Sports Nutrition- and Strength and Conditioning-based Interventions to Bolster Health and Human Performance in Male and Female Tactical Personnel

Harry Paul Cintineo

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Sports Nutrition- and Strength and Conditioning-based Interventions to Bolster Health and Human Performance in Male and Female Tactical Personnel

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Submitted in Partial Fulfillment of the Requirements
For the Degree of Doctor of Philosophy in
Exercise Science
The Norman J. Arnold School of Public Health
University of South Carolina
2022

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ACKNOWLEDGEMENTS

First off, I would like to thank my doctoral supervisor, Dr. Shawn Arent, for guiding and supporting me through this process. I have gained an abundance of knowledge and skills in the field of exercise science and the scientific research process during my time at Rutgers University and the University of South Carolina. I would also like to thank my doctoral committee members, Drs. Yeargin, Lane-Cordova, and Ferrando, for their time and patience in providing their expertise to my dissertation. Further, the research conducted in this dissertation would not be possible without the support provided by Compound Solutions Inc. and the United States Department of Defense.

This research would not have been completed without the help of my lab mates, especially Dr. Bridget McFadden and Alexa Chandler. Bridget, you have provided me with a great deal of assistance and mentorship during my doctoral studies, and I look forward to working together in the future. Alexa, I could not have completed these projects without your help. Working out the logistics, coordinating research participants and lab staff, and staying organized along the way would have been a Sisyphean task without your help. To all my other lab mates, current and past, my dissertation could not have been completed without your help, and I am extremely grateful for that.

Lastly, I want to acknowledge my family, especially my parents, John and Lenore, for supporting me through this arduous journey of higher education. I could not have completed this process without your constant and unwavering encouragement.
ABSTRACT

Military and law enforcement personnel are required to possess sufficient physical and cognitive fitness to perform their official duties. Tactical athletes must have fast reaction times (RT), high levels of various aspects of muscular performance, including power, strength, and endurance, as well as high anaerobic and aerobic capacities. The purpose of this dissertation was to investigate acute sports nutrition and chronic strength and conditioning strategies to improve health and human performance in tactical athletes, including law enforcement officers, active-duty military service members, and Reserve Officers’ Training Corps (ROTC) cadets and midshipmen.

The first study tested the effects of a combination of caffeine, methylxantine, and theacrine compared to caffeine alone and placebo on RT and marksmanship following a sustained vigilance task along with hemodynamic responses using a double-blind, randomized, placebo-controlled design. Male law enforcement officers, military service members, and ROTC cadets and midshipmen (N=49) were randomized into one of three groups: 1) a combination of 150 mg caffeine, 100 mg methylxantine, and 50 mg theacrine, 2) 300 mg caffeine alone, or 3) placebo. They then participated in a 150-min protocol consisting of two rounds. Each round began with leisurely reading followed by a 30-min vigilance task before beginning two trials of movement and marksmanship tasks. The results showed the combination of 150 mg caffeine, 100 mg methylxantine, and 50 mg theacrine as well as the 300 mg caffeine alone improved vigilance RT over
the 150-min protocol while placebo did not, and there were no differences in
marksmanship performance between groups. However, caffeine alone resulted in large
increases in diastolic blood pressure above placebo while the combination did not.

The second study tested the effects of six weeks of minimal-equipment
resistance exercise training (RET) with and without blood flow restriction (BFR) on the
military-relevant performance tasks of the Army Combat Fitness Test (ACFT) along with
laboratory-based performance and body composition measures compared to
traditional-equipment RET using a randomized, parallel-group, between-subjects design.
Male and female ROTC cadets and midshipmen (N=54, 40.7%) were randomized into
one of three groups: 1) traditional-equipment RET, 2) minimal-equipment RET, or 3)
minimal-equipment RET with BFR. Performance and body composition changes were
assessed from pre- to post-training, and measures of intensity and overall workload
were evaluated throughout the study. The results showed RET with minimal equipment
improves multiple aspects of human performance and body composition over six weeks,
though traditional-equipment RET showed greater improvements in muscular strength.
Further, the addition of BFR did not augment changes performance or body composition
following minimal-equipment RET, though this finding may be sex-specific as males
improved strength to a greater extent with BFR. Subjective and objective workload
measures were higher for both minimal-equipment RET groups compared to traditional-
equipment RET.

