A COMPARISON OF TWO SPORT-CLIMBING SPECIFIC AEROBIC POWER PROTOCOLS AND THEIR RELATIONSHIP TO SPORT-CLIMBING ABILITY

By

Alexander J. Cross

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written by Alexander Joseph Cross

has been approved for the Department of Integrative Physiology

____

William C. Byrnes, Ph.D

____

Alena M. Grabowski, Ph.D.

____

Rodger Kram, Ph.D

____

Gary McCall, Ph.D

Date______________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline. IRB protocol # 16-0105

Abstract

Cross, Alexander Joseph (M.S., Integrative Physiology)

A COMPARISON OF TWO SPORT-CLIMBING SPECIFIC AEROBIC POWER PROTOCOLS AND THEIR RELATIONSHIP TO SPORT-CLIMBING ABILITY

Thesis directed by Associate Professor William C. Byrnes

Aerobic power has been proposed as an important determinant of rock climbing performance but how to access aerobic power and relate it to climbing performance remains controversial. PURPOSE: To contrast how two sport climbing-specific aerobic power protocols (SCAPP) discriminate sport climbers differing in climbing ability. Parameters from the two SCAPPs (peak aerobic power (VO_{2peak}), time to exhaustion (TTE), relative peak power output (PPO_{rel}), time spent at RER ≥ 1.00 ($RER_{1.0}$), and economy) were used to discriminate climbers differing in their on-sight (OS) and redpoint (RP) climbing abilities. METHODS: Twenty-two healthy, active, rock climbers (14M, 8F) performed treadwall (SCAPP-CT) and vertically mounted rowing ergometer (SCAPP-AE) graded exercise tests. SCAPP-CT RESULTS: TTE and $RER_{1.0}$ both correlated significantly ($P \leq 0.05$) with climbing ability and were both significantly greater in the high ability groups ($P \leq 0.05$). TTE was the most consistent correlate for the full SCAPP-CT sample (n=21). VO_{2peak} was significantly higher ($P \leq 0.05$) in the high ability group (52.8 ± 3.0 vs. 47.0 ± 6.2 mL/kg/min). SCAPP-AE RESULTS: PPO_{rel} correlated significantly ($P \leq 0.05$) with climbing ability and was significantly greater ($P \leq 0.05$) in the high ability group. VO_{2peak} correlated significantly ($P \leq 0.05$) with climbing ability and was significantly greater ($P \leq 0.05$) in the high ability group (35.9 ± 4.4 vs. 30.0 ± 4.1 mL/kg/min). TTE was significantly greater ($P \leq 0.05$) in the high ability groups. BETWEEN TEST COMPARISONS: As expected, due to the larger amount of activated muscle mass, VO_{2peak} (+58.0%), HR_{peak} (+12.8%), and VE_{peak} (+18.3%) values were significantly greater ($P \leq 0.05$) for the SCAPP-CT than the SCAPP-AE. CONCLUSION: The SCAPP-CT is a better protocol for testing potential aerobic predictors of sport-climbing performance. TTE and $RER_{1.0}$ appear to be the best predictors of sport-climbing performance measured in this study, and a SCAPP: CT VO_{2peak} of 50-55 mL/kg/min for males (45-50 mL/kg/min for females) is beneficial to sport climb at more advanced levels.

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Chapter I

Introduction

Sport climbing is a discipline of rock climbing that is performed indoors and outdoors, in which the goal is to ascend the route to the top without weighting the rope by either falling or sitting. While climbing the route, the climber is guarded from injury during a fall by protection fixed in the rock (bolts) before the ascent (Booth et al., 1999). During the ascent, the climber uses specialized equipment (climbing rope and quickdraws) to connect to the bolts to create points of safety to keep the climber from falling to the ground, if a fall should occur. Sport climbing is increasing in popularity as an option for rock climbing performance and as a recreational activity (Watts 2004).

In 2004, Watts published an extensive review paper on the physiology of rock climbing. He concluded that there was not enough information on the role of an individual's peak aerobic power as a factor in determining rock-climbing performance. Since then, researchers have been developing or using established, easily repeatable, peak aerobic power protocols in the hopes of achieving a test with higher specificity to sport climbing that could help answer this question (Balas et al. 2012, Booth et al. 1999, Espana-Romero et al. 2009, Michailov et al. 2015, Pires et al. 2011).

In 1999, Booth et al. utilized a rock climbing specific ergometer, called a treadwall (Figure 1), to develop a sport-climbing aerobic power protocol (SCAPP) to measure peak aerobic power (VO_{2peak}) in a small group (n=7) of male and female climbers. The test that was developed was an incremental speed protocol (ISP). The ISP was meant to allow climbers to climb to exhaustion so that researchers could compare variables measured during indoor climbing (e.g.VO_{2peak}) to values obtained during

Figure 1. Performing the SCAPP-CT on the climbing ergometer (treadwall).

outdoor climbing. While Booth et al. (1999) did not look at comparisons to reported sport climbing ability, other groups of researchers have since utilized or adapted the ISP protocol to investigate the relationship between potential aerobic predictor variables and reported sport climbing ability.

In 2009, Espana-Romero et al. repeated Booth et al.'s (1999) protocol exactly to compare VO_{2peak} in a group of male and female, expert and elite sport climbers. Expert (avg. 5.12b) and elite (avg. 5.13d) climbing ability groups were established by an arbitrary sex-specific 75^{th} percentile (when climbers were ranked by sex from lowest climbing ability to highest climbing ability, the lowest 75%, for men and women, fell into the expert group, and the remaining top 25% became the elite group). While data did not indicate that VO_{2peak} was a potential predictor of sport climbing performance between expert (VO_{2peak} = 51.3 ± 4.5 mL/kg/min) and elite (VO_{2peak} = 51.9 ± 3.4 mL/kg/min) sport climbers, climb time to exhaustion (TTE) was found to be a potential predictor of performance (407.7 ± 150 s expert vs. 770.2 ± 385 s elite).

However, Balas et al. (2012) found both VO_{2peak} (45-50 ml/kg/min) and attained climbing speed, a similar variable to TTE, to be "indispensable to climb hard routes" when using their own ISP on a treadwall to test a wide range of climbing abilities (5.3-5.13d), beginner to elite abilities, in females. While these studies differed in populations, ability ranges tested, and protocols used, results from both studies suggest that TTE is a potential predictor of sport climbing performance, and that an ISP specific VO_{2peak} of 45-50 mL/kg/min, as suggested by Balas et al. (2012), or higher, as potentially indicated by the data from Espana-Romero et al. (2009) (expert and elite climber groups each had an average VO_{2peak} over 50 mL/kg/min), could be valuable to reaching expert and elite levels of sport climbing ability. Therefore, the ISP may only be able to predict rock-climbing performance based on peak aerobic power up to a certain ability range, and not within expert or elite sport climbers. Regardless, the ISP requires further testing across climbing ability groups (e.g. low and high), within elite climbers only, and by sex, to truly assess the limitations and strengths of the protocol.

It has been suggested by Michailov et al. (2015) that the ISP may not be specific enough to climbing, since the speeds achieved on the treadwall are too fast and do not represent speeds during actual climbing activities. Therefore, Michailov et al. (2015) developed a new upper-body test (UBT) using a rowing ergometer that was mounted vertically to a wall, which utilized mainly the upper body, and incremented the workloads in an attempt to more accurately simulate climbing upper body work-rest ratios and models of fatigue, while also minimizing the subjectivity of the test (Figure 2). When using the UBT to assess a group of elite sport climbers (5.11d-5.13b), Michailov et al. (2015) were able to demonstrate with correlations that VO_{2peak} (r=0.85) and relative peak power output (PPO_{rel}) (r=0.75) were potential predictors of climbing performance in elite climbers.

Michailov et al. (2015) also reported results on time spent exercising at a respiratory exchange ratio of 1.0 or greater ($RER_{1.0}$), which is sometimes used to estimate ventilatory anaerobic threshold and is reflective of high metabolic workrate sustained by anaerobic glycolysis. Although they reported some of their results based on $RER_{1.0}$ (e.g. heart rate at $RER_{1.0}$, VO_{2peak} at $RER_{1.0}$), they did not report on whether they looked at time spent at $RER_{1.0}$ as an individual parameter of sport climbing performance. Since the ability to sustain a high level of anaerobic metabolism is a reasonable predictor of climbing ability, I decided to include it as its own variable, similar to TTE, as a potential predictor of performance.

Similar to the UBT, Pires et al. (2011) used a hand cycling ergometer to perform their own UBT to test for VO_{2peak} in elite and intermediate climbers (5.12d and higher, 5.11c and lower, respectively). Unlike Michailov et al. (2015), aerobic performance was not found to be a predictor of rock climbing performance, but TTE was once again found to be a predictor of performance. This discrepancy could potentially be due to the use of different equipment and the specificity of the tests.

Therefore, evaluation of both an ISP and the new UBT developed by Michailov et al. (2015) was required to test the potential predictive power of both protocols across a range of climbers. Thus, the aim of this study was to compare two sport-climbing aerobic power protocols (SCAPP), re-test the UBT, and to further assess peak aerobic power (VO_{2peak}), relative peak power output (PPO_{rel}), climb time to exhaustion (TTE), and time spent at an RER of 1.0 or greater ($RER_{1.0}$) as predictors of sport climbing performance in men and women, as well as across a range of sport climbing abilities. In addition, we looked at economy, a factor that has been found to be predictive of performance in endurance sports (e.g. running and cycling) but has not been evaluated as a factor for climbing performance. We had three hypotheses: 1. VO_{2peak}, PPO_{rel}, TTE, $RER_{1.0}$, and climbing economy, would each be significantly higher in the “high” vs. “low” climbing ability groups by either reported sport-climbing on-sight ability (OS),or redpoint ability (RP); 2. VO_{2peak}, PPO_{rel}, TTE, $RER_{1.0}$, and climbing economy would each positively correlate with both the OS or RP reported sport-climbing abilities among all climbers; 3. That the SCAPP-CT would be a better test for studying aerobic predictors during sport-climbing than the SCAPP-AE due to the movement pattern and muscle activation patterns being more similar to actual climbing during the SCAPP-CT than the SCAPP-AE.

