater ankle flexion strength and perform significantly better in a static one-leg standing stabilometry test. Ankle movements tend to be slower and more controlled, specifically while in plantar flexion, during climbing, resulting in a higher degree of stability and strength than soccer players (Schweizer et al., 2005). The male climbers in the current study had slightly higher overall stability index (OSI) scores for a single-leg stance (2.40 ± 1.38 cm) than in Schweizer et al., (2005) (1.19 ± 2.11 cm), but a dynamic plate was used versus a static plate.

The development of climbing-specific balance in rock climbers is best showcased when compared with non-climbers. Riemann and Davies (2013) administered the same stabilometry test as in the current study (i.e., Athlete Single Leg Stability test) on a healthy, average population using the Biodex Balance System SD. The male and female climbers in the current study had better overall functional balance than the normal population; differences in height and weight could partially explain the rock climbers’ superior balance. Elite climbers, especially females, are often shorter in stature and lighter in weight than control samples (Watts, 2004). Gymnasts, when compared to other athletes, are frequently the shortest and lightest athletes, but have the best dynamic balance (Davlin, 2004; Watts, 2004). Shorter and lighter statures often have a lower center of gravity (CoG) than their taller, heavier counterparts. A lower CoG translates into a lower moment of inertia, which could result in less center of pressure (CoP) displacement. In other words, less movement of the COM and better stability (Chiari, Rocchi, & Cappello, 2002; Juntunen et al., 1987). Although a couple of studies found height and weight did not significantly correlate with CoP displacement (Ageberg, Zitterstrom, Friden, & Moritz, 2001; Ekdahl, Jarnlo, & Andersson, 1989; Thomas & French, 1985), another study noted the amount of oscillation in upright standing positions was strongly dependent on height and partly
on weight (Chiari et al., 2002). This may possibly explain why weight strongly correlated with balance in the present study. Individuals who are obese (> 30 BMI) have worse postural sway than those who are of normal weight (Nolan, 2008). Even football players, despite being athletes, have an equivalent sway level as obese subjects when their body weights are similar (Handrigan et al., 2012). There was no significant difference in balance between males and females in the present study. Though the female sample was very small, other studies have shown there is no significant difference between genders (Nolan, 2008; Davlin, 2004). This likely holds true for rock climbing as well. As noted with other trainable factors, the differences between genders tend to become less evident as climbing ability increases (Baláš et al., 2012).

Functional tasks, such as climbing stairs or kicking a soccer ball, causes individuals to place different demands on their dominant and non-dominant legs (Carey et al., 1998; Riemann & Davies, 2013). Despite the dominant leg being stronger and more powerful, it often has less postural stability than the non-dominant leg (Johnson & Leck, 2010; Riemann & Davies, 2013). Even in studies claiming no significant difference between legs, the non-dominant leg tended to have a smaller sway area (Hoffman, Schrader, Applegate, & Koceja, 1998; Lin, Liu, Hsieh, & Lee, 2009). This may be due to the non-dominant leg needing to support the individual’s body weight and maintain balance, while the dominant leg is kicking or stepping up on to a step (Knight & Weimar, 2010; Riemann & Davies, 2013). Surprisingly, the current study’s participants had almost identical OSI scores for both legs, despite the majority being right leg dominant.

Particular tasks tend to develop certain balance capabilities. Although visual input is important, balance is also affected by the frequency and length of sport-specific postures or activity (Kiers, van Dieën, Dekkers, Wittink, & Vanhees, 2013). This is supported by the fact
that athletes have better postural stability than non-athletes, and balance increases with competition level. Sports that require longer periods of balance, especially unilaterally, tend to outperform other sports in balance tests. Gymnastics, soccer, and shooting, in which balance is a key component, consistently rank above other athletic activities, such as basketball, swimming, or cycling (Hrysomallis, 2011; Kiers et al., 2013). Rock climbing is unique in that it requires equal balancing capabilities from both legs because each leg spends a similar amount of time in a unilateral position (Zampagni et al., 2011). This likely describes why OSI scores for the current subjects’ right and left legs were nearly the same.