The results of these studies show the efficacy of sports nutrition and strength
and conditioning interventions for improving health and human performance outcomes
in law enforcement officers and military personnel. Tactical athletes can use the supplementation strategy of combined caffeine, methylxanthine, and theacrine prior to periods of overwatch to maintain vigilance without experiencing substantial adverse hemodynamic responses induced by higher-dosed caffeine alone. Further, military personnel can expect similar improvements in ACFT score, muscular power, muscular endurance, anaerobic and aerobic capacity, and body composition, albeit an attenuation in muscular strength, during periods of limited access to traditional RET equipment. Both strategies tested in this dissertation can be used concomitantly as caffeine and caffeine-like supplements improve health and human performance outcomes acutely and the strength and conditioning intervention tested confers chronic benefits on these measures.
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LIST OF ABBREVIATIONS

ACFT ............................................................................................ Army Combat Fitness Test
CAF ..................................................................................................... 300 mg caffeine group
CRT ................................................................................................. Choice reaction time
CMT .............................................................. 150 mg caffeine, 100 mg methylxanthine, and 50 mg theacrine group
CSCS .......................................................... Certified Strength and Conditioning Specialist
DBP ................................................................................................. Diastolic blood pressure
DOMS .............................................................. Delayed onset muscle soreness
FAS .............................................................................................................. Felt arousal scale
GH .............................................................................................................. Growth hormone
IGF-1 ........................................................................................... Insulin-like growth factor-1
IL ........................................................................................................................... Interleukin
MIN .......................................................................................... Minimal-equipment resistance training group
MIN+BFR .......... Minimal-equipment resistance training with blood flow restriction group
MTDS .......................................................................................... Multicomponent training distress scale
NSCA .......................................................... National Strength and Conditioning Association
PLA ..................................................................................................... 300 mg cellulose placebo group
RET ............................................................................................ Resistance exercise training
RM ....................................................................................................... Repetition maximum
ROTC ................................................................................... Reserve Officers’ Training Corps
RPE ....................................................................................................... Rating of perceived exertion
RT .......................................................... Reaction time
SBP .......................................................... Systolic blood pressure
SRT .......................................................... Simple reaction time
TRAD ...................................................... Traditional-equipment resistance training group
CHAPTER 1

EFFECTS OF CAFFEINE AND CAFFEINE-DERIVATIVES ON REACTION TIME AND MARKSMANSHIP: A LITERATURE REVIEW

Tactical athletes and performance

Military and law enforcement personnel are required to possess sufficient physical and cognitive fitness to perform their official duties. As such, these populations have often been deemed “tactical athletes” to emphasize these requirements. Tactical athletes must have fast reaction times (RT), high levels of various aspects of muscular performance, including power, strength, and endurance, as well as high anaerobic and aerobic capacities (Scofield & Kardouni, 2015). Other characteristics of performance that are specific to the tactical athlete include the ability to maintain task vigilance and shooting marksmanship (Scofield & Kardouni, 2015). Most importantly, physical fitness and performance parameters can have an effect on mission success in these populations (Austin & Deuster, 2015).

Caffeine to improve tactical athlete performance

One strategy to improve performance in a tactical population is the use of sports nutrition supplements, such as caffeine and caffeine-like purine alkaloids. Numerous narrative reviews on the effects of caffeine on exercise and athlete performance have been published (Burke, 2008; Goldstein et al., 2010; Paluska, 2003; Sinclair & Geiger,
2000; Sokmen et al., 2008; Spriet, 1995, 2014; Tarnopolsky, 2010), the most recent of which (Guest et al., 2021) concluded that caffeine in the range of 3-6 mg/kg has positive ergogenic effects on both physical and cognitive performance. More specifically, these doses of caffeine appear to have the largest effects on improving aerobic performance with more trivial effects on muscular power, strength, and endurance (Guest et al., 2021).

The primary mechanism of action by which caffeine exerts its ergogenic effects is central nervous system stimulation, primarily through adenosine receptor antagonism (Faudone et al., 2021). As a neuromodulator, adenosine affects neurotransmission in the central nervous system in a fashion that generally acts to inhibit neural activity through binding to one of its four G-protein coupled receptors: A<sub>1</sub>, A<sub>2A</sub>, A<sub>2B</sub>, and A<sub>3</sub> (Nehlig et al., 1992). Cellular work resulting in the catabolism of adenosine triphosphate and production of adenosine culminates in the accumulation and release of adenosine from cytoplasm to the extracellular fluid via nucleoside transporters (Fredholm, 2014; Layland et al., 2014). This is where adenosine can bind to its receptors and exert inhibitory effects on neurons in the central nervous system (Sperlagh & Vizi, 2011), ultimately resulting in feelings of drowsiness and fatigue (Berne, 1986). Therefore, caffeine attenuates the physiological effects of adenosine via competitive inhibition with all subtypes of the adenosine receptor.