Figure 2. Performing the SCAPP-AE on the rowing ergometer.
Starting and end positions are presented

Chapter II

Methods

Subjects

Twenty-two healthy and physically active subjects from Boulder, CO, USA volunteered for the study. All subjects were required to reside at an altitude of approximately 1625 m (5,331 ft) for at least three weeks preceding the first visit and to remain at a similar altitude for the duration of the study. The twenty-two subjects were comprised of 14 males (25.6 ± 4.1 years, 174.5 ± 5.1 cm, 69.4 ± 6.4 kg) and 8 females (23.1 ± 4.0 years, 163.1 ± 9.1 cm, 55.3 ± 6.9 kg). Using the Yosemite Decimal System (YDS) (Table 1), subjects reported their current sport-climbing grade achievements in terms of on-sight climbing ability (OS) (the most difficult route completed without falls on the first try and without any prior knowledge), and redpoint climbing ability (RP) (the most difficult route completed without falls any attempt after the first). The YDS is based on an alphanumerical scale, ranging from 5.0 (easy for most beginners) to 5.15 (achievable by only the most elite), with letter subdivision of ‘a’, ‘b’, ‘c’, and ‘d’ from 5.10a to the top, with 5.15c being the hardest confirmed grade by elite climbers at this time (Table 1). Detailed information about climbing ability (OS and RP), experience (years), and frequency (days per month) was recorded according to Wall et al. (2004). Average current climbing grades for OS and RP for this study sample were 5.12c (range 5.10c - 5.14a) and 5.13b (range 5.11d – 5.14c) for men, and 5.12b (range 5.12a – 5.13a) and 5.12d (range 5.12b – 5.13d) for women, respectively. Mean climbing experience and climbing frequency were 10.1 ± 5.5 years and 14.1 ± 3.8 days per month for men, and 10.2 ± 3.0

Table 1. Climbing Ability Table: Yosemite Decimal System and the French Numerical Scale

Yosemite Decimal System (YDS)	French Numerical Scale (FNS)
3rd - 4th class	1
5.0	
5.1	2
5.2	
5.3	3
5.4	4a
5.5	4b
5.6	4c
5.7	5a
5.8	5b
5.9	5c
5.10a	6a
5.10b	6a+
5.10c	6b
5.10d	6b+
5.11a	
5.11b	6c
5.11c	6c+
5.11d	7a
5.12a	7a+
5.12b	7b
5.12c	7b+
5.12d	7c
5.13a	7c+
5.13b	8a
5.13c	8a+
5.13d	8b
5.14a	8b+
5.14b	8c
5.14c	8c+
5.14d	9a
5.15a	9a+
5.15b	9b
5.15c	9b+

Note: Climbing grades between scales are not always a direct equivalent.

years and 15.6 ± 2.9 days per month for women, respectively. See Table 2 for individual subject characteristics, and Table 3 and Table 4 for mean data ± SD. All subjects gave written informed consent, which was obtained by a research investigator prior to participation. This project was approved by the Institutional Review Board of the University of Colorado at Boulder.

Protocol

Subjects participated in 2 testing sessions with at least 48 hrs of rest between sessions. The order of tests was randomly assigned for each subject. One session consisted of the sport climbing aerobic power protocol using an arm ergometer (SCAPP-AE). This protocol involved both submaximal and maximal testing, and a full body dual energy X-ray absorptiometry (DEXA) scan for the assessment of body composition. The other session consisted of the sport climbing aerobic power protocol using a climbing treadwall (SCAPP-CT). Oxygen uptake (VO_2), carbon dioxide production (VCO_2), ventilation (V_E), and heart rate (HR) were continuously measured during both SCAPPs. Both height and weight were recorded during the subject's first visit.

During both tests (SCAPP-AE and SCAPP-CT), a portable open circuit indirect calorimetry system (Oxycon Mobile, VIASYS Healthcare) was used to measure VO_2, VCO_2, V_E, respiratory exchange ratio (RER), and heart rate (HR) data, providing 5-second averages for these measurements. Similar to the device shown in Figure 2, the unit was worn by the subject, but breath-by-breath measures were recorded through a mouthpiece, not a mask. Due to the use of a mouthpiece, a nose clip was used to ensure collection of expired air. HR was measured continuously using a Polar chest strap (Polar Electro, Finland) wirelessly transmitted to the Oxycon Mobile system.

Table 2. Tests completed, climbing ability, climbing experience, and anthropometrics ranked by subject on-sight climbing ability (n=22)

Subjects	SCAPP-CT	SCAPP-AE	On-sight Climbing Ability	Redpoint Climbing Ability	Climb Exp. (years)	Climbing Frequency (days/mon)	Age	Sex	%BF	Weight (kg)	Height (cm)	BMD (g/cm^2)
C11	X	-	5.10c	5.11d	4.0	8.5	22	M	8.8	75.0	182.9	1.357
C21	X	X	5.11b	5.12c	10.0	12	21	M	11.5	72.7	180.3	1.245
C02	X	X	5.11d	5.12b	9.0	10	27	M	13.7	73.6	172.7	1.214
C04	X	X	5.11d	5.12c	1.3	9	32	M	20.5	68.4	179.1	1.247
C17	X	-	5.12a	5.12b	9.0	20	20	F	-	45.9	156.2	-
C10	X	X	5.12a	5.12b	10.0	10	30	M	-	79.1	174.0	-
C01	X	X	5.12a	5.12c	4.7	15	26	F	18.5	49.1	156.2	1.189
C16	X	-	5.12a	5.12c	11.0	15	19	F	-	65.5	175.3	-
C07	X	X	5.12b	5.12c	10.0	14	25	F	15.7	57.3	165.1	1.164
C09	X	X	5.12b	5.12d	10.0	14	30	F	9.4	62.7	175.3	1.131
C19	X	X	5.12b	5.12d	11.0	15	21	F	-	50.9	152.4	-
C05	X	X	5.12b	5.13a	8.0	15	22	M	16.3	67.7	171.5	1.280
C22	X	X	5.12c	5.13a	10.0	12	19	F	20.0	59.3	155.4	1.239
C13	X	-	5.12c	5.13a	10.0	20	30	M	-	72.7	172.7	-
C12	X	X	5.12d	5.13b	5.5	14	29	M	5.5	74.1	180.3	1.243
C14	X	X	5.12d	5.13b	5.5	16	24	M	-	69.1	174.6	-
C18	X	-	5.13a	5.13d	15.0	14	27	M	-	54.1	168.9	-
C15	X	-	5.13a	5.13d	15.5	20	25	F	-	51.8	167.6	-
C03	X	X	5.13b	5.13d	8.5	20	19	M	7.2	67.7	175.3	1.213
C20	X	X	5.13b	5.13d	18.0	16	21	M	8.9	68.2	177.8	1.346
C06	X	X	5.13c	5.14a	15.0	15	29	M	10.0	70.2	166.4	1.241
C08	-	X	5.14a	5.14c	21.0	17.5	26	M	4.9	59.1	167.6	1.182
Average	21 (total)	16 (total)	5.12b/c (5.10c-5.14a)	5.13a (5.11d-5.14c)	10.1 ± 4.7	14.6 ± 3.5	24.7 ± 4.2	14M 8F (total)	12.21 ± 5.26	64.3 ± 9.5	170.3 ± 8.8	1.235 ± 0.063

Averages are expressed as Mean ± SD. Abbreviations: SCAPP, sport climbing-specific aerobic power protocol: arm ergometer, AE, arm ergometer, CT, climbing treadwall, Climb Exp., climbing experience, %BF, percent body fat, BMD, bone mineral density, X, subject completed that portion of the protocol. Note: Subjects also in order for redpoint climbing ability (RP) except for subjects C21 & C04. When tied by on-sight climbing ability (OS), subjects ordered next by climbing experience, then climbing frequency. Climbing experience reported as total years of climbing experience. Climbing frequency reported as average days per month in the last year.

Table 3. Climbing experience, climbing ability, and anthropometrics of the study sample by on-sight (OS) and redpoint (RP)

	On-sight Ability			**Redpoint Ability**		
	Ability Group by OS		**All Subjects by OS**	**Ability Group by RP**		**All Subjects by RP**
Subjects	**Low (n=8)**	**High (n=8)**	**Spearman r (n=22)**	**Low (n=9)**	**High (n=8)**	**Spearman r (n=22)**
Age (year)	24.6 ± 4.8	25.0 ± 3.6	-0.01	24.7 ± 4.5	25.0 ± 3.6	-0.01
Climbing Exp. (years)	7.4 ± 3.6	13.0 ± 5.8*	0.56^^	7.667± 3.4	13.0 ± 5.8*	0.53^
Climbing Freq. (days/month)	12.4 ± 4.0	16.6 ± 2.4**	0.62^^	12.6 ± 3.7	16.6 ± 2.4*	0.56^^
OS Ability	5.11c /d (5.10c-5.12a)	5.13b (5.12d-5.14a)**	-	5.11d (5.10c-5.12b)	5.13b (5.12d-5.14a)**	0.96^^
RP Ability	5.12b (5.11d-5.12c)	5.13d (5.13b-5.14c)**	0.96^^	5.12b (5.11d-5.12c)	5.13d (5.13b-5.14c)**	-
Weight (kg)	66.2 ± 12.3	64.3 ± 8.2	0.22	65.2 ± 11.8	64.3 ± 8.2	0.19
Height (cm)	172.2 ± 10.4	172.2 ± 5.3	-0.23	67.4 ± 3.9	67.8 ± 2.1	-0.11
Sample sizes for %BF and BMD (n)	*5*	*5*	*14*	*6*	*5*	*14*
%BF	14.60 ± 4.85	7.30 ± 2.17*	-0.46	14.78 ± 4.36	7.30 ± 2.17**	-0.47 ***(P=0.08)***
BMD (g/cm^2)	1.250 ± 0.064	1.245 ± 0.062	-0.27	1.236 ± 0.067	1.245 ± 0.062	-0.11

Data are expressed as Mean ± SD. Abbreviations: OS, on-sight climbing ability, RP, redpoint climbing ability, %BF, percent body fat, BMD, bone mineral density. Note: Low and High ability groups were always separated by at least 2 climbing grades, the 'Low' ability groups always stopped at 5.12a for OS, and 5.12c for RP, the 'High' ability groups always started at 5.12d for OS, and 5.13b for RP, unless otherwise noted in the table. All Males by OS/RP shows that splitting the males by on-sight climbing ability or redpoint climbing ability resulted in the same separation of subjects., though Spearman values differed due to changes in rank for OS vs. RP.