Aside from UB/hand strength and endurance, BF% appears most often throughout the literature as being a prerequisite for rock climbing. Although climbers often exhibit lower body fat levels than non-climbers, it is still debated whether this difference is significant (Watts, Joubert, Lish, Mast, & Wilkins, 2003) or not (Grant et al., 1996). It is clear, however, that a higher proportion of fat-free mass correlates with higher climbing levels (Tomaszewski et al., 2011). BF% was the only trainable factor that both correlated and significantly predicted CPS in the current study. Several other studies have also shown BF% correlates and indicates climbing performance (Balás et al., 2012; Mermier et al., 2000; Tomaszewski et al., 2011; Sheel, 2004; Watts et al., 1993).

As noted by Baláš et al. (2012), BF% is distinctive because it influences other physical factors in climbing. Lean body mass is linked to greater dynamic strength; performance decreases dramatically for pull-ups, sit-ups, dips, handgrip strength and vertical jumps when BF% increases (>10% for men and >19% for women) (Bale, 1980; Mcleod, Hunter, & Etchison, 1983). For females, BF% partly affects the ability to successfully complete a pull-up (Flanagan, Vanderburgh, Borchers, & Kohstall, 2003). Lower body fat levels have also been connected with
a higher lung capacity, which may clarify why BF% and VO\textsubscript{2max} were correlated in the present study (Bale, 1980). BF% is also associated with UB endurance, which was strongly correlated with CPS. A low BF% may not be essential to elite-level climbing, but its catalyst-like effect on other factors makes it an advantageous variable to possess (Baláš et al., 2012; Tomaszewski et al., 2011).

Conclusion

The conclusion of this study was UB power, grip strength, pincer strength and endurance, BF% and balance significantly explains 85.1% of the variance seen in CPS. Additionally, factors such as gender, age, height, and weight do not determine climbing ability. To the best of the researcher’s knowledge, a number of the findings in the current study have not been previously published. This was the first study to not only find UB power significantly impacts climbing performance, but also suggests it could be the most important predictor. Absolute handgrip and pincer strength determines CPS, which may imply having strong hands is the basis of STW ratios, not body mass. Having high strength relative to body mass is, therefore, beneficial, but not necessary to elite-level climbing. Balance was one of the top three factors in predicting climbing ability. Lastly, this was the first study to measure core stability in rock climbers. Although it was not a predictor, it did have significant correlation with CPS.

Recommendations for Future Research

In the future, research should include a larger sample size, especially focusing on the female population. The age range should be expanded to include older and younger climbers. Physical factors should be assessed with tests that are more reflective of natural climbing. For example, the foot-loading test (Draper et al., 2009) may give a better representation of hip flexion flexibility in climbers than the footraise test (Grant et al., 1996). Further research should
be conducted on the strength and endurance of different types of grips used while rock climbing and their impact on performance. Although not significant, LB power was the next strongest predictor of climbing performance; more effort should be made to understand the contributions of the LB to climbing ability. Lastly, psychological factors should be assessed alongside anthropometric and physiological factors to present a more complete picture of which variables affect climbing performance.
References


USA Climbing. (2013). *USA Climbing Rulebook 2013*.


Waldhelm, A., & Li, L. (2012). Endurance tests are the most reliable stability measurements. *Journal of Sport and Health Science, 1*, 121-128.


Do you love to rock climb?

Want to know how to improve your climbing ability?

We need participants for a research study:
“What trainable factors are most important in rock climbing performance?”

**Description of Project:** We are researching what trainable physical features makes the most difference in climbing ability. Your participation will take place over three separate visits, visit one ~45 minutes and visit two and three ~45-60 minutes. We will ask you to complete a climbing history questionnaire, a climbing performance test and various other physical fitness assessments (e.g. flexibility, grip strength, etc.).

**To participate:** You must be least 18 years old, healthy and fit, and have previous rock climbing experience.

THE FIRST SESSION (the climbing performance test) WILL TAKE PLACE TUESDAY 10/14 8am-1:30pm! You only need 30 minutes. EMAIL Kiehl@ucmo.edu to sign up for a time slot!