With this primary mechanism of action in mind, the effects of caffeine have been tested on tactically relevant outcomes, including RT, vigilance, and marksmanship. In fact, studies showing the positive effects of caffeine on various measures of RT date
back to the 1930s (Horst & Jenkins, 1935; Thornton et al., 1939). The results of this early work showed generally favorable effects of absolute doses of 300 mg and relative doses of 2 to 4 mg/kg caffeine in the form of coffee or a powdered extract consumed between 15 and 75 min before testing on simple and choice RT (SRT; CRT) in males compared to placebo conditions in the form of decaffeinated coffee and other non-caffeine containing solutions. Further, it was established that higher doses in the range of 600 mg caffeine did not result in positive effects compared to placebo (Thornton et al., 1939). More recent work has corroborated these findings as Jacobson and Edgley (1987) showed ergogenic effects on RT and movement time in young males and females consuming 300 mg, but not 600 mg, caffeine compared to placebo. In athletes, 5 mg/kg caffeine consumed 60 min before testing has consistently shown improvements on RT compared to placebo (Santos et al., 2014; Souissi et al., 2012) and also offers benefits following periods of sleep deprivation (Souissi et al., 2014). Similarly, Doyle et al. (2016) conducted an extensive dose-response study on the effects of caffeine ranging from 0 to 7.5 mg/kg in 1.5 mg/kg increments consumed 60 min before testing on RT and accuracy in collegiate fencers and found a slightly higher dose of 6 mg/kg caffeine resulted in the greatest improvement in overall fencing-specific performance determined through a composite score of RT and accuracy. Together, these studies show the ergogenic effects of caffeine on RT, movement time, and accuracy, but higher doses are not always better than more moderate doses.

In tactical populations, the ergogenic effects of caffeine have typically been assessed in the context of vigilance, or the ability to maintain alertness during extended
periods, as well as during periods of sleep restriction or deprivation (Bonnet et al., 1995; Kamimori et al., 2005; Kamimori et al., 2015; Kamimori et al., 2000; McLellan et al., 2007). These studies employed various caffeine dosing strategies and outcome measures. Bonnet et al. (1995) compared the efficacy of naps ranging from 2 to 8 hours to a 400-mg single caffeine dose or 150- or 300-mg doses administered every 6 hours during a period of sleep deprivation in 140 young males. It was found that consecutive doses of both 150 and 300 mg caffeine resulted in similar improvements in cognitive task performance as the groups who took 2- and 4-hour naps, though the group that took an 8-hour nap exhibited the greatest improvements in cognitive performance (Bonnet et al., 1995). Kamimori et al. (2000) compared 2.1, 4.3, and 8.6 mg/kg caffeine to placebo on measures of sleepiness and CRT during vigilance following 48 hours of sleep deprivation and found no effect of caffeine dose on these measures. However, a follow-up study by the same group tested the effects of multiple doses of 50, 100, and 200 mg caffeine during overnight vigilance following 24-hour sleep deprivation in 48 young males and females and, although no differences were found for RT during a psychomotor vigilance task, the placebo group showed the greatest number of lapses, or occurrences in which RT exceeded one second, while the 200 mg caffeine group showed the fewest (Kamimori et al., 2005). Further, McLellan et al. (2007) provided multiple 200-mg caffeine doses during an overnight vigilance task which required soldiers to record all activities that occurred in an illuminated building situated 175-200 meters away for 120 min in 20 special operators and showed maintenance of vigilance in the caffeine condition while placebo resulted in decrements. Caffeine also improved
4-km run times in an obstacle course while placebo did not. In a similar design, Kamimori et al. (2015) tested the effects of four consecutive doses of 200 mg caffeine during the same overnight vigilance task used by McLellan et al. (2007) and showed improvements in RT during a psychomotor vigilance task consisting of 85 visual stimuli with 1 to 5 seconds between each in the caffeine group but not placebo with no differences in lapses.