* $P \leq 0.05$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups, ** $P \leq 0.01$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups

^ $P \leq 0.05$; correlation coefficients (Spearman r), ^^ $P \leq 0.01$; correlation coefficients (Spearman r)

Table 4. Climbing experience, climbing ability, and anthropometrics of the study sample by sex, on-sight (OS), and redpoint (RP)

	Sex		Ability Group by Male OS/RP		All Males by OS/RP	All Females by OS/RP
Subjects	**Males (n=14)**	**Females (n=8)**	**Low (n=5)**	**High (n=7)**	**Spearman (r) (n=14)**	**Spearman (r) (n=8)**
Age (year)	25.6 ± 4.1	23.1 ± 4.0	26.4 ± 4.8	25.0 ± 3.9	0.11/0.19	0.13/0.13
Climbing Exp. (years)	10.1 ± 5.5	10.2 ± 3.0	6.9 ± 4.0	12.6 ± 6.2 ***(P=0.08)***	0.57^/0.55^	0.60/0.64 **(*P*=0.08)**
Climbing Freq. (days/month)	14.1 ± 3.8	15.6 ± 2.9	9.9 ± 1.3	16.1 ± 2.1**	0.75^^/ 0.72^^	-0/15/-0.14
OS Ability	5.12c (5.10c-14a)	5.12b (5.12a-5.13a)	5.11c (5.10c-5.12a)	5.13b (5.12d-5.14a)**	0.96^^	0.91^^
RP Ability	5.13b (5.11d-5.14c)	5.12d (5.12b-5.13d)	5.12b (5.11d-5.12c)	5.13d (5.13b-5.14c)**	0.96^^	0.91^^
Weight (kg)	69.4 ± 6.4	55.3 ± 6.9*	73.8 ± 3.9	66.1 ± 7.0*	-0.60^/ -0.69^^	0.26/0.34
Height (cm)	174.5 ± 5.1	163.1 ± 9.1*	177.8 ± 4.3	173.0 ± 5.3	-0.60^/ -0.54^	-0.02/0.00
Sample sizes for %BF and BMD (n)	*10*	*4*	*4*	*5*	*10*	*4*
%BF	10.73 ± 4.91	15.9 ± 4.69	13.6 ± 5.0	7.3 ± 2.2 ***(P=0.08)***	-0.48/-0.50	-
BMD (g/cm^2)	1.257 ± 0.056	1.181 ± 0.046*	1.266 ± 0.063	1.245 ± 0.062	-0.56 **(P=0.09)**/ -0.51	-

Data are expressed as Mean ± SD. Abbreviations: OS, on-sight climbing ability, RP, redpoint climbing ability, %BF, percent
body fat, BMD, bone mineral density. Note: Low and High ability groups were always separated by at least 2 climbing grades, the 'Low' ability groups always stopped at 5.12a for OS, and 5.12c for RP, the 'High' ability groups always started at 5.12d for OS, and 5.13b for RP, unless otherwise noted in the table. All Males by OS/RP shows that splitting the males by on-sight climbing ability or redpoint climbing ability resulted in the same separation of subjects., though Spearman values differed due to changes in rank for OS vs. RP.

* $P \leq 0.05$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups, ** $P \leq 0.01$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups

^ $P \leq 0.05$; correlation coefficients (Spearman r), ^^ $P \leq 0.01$; correlation coefficients (Spearman r)

Sport-climbing aerobic power protocol: climbing treadwall (SCAPP-CT)

The SCAPP-CT was performed on a treadwall (Brewersledge, model: Adapted M6), set at a slight overhang (5-degrees from vertical), with specific climbing holds (Atomik, model: medium simple jugs) set in a uniform pattern to create a similar movement pattern throughout the entirety of the test. The difficulty of the route, when assuming a total of 40ft of continuous climbing, was rated as 5.8 by a USA Climbing - Level 5 certified route setter. Subjects were allowed up to 15 minutes to warm-up and familiarize themselves with the treadwall before testing began. Climbing speed was controlled with a resistance lever, and the resistance was adjusted by a researcher to achieve the desired climbing speed for each stage. Climbing speed was measured by digital output that displayed both instantaneous and average speed, and accuracy of the display was confirmed by use of a tachometer.

The SCAPP-CT followed a similar protocol as Balas et al. (2012). Stages lasted 3 minutes, but where Balas et al. (2012) established their speed scale based upon movements/min, we established our scale using meters/min. Therefore, climbing speed for our protocol began at 8 m/min, and increased by 2 m/min every 3-minutes. The protocol began with the resistance set to maximum; the subject then mounted the treadwall, and the resistance was adjusted to achieve the desired speed. Testing ended when the subject either fell off or stopped due to volitional exhaustion.

Climbing speeds were recorded as the averaged data from the last 2-minutes 30-seconds of each stage. The first 30-s of each stage was excluded to allow researchers to set the resistance required to achieve the specified climbing speed. VO_{2peak} was recorded as the highest 30-sec rolling block average during the final stage. Peak heart rate (HR_{peak}), peak ventilation (VE_{peak}), and RER_{peak}, were all recorded during the same 30-s block as VO_{2peak}. If the subject completed a minimum of four full stages of the SCAPP-CT, the final minute of the first three stages were used to calculate economy.

Sport-climbing aerobic power protocol: arm ergometer (SCAPP-AE)

During the SCAPP-AE visit, a full body dual energy X-ray absorptiometry (DEXA) scanner (GE Lunar Model) was used to measure percent body fat (%BF) and bone mineral density (BMD). For the SCAPP-AE, an indoor rower (Model: Concept 2, Morrisville, VT, USA) was mounted vertically to a laboratory wall, and the damper level was set at 10 (Figure 2). Subjects were allowed 15 minutes to warm-up and familiarize themselves with the rower. Work rate was shown by a built-in digital display that showed both single repetition work rates and averaged work rates over the exercise duration. Subjects controlled the work rate by the frequency of their repetitions and were instructed to focus on maintaining a constant single repetition work rate as they exercised.

The SCAPP-AE was separated into two tests: submaximal and maximal. The submaximal testing was completed first, and consisted of three 3-minute stages, with the work rate beginning at 20 W, and incrementing by 10 W each stage for the purpose of assessing economy. Economy was calculated from the final minute of each of the first three stages. The SCAPP-AE maximal testing followed the upper-body test (UBT) protocol proposed by Michailov et al. (2015). Stages lasted 95s, and were split into 80s work phase with a 15s rest phase. It has been suggested by Michailov et al. (2015) that this protocol more closely reflects the work-rest ratios found in typical rock climbing. The workload for the first stage was 20 W, and incremented by 15 W each stage.

Maximal testing ended when the subject either could not maintain the work rate of the current stage, or chose to stop due to volitional exhaustion. The protocol's start position (submaximal and maximal) began with both arms raised vertically, holding the ergometer handle with both hands in a pronated grip. The subject then had to pull the handle downward repeatedly to full flexion in the elbow joints, and finished the movements with extension of the shoulders (Michailov et al. 2015) (Figure 2). During the rest phase of the maximal test, subjects were instructed to relax their arms by their side.

Work rates for the submaximal test stages were recorded as the average from the last 2-minutes 30-seconds of each stage. The first 30-s was washed out to allow subjects some time to adapt to the new work rate. Work rates for the maximal test stages were recorded in a similar fashion, but data was averaged over the last 60-s of each work phase, which allowed for an initial 20-s wash out/adaption period. After each wash out period of the submaximal and maximal testing, the display was cleared. VO_{2peak} was recorded as the highest average of a 20-s block of data obtained during the subject's final stages (Michailov et al. 2015). Blocks of data consisted of 0 to 20-sec, 20 to 40-sec, 40 to 60-sec, and 60 to 80-sec. Peak heart rate (HR_{peak}), peak ventilation (VE_{peak}), and peak respiratory exchange ratio (RER_{peak}), were all recorded during the same 20-s block as VO_{2peak}.

Calibration

The DEXA was calibrated just prior to analyzing each subject by using a phantom to simulate tissue densities. If the calibration ran, and the results did not meet standard, a researcher would be prompted to run the scan again.

The indirect calorimetry system was calibrated before each testing session. Gas fractions were calibrated with a primary standard gas mixture within a physiological range (16.01% O_2 and 4.01% CO_2). The volume was calibrated using an automatic volume calibration hardware and software application provided by the Oxycon Mobile system.

Data Analysis

Arbitrary OS and RP grades were established to split the sample into low and high climbing ability groups based off of the sample populations reported abilities. As such, the low OS and low RP groups consisted of subjects who reported being able to on-sight sport climbs of 5.12a, and redpoint sport climbs of 5.12c, or lower, respectively, while the high OS and high RP groups contained subjects who reported an on-sight climbing ability of 5.12d, and a redpoint climbing ability of 5.13b, or higher, respectively. Splitting the low and high ability groups in this way allowed for a 2-grade gap in reported climbing abilities between low and high groups. This gap was used to create two groups with clear differences in ability, while also eliminating the fewest results for low and high ability group comparisons.

Economy for the SCAPP-CT was calculated by taking the weight of the subject (kg) multiplied by the vertical distance travelled during one minute (taking into account a 5-degree overhang), based on the average speed (m/min) during the stage, then divided by 60-s to get power in kgm/s, converted into Watts, and finally divided by the average VO_2 (L/min) data from the last minute of the respective submaximal stage to get units in W/L/min (For example, subject C10 weighed 79.1 kg, climbed at an average speed of 7.81 m/min during the first stage of the test, and had an average VO_2 of 2.51 L/min during the first stage, and the relationship for vertical distance travelled on a 5-degree overhang is 1:0.996. Therefore, I multiplied 79.1 kg x 7.81 m/min x 0.996, and divided the answer by 60 s to get 10.25 kgm/s. I then converted 10.25 kgm/s to Watts using the conversion factor of 0.102 W/kgm/s giving me a power of 100.54 W. Finally, this was divided by the subjects VO_2 of 2.71 L/min to get an economy of 40.06 W/L/min). Economy for the SCAPP-AE was calculated by taking the average work rate (W) from the last minute of a submaximal stage and dividing it by the respective average absolute VO_2 (L/min) from the same minute, to get economy in W/L/min. Economy data in Table 5 was than averaged per subject across the three submaximal stages for each protocol. PPO_{rel} was recorded as the average work rate from the final minute of each maximal stage of the SCAPP-AE, then divided by the respective subject's body weight in kilograms.