To learn more, contact the principle investigator of the study, Shannon Kiehl, at (573)823-7337 or Kiehl@ucmo.edu.

This research is conducted under the direction of Dr. Steve Burns, Department of Kinesiology, and has been reviewed and approved by the UCM Institutional Review Board.
CONSENT FORM

Identification of Researchers: This research is being done by Shannon Kiehl, a graduate student within the Department of Nutrition and Kinesiology at the University of Central Missouri.

Purpose of the Study: The purpose of this study is to determine which trainable physical variables are the most important in rock climbing performance.

Request for Participation: We are inviting you to participate in a study on trainable variables in rock climbing performance. It is up to you whether you would like to participate. If you decide not to participate, you will not be penalized in any way. You can also decide to stop at any time without penalty. If you do not wish to answer any of the questions, you may simply skip them. You may withdraw your data at any time or at the end of the study.

Exclusions: You must be a male 18-45 or female 18-55 years of age to participate in this study. Preexisting medical conditions, pregnancy, and/or lack of climbing experience may cause exclusion from the study.

Description of Research Method: This study includes a climbing history questionnaire along with various physical assessment tests. Testing will take place over three visits. The first visit, approximately 40 minutes, will include the screening and performance climbs using a top-rope with experienced belayers. The second and third visits will take about 45-60 minutes. The second visit will include a bent arm hang test, isokinetic testing of knee and shoulder strength on the Biodex, and a lower-body Wingate test. The third visit will include body fat percentage using the DEXA, grip and pinch strength and endurance using dynamometers, core endurance tests, upper-body medicine ball put, and 1-leg stability test on a balance system. The purpose and protocol for each test will be fully explained at that time.

Privacy: All of the information we collect will be confidential. All data collected will be published only as aggregate data in summarized form with no disclosure of names.

Explanation of Risks: As with any exercise, there exists the possibility of certain changes occurring during the exercise. Risks include: delayed muscle soreness, an abnormal response of blood pressure, fainting, irregular fast or slow heart rhythm, and in rare instances, heart attack, stroke, or death. Additional risks associated with rock climbing are those you take as a current rock climber. However, we will take appropriate measures to be safe during climbing by using current experienced belayers.

Explanation of Benefits: You may benefit from participating in this study by getting firsthand experience in a unique rock climbing study. You may also enjoy knowledge gained through the physical assessments, which could be useful to your personal training regimen.

Questions: If you have any questions about this study, please contact kiehl@ucmo.edu or (573) 823-7337. If you have any questions about your rights as a research participant, please contact the Human Subjects Protection Program at (660) 543-4621.

If you would like to participate, please sign a copy of this letter and return it to me. The other copy is for you to keep.

I have read this letter and agree to participate.

Signature: ___________________________ Printed name: ___________________________

Date: __________________________

Person obtaining consent: __________________________

APPENDIX C
CLIMBING HISTORY QUESTIONNAIRE
1.) Gender (circle one): Male Female

2.) How many years have you been climbing? _______________

3.) On average, how many hours a week do you climb? ________________

4.) What type(s) of climbing experience do you have? Circle all that apply. Definitions on back.

- Bouldering
- Aid Climbing
- Top-roping
- Traditional Climbing
- Sport (Lead) Climbing
- Ice Climbing
- Competitive Climbing
- Mountaineering

5.) Based on the Yosemite Decimal Scale (YDS), what is the highest rating you consistently climb? (Circle one)

a. 5.5 (Very Easy)
b. 5.6 (Very Easy)
c. 5.7 (Beginner)
d. 5.8 (Beginner)
e. 5.9 (Beginner-Intermediate)
f. 5.10 (Beginner-Intermediate)
g. 5.11 (Intermediate)
h. 5.12 (Advanced)
i. 5.13 (Very advanced)
j. 5.14 (Elite)
k. Unknown

6.) Whether climbing-specific or not, describe your current training regimen. Continue on back if needed.