Table 5. Physiological variables and individual correlation coefficients for economy for subjects ordered by on-sight climbing ability (n=22)

Subjects	SCAPP-CT					SCAPP-AE					
	VO_{2peak} (mL/kg/min)	TTE (s)	$RER_{1.0}$ (s)	Econ. (W/L/min)	r value for VO_2 vs. Speed	VO_{2peak} (mL/kg/min)	TTE (s)	$RER_{1.0}$ (s)	Relative PPO (W/kg)	Econ. (W/L/min)	r value for VO_2 vs. power
C11	47.7	500	200	-	-	-	-	-	-	-	-
C21	53.9	545	120	-	-	34.1	837	240	1.86	27.4	0.953
C02	49.6	545	310	-	-	33.6	760	380	1.59	31.0	0.999
C04	48.2	525	50	-	-	28.8	523	95	1.48	28.5	0.990
C17	41.2	465	110	-	-	-	-	-	-	-	-
C10	55.7	905	30	42.9	0.999	30.7	760	300	1.50	27.8	0.996
C01	41.4	390	170	-	-	22.9	380	150	1.22	36.6	0.999
C16	38.6	580	210	-	-	-	-	-	-	-	-
C07	45.1	620	130	43.4	0.977	30.0	570	150	1.64	EQ	-
C09	50.9	875	185	44.0	0.994	25.0	386	165	1.29	38.2	0.999
C19	40.1	540	185	-	-	23.1	321	135	1.10	35.8	0.991
C05	54.4	730	5	39.5	1.000	32.4	760	345	1.82	35.3	0.999
C22	46.8	768	155	46.9	0.970	35.8	523	EQ	1.45	35.4	1.000
C13	52.5	1080	385	42.2	0.982	-	-	-	-	-	-
C12	55.9	1085	465	39.8	0.999	42.2	1045	380	2.30	29.5	0.997
C14	54.2	1085	360	40.5	1.000	31.0	760	130	1.74	33.5	0.967
C18	54.3	1085	550	40.7	0.998	-	-	-	-	-	-
C15	54.8	900	125	41.4	0.991	-	-	-	-	-	-
C03	49.1	915	420	42.2	0.943	38.0	855	200	2.00	25.7	0.948
C20	48.1	1080	490	45.5	1.000	31.9	760	440	1.87	EQ	-
C06	53.1	985	330	43.3	0.904	33.4	808	270	1.79	28.5	0.992
C08	-	-	-	-	-	38.7	760	530	2.01	28.9	0.935
Average	49.3 ± 5.4	771.6 ± 243.7	237.4 ± 158.5	42.5 ± 2.2	0.98 ± 0.03	32.0 ± 5.4	675.5 ± 201.6	260.7 ± 130.9	1.67 ± 0.32	31.6 ± 4.1	0.98 ± 0.02

Averages are expressed as Mean ± SD. Abbreviations: SCAPP, sport climbing-specific aerobic power protocol: arm ergometer, AE, arm ergometer, CT, climbing treadwall, Econ, economy averaged over the first three submaximal stages, VO_{2peak}, peak aerobic power, TTE, time to exhaustion, $RER_{1.0}$, time spent at RER ≥ 1.0, PPO, peak power output, r, Pearson correlation coefficient, EQ, equipment error. Note: Subjects also in order for redpoint climbing ability (RP) except for subjects C21 & C04. When tied by on-sight climbing ability (OS), subjects ordered next by climbing experience, then climbing frequency.

Differences between sex, low and high ability groups, and male-specific low and high ability groups in climbing history, training status, anthropometrics, and physiological variables were compared with independent and dependent samples t-test for each protocol, and between protocols, using Microsoft Office Excel 2010 (Microsoft Corporation, Redmond, WA). Additional statistical analysis was run using IBM SPSS Statistics version 21 (IBM Corporation, Armonk, New York). Reported climbing abilities were transformed into an ordinal scale adapted from Watts et al. (1993) (Table 6) to calculate average climbing abilities per group, and for t-test comparisons between reported climbing abilities for low and high climbing ability groups. Spearman's rank correlation was used to examine the relationships between reported sport-climbing ability (OS and RP) and climbing history, training status, anthropometrics, and physiological variables for both sexes, together and separately, and for each protocol. Linear regression analysis was also used to determine how well VO_{2peak}, HR_{peak},, RER, VE_{peak}, TTE, and economy recorded for each protocol correlated with each other.

Due to subject attrition and equipment failure throughout the protocol, final sample size varied among the test conditions; SCAPP-AE (n=16), SCAPP-CT (n=21), both tests (n=15). Values are reported as mean and standard deviation (mean ± SD). The level of significance was set at $P \leq 0.05$.

Table 6. Conversion chart used to standardize climbing ability

Yosemite Decimal System (YDS)		Ordinal Adaption Scale	Yosemite Decimal System (YDS)		Ordinal Adaption Scale
5.0		0.50	5.12	a	5.00
5.1		0.75		b	5.25
5.2		1.00		c	5.50
5.3		1.25		d	5.75
5.4		1.50	5.13	a	6.00
5.5		1.75		b	6.25
5.6		2.00		c	6.50
5.7		2.25		d	6.75
5.8		2.50	5.14	a	7.00
5.9		2.75		b	7.25
5.10	a	3.00		c	7.50
	b	3.25		d	7.75
	c	3.50	5.15	a	8.00
	d	3.75		b	8.25
5.11	a	4.00		c	8.50
	b	4.25			
	c	4.50			
	d	4.75			

Reproduced and adapted from Watts et al. (1993) to perform statistical analysis (independent t-tests) between low and high ability groups for on-sight climbing ability (OS) and redpoint climbing ability (RP), as well as perform Pearson regression (r) and multiple linear regression tests (r).

Chapter III

Results

Climbing History, Training Status, and Anthropometrics (n=22)

When considering whether to report OS or RP results, we realized that OS involves physical and mental aspects (e.g. ability to “read” a route), whereas RP is more of a direct measure of what you are physically capable of. Since the tests that subjects participated in were not complicated and were more direct measures of physiology, we feel RP is a better variable for comparison than OS. Due to this, we have emphasized reporting the RP results, while still included the OS results in the tables and figures. It is important to note that OS and RP data were very highly correlated ($r \geq 0.96$), therefore results for both groups were very similar.

By climbing ability groups, recorded data for climbing experience, climbing frequency, and percent body fat, were significantly different between low and high climbing ability groups ($P \leq 0.05$). The high ability group had significantly higher reported values for climbing experience and climbing frequency, and significantly lower recorded values for percent body fat. Each of these variables also correlated significantly with reported RP, except for percent body fat (Spearman r, $P \leq 0.05$). Neither age nor BMD results were significantly different or significantly correlated. (Table 3)

By sex, recorded data for: age, climbing experience, climbing frequency, reported sport-climbing ability, and percent body fat, were not significantly different between sexes. However, males had significantly higher ($P \leq 0.05$) mean body mass, height, and bone mineral density than females. When comparing sex-specific ability groups, data for males for climbing experience ($r = 0.55$), climbing frequency ($r = 0.72$), weight (r = -

0.69), and height (r = -0.54) each correlated significantly (Spearman r, $P \leq 0.05$). Climbing frequency and weight were also significantly different ($P \leq 0.05$) between low and high, male, climbing ability groups when comparing means. Low and high ability groups were not used for females due to the close grouping of ability for all females in the study. When correlations were performed for female subject data, reported sport-climbing ability between OS and RP was the only significant correlation present. (Table 4)

Reported climbing abilities were compared using the ordinal adaptions for climbing ability provided in Table 6. When comparing ability between respective low and high ability groups, data were always significantly different throughout the entire protocol ($P \leq 0.01$) with the high ability group having significantly higher reported RP than the low ability group.

SCAPP-CT – Climbing ability and physiological variables (n=21)

VO_{2peak}, TTE, and $RER_{1.0}$, were all significantly higher ($P \leq 0.05$) for the high ability group compared to the low ability group. Both TTE (r = 0.76) and $RER_{1.0}$ (r = 0.54) correlated significantly with reported climbing ability, while VO_{2peak} (r = 0.40) did not (Spearman r, $P \leq 0.05$). Economy results were similar between groups. (Table 7) (Figure 3)

VO_{2peak}, TTE, and $RER_{1.0}$, were all significantly higher in males than females ($P \leq 0.05$). When comparing sex-specific ability groups, data for: TTE (r = 0.72) and $RER_{1.0}$ (r = 0.68), each correlated significantly (Spearman r, $P \leq 0.05$), and mean values were significantly different ($P \leq 0.05$) between low and high, male, climbing ability groups. The mean VO_{2peak} and economy were similar for males in the low and high ability groups. For females, TTE and climbing ability were significantly correlated (Spearman r = 0.77, $P \leq 0.05$). VO_{2peak} was correlated with OS (Spearman r = 0.76, $P \leq 0.05$), but not RP (r = 0.66). No female data was calculated for economy due to too few subject results in that data set (n=4) (Table 8).

Table 7. SCAPP-CT physiological variables of the study sample by on-sight climbing ability and redpoint climbing ability (n=21)

Test		On-sight Ability			Redpoint Ability		
		Ability Group by OS		All Subjects by OS	Ability Group by RP		All Subjects by RP
SCAPP-CT	Subjects	Low OS (n=8)	High OS (n=7)	Spearman OS (r) (n=21)	Low RP (n=9)	High RP (n=7)	Spearman RP (r) (n=21)
	OS Ability	5.11c/d (5.10c-5.12a)	5.13a (5.12d-5.13c)**	-	5.11d (5.10c-5.12b)	5.13a (5.12d-5.13c)**	.94^^
	RP Ability	5.12b (5.11d-5.12c)	5.13c/d (5.13b-5.14a)**	.94^^	5.12b (5.11d-5.12c)	5.13c/d (5.13b-5.14a)**	-
	VO_{2peak} (mL/kg/min)	47.0 ± 6.2	52.8 ± 3.0*	0.32	46.8 ± 5.8	52.8 ± 3.0*	0.40
	TTE (s)	551.9 ± 152.2	1019.3 ± 84.6**	0.80^^	555.0 ± 142.7	1019.3 ± 84.6**	0.76^^
	$RER_{1.0}$ (s)	150.0 ± 91.8	391.4 ± 139.5**	0.57^^	147.8 ± 86.1	391.4 ± 139.5**	0.54^
	Econ. (W/L/min)	42.5 ± 2.0 (5.12a-5.12b) (n=4)	42.6 ± 1.9 (5.13a-5.13c) (n=5)	0.01	43.1 ± 2.4 (5.12b-5.13a) (n=6)	42.6 ± 1.9 (5.13d-5.14a) (n=5)	0.17

Data are expressed as Mean ± SD. Abbreviations: OS, on-sight climbing ability, RP, redpoint climbing ability, VO_{2peak}, peak aerobic power, TTE, time to exhaustion, $RER_{1.0}$, time spent at RER ≥ 1.0, Econ., average of first three submaximal stages. Note: Low and high ability groups were always separated by at least 2 climbing grades, the low ability groups always stopped at 5.12a for OS, and 5.12c for RP, the high ability groups always started at 5.12d for OS, and 5.13b for RP, unless otherwise noted in the table.
* $P \leq 0.05$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups, ** $P \leq 0.01$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups
^ $P \leq 0.05$; correlation coefficients (Spearman r), ^^ $P \leq 0.01$; correlation coefficients (Spearman r)

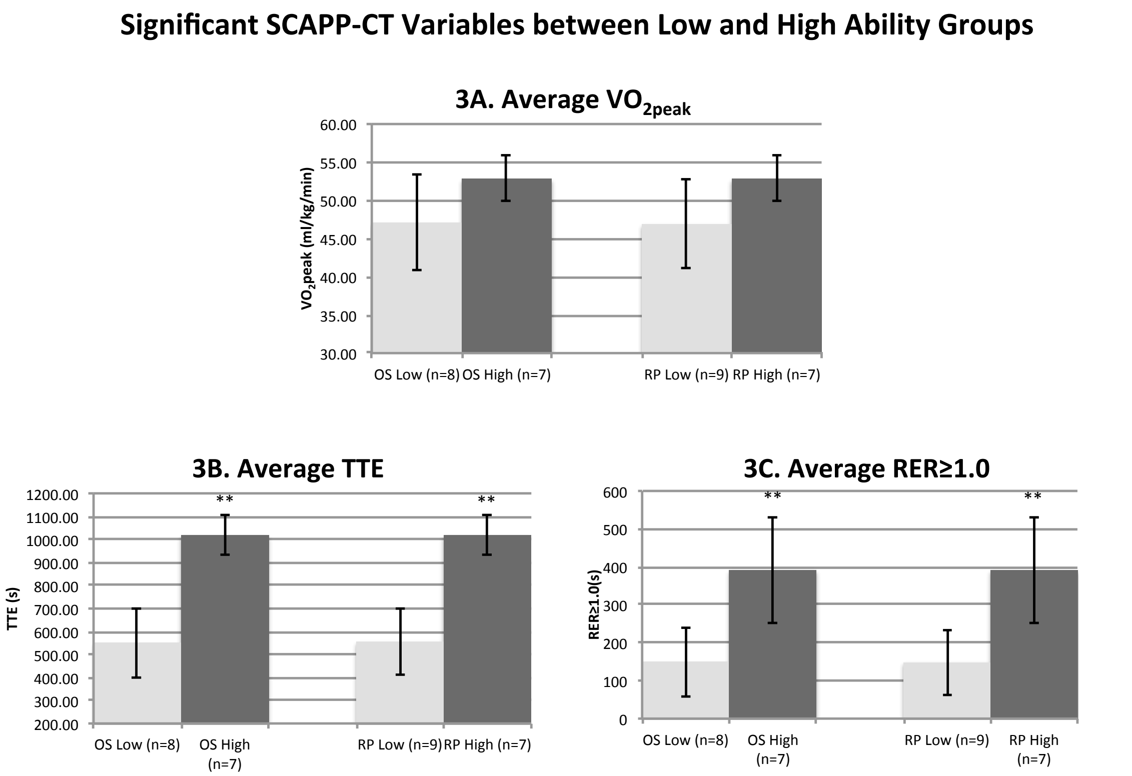

Figure 3. Significant physiological variables for the SCAPP-CT (n=21), data shown as: mean ± SD, Abbreviations: TTE, time to exhaustion, RER≥1.0, time spent at an RER of 1.0 or greater
* $P \leq 0.05$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups, ** $P \leq 0.01$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups

Table 8. SCAPP-CT physiological variables of the study sample by sex, on-sight climbing ability, and redpoint climbing ability (n=21)

Test		Sex		Ability Group by Male OS/RP		All Males by OS/RP	All Females by OS/RP
SCAPP -CT	**Subjects**	**Males (n=13)**	**Females (n=8)**	**Low (n=5)**	**High (n=6)**	**Spearman (r) (n=13)**	**Spearman (r) (n=8)**
	OS Ability	5.12b/c (5.10c-5.13c)	5.12b (5.12a-5.13a)	5.11c (5.10c-5.12a)	5.13a (5.12d-5.13c) **	0.95^^	0.91^^
	RP Ability	5.13a (5.11d-5.14a)	5.12d (5.12b-5.13d)	5.12b (5.11d-5.12c)	5.13c (5.13b-5.14a) **	0.95^^	0.91^^
	VO_{2peak} (mL/kg/min)	52.1 ± 3.0	43.4 ± 4.3**	51.0 ± 3.6	52.4 ± 3.1	0.13/0.12	0.76^ /0.66
	TTE (s)	851.2 ± 245.9	605.4 ± 168.5*	531.0 ± 19.2	1039.2 ± 72.6**	0.75^^/ 0.72^^	0.83^^ /0.77^
	$RER_{1.0}$ (s)	285.8 ± 185.8	158.8 ± 34.8*	142.0 ± 115.2	435.8 ± 82.5**	0.67^/0.68^^	-0.18/0.10
	Econ. (W/L/min)	41.9 ± 1.9 (n=9)	43.9 ± 2.3 (n=4)	41.5 ± 1.8 (5.12b-5.13a) (n=3)	42.9 ± 2.0 (5.13d-5.14a) (n=4)	-0.49/ -0.38 (n=9)	- (n=4)

Data are expressed as Mean ± SD. Abbreviations: OS, on-sight climbing ability, RP, redpoint climbing ability, VO_{2peak}, peak aerobic power, TTE, time to exhaustion, $RER_{1.0}$, time spent at RER ≥ 1.0, Econ., average of first three submaximal stages. Note: Low and High ability groups were always separated by at least 2 climbing grades, the 'Low' ability groups always stopped at 5.12a for OS, and 5.12c for RP, the 'High' ability groups always started at 5.12d for OS, and 5.13b for RP, unless otherwise noted in the table. OS/RP shows that by splitting the males by on-sight climbing ability or redpoint climbing ability resulted in the same separation of subjects, though Spearman r-values differed due to changes in rank for OS vs. RP. The ability grouping of Female subjects did not allow for the separation into Low/High ability groups.
* $P \leq 0.05$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups, ** $P \leq 0.01$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups
^ $P \leq 0.05$; correlation coefficients (Spearman r), ^^ $P \leq 0.01$; correlation coefficients (Spearman r)

SCAPP-AE – Climbing ability and physiological variables (n=16)

By climbing ability groups, mean PPO_{rel} was significantly different ($P \leq 0.05$) between low and high ability groups, and correlated significantly (r= 0.60; P<0.05) with reported climbing ability . The mean VO_{2peak} and TTE were significantly different between low and high groups ($P \leq 0.05$). VO_{2peak} was also correlated with reported RP (Spearman r = 0.501, $P \leq 0.05$). No differences in means occurred, and no relationships existed for PPO and economy. (Table 9) (Figure 4)

VO_{2peak}, TTE, $RER_{1.0}$, PPO, PPO_{rel}, and economy, were all significantly higher in males than females ($P \leq 0.05$). There were no significant correlations or significant differences between reported sport-climbing abilities between sexes, but it is important to note that the male sport-climbing abilities encompassed a wider range of abilities, while the females were all fairly close in ability to each other. When comparing sex-specific ability groups, the mean PPO_{rel} was significantly greater in the high vs. low ability groups ($P \leq 0.05$), and correlated significantly (Spearman r = 0.66, $P \leq 0.05$). No differences in means occurred, and no relationships existed for VO_{2peak}, TTE, PPO when comparing sex-specific ability groups. No correlations for female data were performed due to the small sample size (n=4). (Table 10)

Between Tests Comparison of Physiological Data (n=15)

VO_{2peak} (49.8 ± 4.9 vs. 31.5 ± 5.3 mL/kg/min), HR_{peak} (187.2 ± 7.6 vs. 165.9 ± 12.7 bpm) , and VE_{peak} (116.2 ± 29.4 vs. 98.2 ± 29.1 L/min) results were all significantly higher for the SCAPP: CT than the SCAPP: AE ($P \leq 0.05$), while RER_{peak} (1.04 ± 0.1 vs. 1.13 ± 0.1) was the only compared value between tests that had a significantly higher mean during the SCAPP:AE ($P \leq 0.05$). VO_{2peak} (r = 0.60), peak HR (r = 0.84), and peak ventilation (r = 0.76) but not peak RER, were significantly correlated between tests (Pearson r, $P \leq 0.05$). Mean TTE between tests were not significantly different (669.9 ± 207.4 vs. 772.9 ± 235.1 s), however they were significantly correlated (Pearson r = 0.58, $P \leq 0.05$). Mean economy (31.7 ± 4.5 vs. 42.4 ± 2.5 W/L/min) was significantly higher during the SCAPP-CT, but results were not significantly correlated between tests. No differences in means occurred, and no relationships existed, when comparing $RER_{1.0}$ between tests. (Table 11) (Figure 5)