**Bouldering:** Done without ropes, climbing is done about 12-17 feet off the ground with padded mats and spotters.
**Top-roping:** Climbing is done by running a rope through anchors at the top of a route or using an auto belay system.

**Sport (Lead) Climbing:** Climbers clip a rope into secured bolts as they ascend a rockface.

**Competitive Climbing:** Competition climbing done on artificial, indoor climbing walls.

**Aid Climbing:** Climbing is primarily aided through the use of gear.

**Traditional Climbing:** Unlike sport climbing, gear is placed into the rock as climbers ascend.

**Ice Climbing:** Climbing involving snow or ice. Similar rock climbing systems are used in addition to ice axes and crampons.

**Mountaineering:** A mixture of walking, scrambling, ice and rock climbing in mountainous areas.
PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

<table>
<thead>
<tr>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?</td>
<td></td>
</tr>
<tr>
<td>2. Do you feel pain in your chest when you do physical activity?</td>
<td></td>
</tr>
<tr>
<td>3. In the past month, have you had chest pain when you were not doing physical activity?</td>
<td></td>
</tr>
<tr>
<td>4. Do you lose your balance because of dizziness or do you ever lose consciousness?</td>
<td></td>
</tr>
<tr>
<td>5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?</td>
<td></td>
</tr>
<tr>
<td>6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?</td>
<td></td>
</tr>
<tr>
<td>7. Do you know of any other reason why you should not do physical activity?</td>
<td></td>
</tr>
</tbody>
</table>

If you answered YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES:

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

If you answered NO to all questions

You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

“I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction.”

NAME:

SIGNATURE:

DATE:

GUARDIAN (for participants under the age of majority)

WITNESS:

APPENDIX E

CORRELATIONS BETWEEN TRAINABLE PHYSICAL VARIABLES AND CPS

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<table>
<thead>
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<th>Volume</th>
<th>HG End.</th>
<th>HG Strength</th>
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<td>-.418*</td>
<td>.561**</td>
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Note: (*) = (p < 0.05). (**) = (p < 0.01). UB = upper-body. LB = lower-body. End. = endurance. CPS = climbing performance score. BF% = body fat percentage.
<table>
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**Note:** (*) = (p < 0.05). (**) = (p < 0.01). UB = upper-body. LB = lower-body. End. = endurance. CPS = climbing performance score. BF% = body fat percentage.
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<td>.220</td>
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<td>UB Strength (kg)</td>
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<td>.321</td>
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<tr>
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<td>-.120</td>
<td>.486*</td>
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<td>.315</td>
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<tr>
<td>LB Power (watts)</td>
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<td>.249</td>
<td>.054</td>
<td>.291</td>
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<tr>
<td>VO2max (ml/kg/min)</td>
<td>-.007</td>
<td>.130</td>
<td>-.315</td>
<td>-.257</td>
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</table>

Note: (*) = (p < 0.05). (**) = (p < 0.01). UB = upper-body. LB = lower-body. End. = endurance. CPS = climbing performance score. BF% = body fat percentage.
<table>
<thead>
<tr>
<th></th>
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<th>LB Strength</th>
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<td>Hip Flexion (cm)</td>
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<td>Balance (cm)</td>
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<td>.486</td>
<td>.116</td>
<td>.291</td>
<td>-.257</td>
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<td>.499*</td>
<td>.470*</td>
<td>.261</td>
</tr>
<tr>
<td>LB Strength (kg)</td>
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<td>.422*</td>
<td>.456*</td>
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<td>Med Ball Put (cm)</td>
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<td>VO2max (ml/kg/min)</td>
<td>.261</td>
<td>.124</td>
<td>.236</td>
<td>.262</td>
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</table>

Note: (*) = (p < 0.05). (**) = (p < 0.01). UB = upper-body. LB = lower-body. End. = endurance. CPS = climbing performance score. BF% = body fat percentage.