Table 9. SCAPP-AE physiological variables of the study sample by on-sight climbing ability and redpoint climbing ability (n=16)

Test		**Ability Group by OS**		**All Subjects by OS**	**Ability Group by RP**		**All Subjects by RP**
SCAPP -AE	**Subjects**	**Low OS (n=5)**	**High OS (n=6)**	**Spearman OS (r) (n=16)**	**Low RP (n=6)**	**High RP (n=6)**	**Spearman RP (r) (n=16)**
	OS Ability	5.11d (5.11b-5.12a)	5.13b (5.12d-5.14a)**	-	5.11b/5.12a (5.11b-5.12b)	5.13b (5.12d-5.14a)**	0.94
	RP Ability	5.12b/c (5.12b-5.12c)	5.13d (5.13b-5.14c)**	0.94	5.12b/c (5.12b-5.12c)	5.13d (5.13b-5.14c)**	-
	Abs. VO_{2peak} (L/min)	2.09 ± 0.58	2.44 ± 0.37	0.19	2.03 ± 0.54	2.44 ± 0.37	0.22
	Rel. VO_{2peak} (mL/kg/min)	30.00 ± 4.55	35.87 ± 4.42 **(*P*=0.06)**	0.45 **(*P*=0.08)**	30.00 ± 4.07	35.87 ± 4.42*	0.50^
	TTE (s)	652.0 ± 192.5	831.3 ± 111.4	0.35	638.3 ± 175.4	831.3 ± 111.4*	0.41
	$RER_{1.0}$ (n=15)	233.0 ± 114.1	325.0 ± 151.6	0.36	219.2 ± 107.5	325.0 ± 151.6	0.33
	PPO (W)	106.36 ± 28.70	133.02 ± 19.12	0.38	104.28 ± 26.17	133.02 ± 19.12 **(*P*=0.055)**	0.49 **(*P*=0.055)**
	PPO_{rel} (W/kg)	1.53 ± 0.23	1.95 ± 0.20*	0.53^	1.55 ± 0.21	1.95 ± 0.20**	0.60^
	Econ. (W/L/min)	30.28 ± 3.81 (n=5)	29.21 ± 2.81 (n=5)	0.08 (n=14)	30.28 ± 3.81 (n=5)	29.21 ± 2.81 (n=5)	0.14 (n=14)

Data are expressed as Mean ± SD. Abbreviations: OS, on-sight climbing ability, RP, redpoint climbing ability, VO_{2peak}, peak aerobic power, TTE, time to exhaustion, $RER_{1.0}$, time spent at RER ≥ 1.0, Econ., average of first three submaximal stages. Note: low and high ability groups were always separated by at least 2 climbing grades, the low ability groups always stopped at 5.12a for OS, and 5.12c for RP, the high ability groups always started at 5.12d for OS, and 5.13b for RP. Note: Only 1 female is included in 'Ability group by OS', and only 2 females are included in 'Ability group by RP'
* $P \leq 0.05$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups, ** $P \leq 0.01$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups
^ $P \leq 0.05$; correlation coefficients (Spearman r), ^^ $P \leq 0.01$; correlation coefficients (Spearman r)

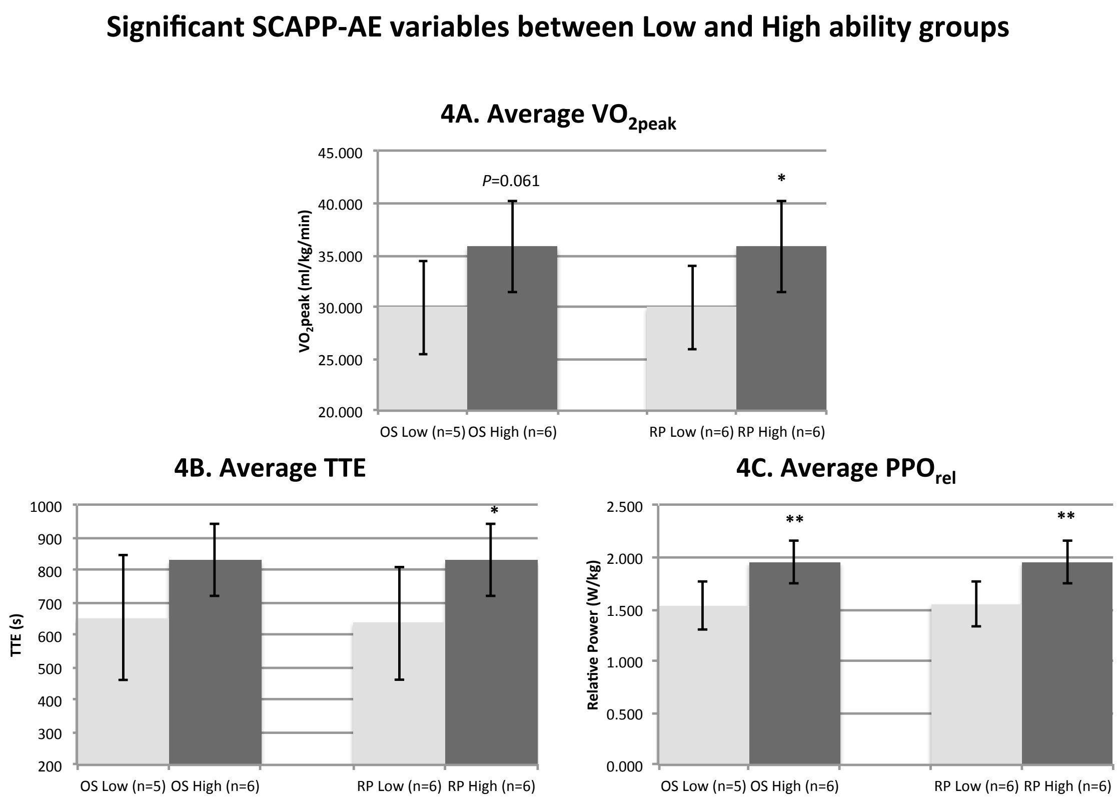

Figure 4. Significant physiological variables for the SCAPP-AE (n=16), data shown as: mean ± SD, Abbreviations: TTE, time to exhaustion, RER≥1.0, time spent at an RER of 1.0 or greater
* $P \leq 0.05$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups, ** $P \leq 0.01$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups

Table 10. SCAPP-AE physiological variables of the study sample by sex, on-sight climbing ability, and redpoint climbing ability (n=16)

Test		**Sex**		**Ability Group by Male OS/RP**		**All Males by OS/RP**
SCAPP-AE	**Subjects**	**Males (n=11)**	**Females (n=5)**	**Low OS (n=4)**	**High OS (n=6)**	**Spearman (r) (n=11)**
	OS Ability	5.12b/c (5.11b-5.14a)	5.12b (5.12a-5.12c)	5.11d (5.11b-5.12a)	5.13b (5.12d-5.14a)**	0.93^^
	RP Ability	5.13b (5.12b-5.14c)	5.12d (5.12c-5.13a) **(*P*=0.07)**	5.12b/c (5.12b-5.12c)	5.13d (5.13b-5.14c)**	0.93^^
	Abs. VO_{2peak} (L/min)	2.38 ± 0.31	1.54 ± 0.41*	2.34 ± 0.25	2.44 ± 0.37	-0.05/ -0.07
	Rel. VO_{2peak} (mL/kg/min)	34.1 ± 4.0	27.4 ± 5.5**	31.8 ± 2.5	35.9 ± 4.4 **(*P*=0.06)**	0.34/0.42
	TTE (s)	784.4 ± 121.7	436.0 ± 105.3**	720.0 ± 136.3	831.3 ± 111.4	0.28/0.35
	$RER_{1.0}$ (s)	300.9 ± 131.4	150.0 ± 12.3 (n=4)**	253.8 ± 120.4	325.0 ± 151.6	0.38/0.27
	PPO (W)	126.7 ± 17.3	75.4 ± 16.6**	106.36 ± 28.70	133.02 ± 19.12	0.33/0.46
	PPO_{rel} (W/kg)	1.81 ± 0.24	1.34 ± 0.21**	1.53 ± 0.23	1.95 ± 0.20*	0.56/0.66^
	Econ. (W/L/min)	29.61 ± 2.91 (n=10)	36.50 ± 1.22** (n=4)	30.28 ± 3.81 (n=5)	29.21 ± 2.81 (n=5)	-0.02/ -0.05 (n=10)

Data are expressed as Mean ± SD. Abbreviations: OS, on-sight climbing ability, RP, redpoint climbing ability, VO_{2peak}, peak aerobic power, TTE, time to exhaustion, $RER_{1.0}$, time spent at RER ≥ 1.0, Econ., average of first three submaximal stages. Note: Low and High ability groups were always separated by at least 2 climbing grades, the ‘Low’ ability groups always stopped at 5.12a for OS, and 5.12c for RP, the ‘High’ ability groups always started at 5.12d for OS, and 5.13b for RP, unless otherwise noted in the table. OS/RP shows that by splitting the males by on-sight climbing ability or redpoint climbing ability resulted in the same separation of subjects, though Spearman r-values differed due to changes in rank for OS vs. RP. The number of Female subjects that completed this protocol did not allow for the separation into Low/High ability groups, or warrant Spearman calculations.

* $P \leq 0.05$ as determined by a 2 sample t-test between respective sex, or ‘Low’ & ‘High’ ability groups, ** $P \leq 0.01$ as determined by a 2 sample t-test between respective sex, or ‘Low’ & ‘High’ ability groups

^ $P \leq 0.05$; correlation coefficients (Spearman r), ^^ $P \leq 0.01$; correlation coefficients (Spearman r)

Table 11. Between test comparison of physiological variables for subjects that fully completed both protocols (n=15)

	SCAPP-CT	SCAPP-AE	Pearson (r)
VO_{2peak} (mL/kg/min)	49.8 ± 4.9	31.5 ± 5.3**	0.60^
RER_{peak} (VCO_2/VO_2)	1.04 ± 0.05	1.13 ± 0.08**	-0.002
$RER_{1.0}$ (s) (n=14)	232.1 ± 162.9	241.4 ± 111.7	0.38
HR_{peak} (bpm) (n=12)	187.2 ± 7.6	165.9 ± 12.7**	0.84^^
VE_{peak} (L/min)	116.2 ± 29.4	98.2 ± 29.1**	0.76^^
TTE (s)	772.9 ± 235.1	669.9 ± 207.4 ***(P=0.07)***	0.58^
Econ. (W/L/min) (n=8)	42.4 ± 2.5	31.7 ± 4.5 **	0.20

Data are expressed as Mean ± SD. Abbreviations: SCAPP, sport climbing-specific aerobic power protocol, AE, arm ergometer, CT, climbing treadwall, VO_{2peak}, peak aerobic power, RER, respiratory exchange ratio, $RER_{1.0}$, time spent at RER ≥ 1.0, HR_{peak}, peak heart rate, VE TTE, time to exhaustion, Econ., average of the first three submaximal stages of each test, then averaged over subjects.
* $P \leq 0.05$ as determined by a paired t-test between protocols ** $P \leq 0.01$ as determined by a paired t-test between protocols
^ $P \leq 0.05$; correlation coefficients (Pearson r), ^^ $P \leq 0.01$; correlation coefficients (Pearson r)
! No significance (paired t-test or Pearson r) was calculated for economy due to the economy for each test being expressed in different units

Significantly different variables between tests: SCAPP-AE & SCAPP-CT

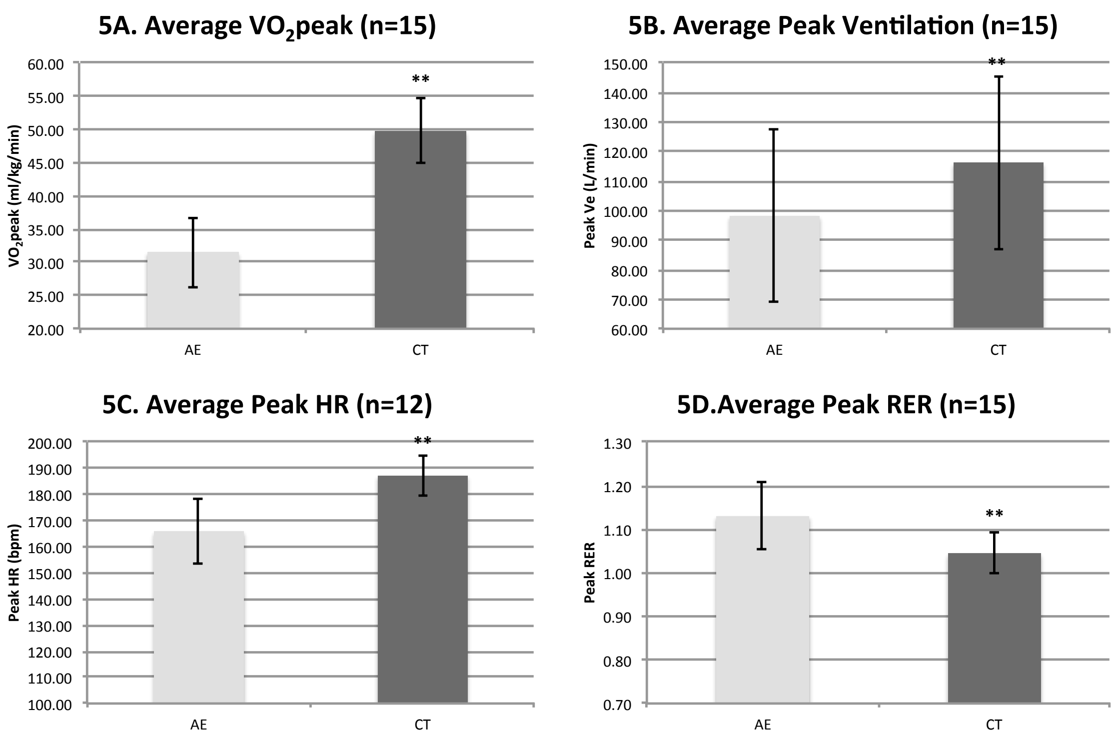

Figure 5. Significant physiological variables for between SCAPPs analysis (n=15), data shown as: mean ± SD, Abbreviations: TTE, time to exhaustion, RER, respiratory exchange ratio (VCO_2/VO_2)
* $P \leq 0.05$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups, ** $P \leq 0.01$ as determined by a 2 sample t-test between respective sex, or 'Low' & 'High' ability groups

Chapter IV

Discussion

Based on our results, we accepted our first and second hypotheses with the exception of economy. Under each hypothesis, VO_{2peak}, TTE, PPO_{rel}, and $RER_{1.0}$, were significantly different between low and high ability groups, and correlated significantly, for either reported OS or RP, when testing the entire sample, for at least one of the tests. Only economy did not meet the requirements for the first and second hypotheses and was rejected (Table 7, Table 9). We also accepted the third hypothesis. Based on the results in Table 11, the SCAPP-CT elicited a higher aerobic response than the SCAPP-AE.

Like previous research, our results show that TTE, measured during a climbing-specific test on a treadwall, was significantly higher in males than females ($P \leq 0.05$) (Table 8) and significantly higher in high ability groups vs. low ability groups ($P \leq 0.01$) (Table 7) (Espana-Romero et al., 2009). Unlike Espana-Romero, our results showed that TTE correlated significantly with OS and RP for both men (r = 0.75, $P \leq 0.01$) and women (r = 0.83, $P \leq 0.01$), whereas they reported TTE only correlating significantly with reported OS for men (r = 0.76, $P < 0.05$), and not women (r = 0.49) (Espana-Romero et al., 2009 did not look at RP for this comparison). This could potentially be due to our sample of women (n=8) having a higher reported OS (avg. 5.12b, range: 5.12a-5.13a) than their sample (n=8) (avg. 5.11d, range not reported), but might also be due to a difference in protocols, since our protocol was much more similar to a classic graded exercise test (GXT), while theirs was a blend between a GXT and a time to fatigue test at a constant workload. Balas et al. (2011) tested a wide range of abilities in females (n=14) (range: 5.3 – 5.13d), and found that attained climbing speed, which can be interpreted as a similar measure to TTE, correlates significantly (r = 0.90, $P \leq 0.01$) with reported climbing ability using a protocol similar to ours (increments 5 movements/minute every 3-minutes). Our VO_{2peak} results for women are also similar to results reported by Balas et al. (2011). They found a significant correlation of r = 0.72 ($P \leq 0.01$) when looking at VO_{2peak} and OS, while we calculated a similarly significant correlation of r = 0.76 ($P \leq 0.05$) with VO_{2peak} and OS climbing ability in women. Therefore, it appears that VO2peak exhibits a similar relationship across wide and narrow ranges of climbing abilities, which might indicate it as a useful measure for sport climbing performance.

Also, although Espana-Romero et al. (2009) did not find VO_{2peak} to be significantly higher in their high ability group vs. low ability group, when more closely analyzing their data, their reported values are in line with ours. For females (n=8) with an average OS climbing ability of 5.11d (range: 5.11a/b - 5.13a), average reported VO_{2peak} was 49.2 ± 3.5 mL/kg/min (Espana-Romero et al., 2009), while in our study, females (n=8) with an average OS climbing ability of 5.12b (range: 5.12a - 5.13a), average VO_{2peak} was 43.4 ± 4.3 mL/kg/min. For males (n=8) with an average OS climbing ability 5.13b (range: 5.12c - 5.14b), average reported VO_{2peak} was 53.6 ± 3.7 (Espana-Romero et al., 2009), while in our study, males (n=13) with an average OS climbing ability of 5.12b/c (range: 5.10c - 5.13c), average VO_{2peak} was 52.1 ± 3.0. To summarize, Espana-Romero et al. (2009) found that expert and elite male ability groups each had an average VO_{2peak} over 50 mL/kg/min. Balas et al. (2011) found that a VO_{2peak} of 45-50 mL/kg/min on a SCAPP-CT is critical for females to climb hard routes, and in our study, we found a significantly higher VO_{2peak} in the high ability group in certain low/high comparisons (*P*

≤ 0.05), and that VO_{2peak} significantly correlates with female OS ability (r=0.76, $P \leq 0.05$). Therefore, all of these results begin to demonstrate more concretely that VO_{2peak} plays a noticeable role in sport climbing ability. Although we did not report it in Table 8, we experimentally dropped the top four male climbers (≥ 5.13a) from the Spearman's rank correlation between OS ability and VO_{2peak} and ran it again with the remaining subjects, specifically to test if VO_{2peak} is a better indicator of performance up to a certain ability range. The new correlation returned a significant r-value of 0.69 ($P \leq 0.05$). This may indicate that VO_{2peak} is more predictive up to a certain ability range, and more important to reaching certain performance levels, and warrants further investigation into what levels of VO_{2peak}, measured during a SCAPP: CT, are important to reaching certain climbing abilities.

Our VO_{2peak} for the SCAPP-AE for men (34.1 ± 4.0 mL/kg/min) are also similar to results reported by Michailov et al. (2015) (34.1 ± 4.1 mL/kg/min), though our results did not significantly correlate to reported OS and RP as in their study. We tested a remarkably similar male subject pool as Michailov et al. (2015) (same sample size, similar climbing abilities, nearly identical mean VO_{2peak} and ranges for climbing abilities), and followed the same protocol as established by Michailov et al. (2015), yet we calculated very different correlation coefficients for VO_{2peak} and climbing ability. We have reported correlations of r = 0.34 and r = 0.42 for VO_{2peak} in our study, for OS and RP, respectively, whereas they reported significant correlation coefficients for VO_{2peak} and climbing ability of r = 0.85 ($P \leq 0.0$) and r = 0.72 ($P \leq 0.05$), for OS and RP, respectively. Unlike Michailov et al. (2015), we split our sample into low and high ability groups and conducted t-tests to explore differences between groups. Although our means were not significantly different between low and high ability groups for VO_{2peak}, they were extremely close with a calculated P=0.06, with the high ability group having a higher recorded mean VO_{2peak} than the low ability group. Continued research is required to draw any definite conclusions about VO_{2peak} during the SCAPP-AE and its relationship to sport climbing ability.