APPENDIX F
MEAN VALUES OF TRAINABLE PHYSICAL FACTORS BY GENDER
<table>
<thead>
<tr>
<th></th>
<th><strong>Men (n=22)</strong></th>
<th></th>
<th><strong>Females (n = 3)</strong></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td><strong>Mean (SD)</strong></td>
<td><strong>Range</strong></td>
<td><strong>Mean (SD)</strong></td>
<td><strong>Range</strong></td>
</tr>
<tr>
<td>CPS</td>
<td>27.6 (5.0)</td>
<td>19.5-37.0</td>
<td>22.9 (6.6)</td>
<td>15.9-28.9</td>
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<tr>
<td>Volume (yds/week)</td>
<td>1085.0 (915.0)</td>
<td>60.0-3600.0</td>
<td>1040.0 (885.0)</td>
<td>150.0-1920.0</td>
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<tr>
<td>Handgrip End. (sec)</td>
<td>66.0 (32.0)</td>
<td>24.0-151.0</td>
<td>65.0 (25.0)</td>
<td>41.0-91.0</td>
</tr>
<tr>
<td>Handgrip Strength (kg)*</td>
<td>48.0 (9.0)</td>
<td>30.5-68.0</td>
<td>21.0 (12.0)</td>
<td>8.0-30.5</td>
</tr>
<tr>
<td>UB End. (sec)*</td>
<td>40.0 (16.0)</td>
<td>17.0-67.0</td>
<td>10.0 (4.0)</td>
<td>7.0-15.0</td>
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<tr>
<td>BF%*</td>
<td>16.2 (8.2)</td>
<td>5.8-33.8</td>
<td>33.2 (10.1)</td>
<td>25.2-44.5</td>
</tr>
<tr>
<td>Pincer End. (sec)</td>
<td>47.0 (16.0)</td>
<td>22.0-75.0</td>
<td>29.0 (21.0)</td>
<td>15.0-54.0</td>
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<tr>
<td>Pincer Strength (kg)</td>
<td>11.4 (1.9)</td>
<td>8.1-15.5</td>
<td>9.8 (2.0)</td>
<td>8.0-12.4</td>
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<tr>
<td>Core End.(sec)</td>
<td>99.0 (35.0)</td>
<td>45.0-170.0</td>
<td>81.0 (17.0)</td>
<td>71.0-101.0</td>
</tr>
<tr>
<td>Hip Abduction (cm)</td>
<td>157.0 (16.0)</td>
<td>125.0-183.0</td>
<td>159.5 (2.0)</td>
<td>158.5-161.5</td>
</tr>
<tr>
<td>Hip Flexion (cm)</td>
<td>109.0 (16.0)</td>
<td>82.0-137.0</td>
<td>120.0 (14.0)</td>
<td>105.0-132.0</td>
</tr>
<tr>
<td>Balance (cm)</td>
<td>2.4 (1.4)</td>
<td>1.0-7.3</td>
<td>1.4 (0.3)</td>
<td>1.2-1.7</td>
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<tr>
<td>UB Strength (kg)*</td>
<td>77.0 (18.0)</td>
<td>52.0-113.0</td>
<td>45.0 (35.0)</td>
<td>23.0-85.0</td>
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<tr>
<td>LB Strength (kg)*</td>
<td>201.5 (46.0)</td>
<td>131.0-290.0</td>
<td>102 (34.0)</td>
<td>77.0-141.0</td>
</tr>
<tr>
<td>UB Power (cm)</td>
<td>309.0 (54.0)</td>
<td>145.0-378.0</td>
<td>252.0 (37.0)</td>
<td>216.0-290.0</td>
</tr>
<tr>
<td>LB Power (watts)*</td>
<td>587.0 (101.0)</td>
<td>343.0-761.0</td>
<td>383.0 (79.0)</td>
<td>302.0-459.0</td>
</tr>
<tr>
<td>VO2max (ml/kg/min)*</td>
<td>34.8 (8.1)</td>
<td>12.0-51.0</td>
<td>22.3 (2.1)</td>
<td>20.0-24.0</td>
</tr>
</tbody>
</table>

Note: (*) = Difference between genders (p < 0.05). UB = upper-body. LB = lower body. End. = endurance. CPS = climbing performance score. BF% = body fat percentage.