When comparing PPO_{rel} data between our study and Michailov et al. (2015), the results are more in line with each other. For our male sample, average PPO_{rel} and correlation coefficients for OS and RP were 1.81 ± 0.24 W/kg, r = 0.56, and r = 0.66 ($P \leq 0.05$), respectively, compared to their results for males of 2.0 ± 0.2 W/kg, r = 0.75 ($P \leq 0.01$), and r = 0.80 ($P \leq 0.01$), respectively. Once again, we conducted low vs. high ability comparisons in our study, and this time found the high ability group to have significantly higher mean PPO_{rel} than the low ability group (1.95 ± 0.20 vs. 1.53 ± 0.23 W/kg). Although results for PPO_{rel} between our study and Michailov et al. (2015) differ slightly, there is a better trend in data between both studies to support that PPO_{rel} for the SCAPP-AE may be a strong predictor of sport-climbing ability, particularly when considering our significantly higher means in the high ability group vs the low ability group, and significant relationships between PPO_{rel} and sport climbing ability, for the entire SCAPP-AE sample. (Table 10)

It is important to note that percent body fat between studies was also similar (14 males in our total sample with %BF data (% BF of 10.73 ± 4.91), 9 males that specifically completed our SCAPP-AE and %BF (%BF 10.94 ± 5.16) in our study vs. 11 males in Michailov et al., 2015 (%BF of 9.8 ± 2.1), so the differences in VO_{2peak} and PPO_{rel} are not explained by differences in lean muscle mass. Michaelov et al. (2015)

reported time spent training in hrs/week, which is a more specific climbing training parameter than training sessions/month. However, the frequency of training sessions are fairly similar between studies (4.4 ± 1.05 per week for Michailov et al., 2015 vs. 13.8 ± 3.2 per month in our study). Therefore, training frequency and volume may partially be able to explain the different results found between studies for VO_{2peak} and PPO_{rel}, but we consider this unlikely due to all of the other similarities between the studies (e.g. training sessions per month, anthropometric characteristics, physiological characteristics). A more likely explanation may lie in how each group of subjects spent their time training for sport climbing. This data is missing from both studies, but type of training and quality of training may be important sets of data for future studies to record and report, thereby allowing better comparisons to be made between studies and allowing for stronger conclusions concerning physiological parameters and their role in sport climbing ability.

The present study was the first to compare two climbing-specific protocols as aerobic predictors of sport-climbing performance and examine climbing economy and $RER_{1.0}$ as predictors of sport-climbing performance. Our study also included more climbers (n=22) than previous studies investigating aerobic predictors of performance. Although there was an issue with obtaining full data sets for all subjects, a sample size of n=15 for between test comparisons is still as large, or larger, than most climbing studies (Bertuzzi et al., 2007, n=13, Booth et al., 1999, n=7, Balas et al., 2011, n=14, Espana-Romero et al. 2009, n=16, Michailov et al., 2015, n=11, Pires et al., 2012, n=21 (14 climbers, 7 controls)). Due to these factors, we arguably had the largest set of data for potential aerobic predictors of sport climbing performance to date.

In terms of climbing economy during the SCAPP-AE test, females unexpectedly had significantly better economy than males during the submaximal phase of the protocol (males: 29.61 ± 2.91 W/L/min vs. females: 36.50 ± 1.22 W/L/min, $P \leq 0.01$). Moreover, the SCAPP-CT results for economy found a weak trend ($P = 0.13$) for females to have better economy than males. No previous data exists to indicate how or why females would be more economical than males while performing these climbing protocols. One possibility, however, is that since the protocols use absolute workloads, the females completed the economy stages at a higher relative workload. This alone could affect the data, as it is understood that economy improves across low workloads in sub-maximal tests for other sports (e.g. running and cycling). Larger sample sizes of females are required to further assess what role economy plays in sport-climbing ability in females. While economy and its relationship to sport climbing ability requires further testing to verify our results, it indicates that economy, measured as such in our study, is most likely not a predictor of sport climbing performance in males for the ability ranges we tested.

Also, it is important to note that due to the constraints on calculating economy for the SCAPP-CT (subjects had to complete a minimum of 4 stages so that the first three stages could be considered submaximal), we recommend that a new submaximal protocol be created to more accurately reflect economy in climbers of all ability levels.

It is noteworthy to mention that economy values increased across the first three stages when analyzing the data by stage. The values recorded were 39.8 ± 2.9 W/L/min, 42.0 ± 2.2 W/L/min, and 45.7 ± 2.5 W/L/min, for stages 1, 2, and 3 of the SCAPP-CT, respectively. This is important because it agrees with what is found while measuring economy for other endurance sports (e.g. running and cycling), and this is the first time it has been demonstrated for sport climbing.

When considering results for $RER_{1.0}$, it was statistically significant for multiple low/high ability comparisons and provided multiple significant correlations (mostly for the SCAPP-CT). Michailov et al. (2015) only reported subjects' time spent at $RER_{1.0}$, but did not indicate if they looked at correlations or differences between low and high ability ranges. This may be because, as we have reported, $RER_{1.0}$ is largely a non-significant variable in the SCAPP-AE protocol (only significant between sexes, Table 10). On the other hand, for the SCAPP: CT, $RER_{1.0}$ was nearly as strong a predictor across low/high, and sex specific low/high, ability groups as TTE, in our study. This is likely due to the similar nature of TTE and $RER_{1.0}$, whereas they are both endurance parameters, with $RER_{1.0}$ providing more specific data of time spent at, or above, the ventilatory anaerobic threshold. Nonetheless, these findings are intriguing to us as we seek to understand the physiological rationale to support the results for $RER_{1.0}$.

Michailov et al. (2015) suggested that stronger climbers have higher anaerobic power and buffering capacities as determined by blood lactate data in their study. This data demonstrated that higher ability climbers have lower levels of blood lactate at the same workload, and the ability to continue climbing with higher levels of blood lactate, when compared to lower ability climbers. This may provide some insight in to what $RER_{1.0}$ represents physiologically. Other potential factors that may effect $RER_{1.0}$ include higher anaerobic energy stores in skeletal muscle, increased ventilation rates to buffer metabolic acidosis, and the ability to change climbing styles and focused muscles groups during testing (specifically during the SCAPP-CT). None of this data is provided in our study, and is something that future studies should seek to analyze.

Since the purpose of this study was to look in to aerobic predictors of sport climbing performance, it was important to assess if differences existed in the aerobic responses between climbing protocols. The VO_{2peak}, HR_{peak}, and VE_{peak} were significantly higher for the SCAPP-CT than the SCAPP-AE. In particular, the mean HR_{peak} results were close to expected maximal HR responses in the SCAPP-CT protocol. Therefore, based on the SCAPP-CT being a whole body exercise more similar to actual sport climbing (entire body vs. upper body alone), and significantly higher responses for each VO_{2peak}, HR_{peak}, and VE_{peak} during the SCAPP-CT, we can conclude that the SCAPP-CT is a better test to use when assessing aerobic predictors of sport-climbing performance.

While the SCAPP-CT looks like the better laboratory test for predicting sport climbing ability when comparing aerobic variables, between low and high ability groups , it is important to consider how these tests could be used outside of a laboratory setting (e,g. at an indoor climbing gym to assess fitness and climbing performance). Our data support using the SCAPP-CT first, since TTE is an easily measured variable with the most data to support the efficacy of its predictive power for climbing ability. The SCAPP-AE might still be utilized however, since the equipment is much more common and PPO_{rel} was a fairly strong predictor of climbing ability in the present study and in Michailov et al. (2015).

Although we have established that there is potential for the SCAPP-CT or SCAPP-AE to be used as predictive tests of sport-climbing ability, more research is needed to establish the predictive value of specific dependent variables (TTE, $RER_{1.0}$,

PPO_{rel}, VO_{2peak}, and economy). Many of our results are more applicable to males as our 'high' ability group was composed of all males for the SCAPP-AE, and all males plus one female for the SCAPP-CT. A study encompassing an even larger range of climbing abilities, with a larger sample population, and a lower rate of subject attrition, is required to truly assess the predictive power of each variable and each test (SCAPP-CT and SCAPP-AE). Due to our sample population and sample size, we were not able to separate climbers in to more distinct categories than 'low' and 'high' ability, and we were not able to categorize climbers as sport-climbers specifically (vs. boulderers vs. trad climbers). This will be an important distinction for future studies to make, as the training for each sub-discipline of climbing varies and almost certainly results in different physiological adaptations.

Future studies should utilize at least a 2-grade gap in arbitrarily assigned ability groups to create distinct groups. We will go further to suggest more specific ability ranges for redpoint sport-climbing ability, and provide, what we feel, are the minimum requirements for rock climbers to be classified as "sport climbers" for future studies. For ability ranges, we suggest redpoint climbing abilities in a rock-climbing gym of: Beginner, 5.0-5.8, Intermediate, 5.9-5.10d, Advanced, 5.11a-5.12d, and Elite: ≥ 5.13a. We also believe there is merit in defining a 'sport climber' as someone who has spent a minimum of 50% of their climbing sessions sport-climbing in the past 3 months. There is no physiological data currently to support either of these classification systems. Regardless, these classification systems will still provide a better basis for categorizing subjects for future climbing research than having each study randomly categorize subjects based on their sample populations, and testing rock climbers for sport-climbing specific protocols who do not train specifically for sport-climbing. This call for cohesion between studies will allow for more accurate comparisons of data between studies, allowing for stronger conclusions to be drawn.

In conclusion, Both SCAPPs require further research to truly ascertain their strengths and weaknesses. The SCAPP-CT was a better protocol to assess aerobic predictors of sport-climbing performance and to predict OS sport-climbing ability than the SCAPP-AE. Potentially, the SCAPP-CT may be able to be utilized to prescribe a sport climbers training regimen to promote improvements in sport-climbing ability. Further research is necessary to establish the significance of VO_{2peak} to sport-climbing ability, but a SCAPP-CT specific VO_{2peak} of 50-55 mL/kg/min appears to be beneficial for climbers, particularly males, to achieve an ‘advanced’ or ‘elite’ level of sport-climbing ability. More research into TTE and $RER_{1.0}$ is necessary to establish if one is a better indicator or predictor of climbing ability, while also furthering our understanding of how these physiological variables characterize climbing ability.

Chapter V

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