Another important measure of performance for the tactical athlete is marksmanship, and numerous studies have examined the effects of caffeine on this skill (Gillingham et al., 2003; Gillingham et al., 2004; Johnson & Merullo, 1999; Kamimori et al., 2015; Tharion et al., 2003). Johnson and Merullo (1999) tested the effects of 200 mg caffeine on target detection time, marksmanship accuracy, and the ability to differentiate between friend and foe compared to placebo in 22 young male and female soldiers. It was found that the caffeine conditions improved RT, accuracy, and friend-foe differentiation. Another study looked at the dose-response effects of 100, 200, and 300 mg caffeine on marksmanship in 62 Navy SEAL trainees during Basic Underwater Demolition/SEAL training, and it was found that 200 and 300 mg caffeine conferred benefits on target sighting time compared to placebo and 100 mg caffeine with no other effects on marksmanship performance (Tharion et al., 2003). Two consecutive studies were conducted by Gillingham et al. (2003; 2004) in military reservists, the first of which showed no differences in marksmanship performance between 300 mg caffeine and placebo conditions during periods of vigilance following sleep deprivation. The subsequent study used a four-condition cross-over design and took a different dosing
approach in which participants received either a bolus dose of 5 mg/kg caffeine or placebo and a second dose of 2.5 mg/kg caffeine or placebo eight hours later. Target detection speed and enemy engagement time was faster in the caffeine-caffeine compared to placebo-placebo condition, and these measures were not different from placebo-placebo in the placebo-caffeine or caffeine-placebo conditions (Gillingham et al., 2004). The authors reported greater feelings of hand trembling and irritability during the caffeine-caffeine condition, a commonly cited negative side effect of caffeine consumption (Humayun et al., 1997; Jacobson & Thurman-Lacey, 1992; Kaplan et al., 1997; Shirlow & Mathers, 1985), though this did not negatively affect marksmanship.

Together, the findings of these studies on measures of tactically relevant performance outcomes including RT, vigilance, and marksmanship in tactical populations show the overall positive effects of moderate doses of caffeine ranging from 200 to 300 mg or 2 to 5 mg/kg with greater sustained effects through subsequent smaller doses 6 to 8 hours after the initial dose. Though many of these studies have somewhat conflicting results, it should be emphasized that although some findings show no ergogenic effects on these measures, especially marksmanship, negative effects are not typically observed when caffeine is consumed in these moderate doses. In fact, the body of literature on the effects of caffeine in tactical populations, general population, and athletes, along with the findings of McLellan et al. (2007), provide a unique interpretation of the utility of caffeine in tactical scenarios. These studies show that caffeine may attenuate decrements in RT, vigilance, and marksmanship, improve other
aspects of physical performance, and provide a benefit above placebo or non-supplementation.

Pharmacodynamics of caffeine and caffeine-derivatives

In addition to the role of caffeine as a central nervous system stimulant through adenosine receptor antagonism described previously, pharmacodynamic data also show that caffeine exerts its effects through reducing catabolism of acetylcholinesterase and phosphodiesterase, resulting in higher concentrations of acetylcholine, a neurotransmitter, and cyclic adenosine monophosphate, an intracellular secondary messenger (Faudone et al., 2021). Further, caffeine has been shown to modulate gamma aminobutyric acid (GABA) A receptors/Cl⁻ channels through the benzodiazepine and picrotoxinin binding sites (Shi et al., 2003). Lastly, caffeine also appears to influence intracellular calcium handling and dynamics, particularly in muscle and neural tissue, through interactions with ryanodine receptors/Ca²⁺ channels (Shi et al., 2003).

Though caffeine is the most widely consumed and studied drug of the purine alkaloids, newly discovered compounds, tetramethylurates such as methylliberine (Dynamine™) and theacrine (TeaCrine®), exhibit structural similarities to caffeine and have been shown to exert similar pharmacodynamic effects (Figure 1.1). Methylliberine and theacrine both act as adenosine receptor antagonists and appear to have the same effects on the nervous system as caffeine. However, different structural properties of methylliberine, including a methyl residue shifted from nitrogen-3 to nitrogen-9, an additional methyl group on oxygen-11, and a ketone functional group on carbon-8 of
the 5-carbon ring, make the overall compound a urate-analogue rather than a xanthine-analogue. Theacrine differs from caffeine as it contains an additional methyl group on nitrogen-9 and, like methylliberine, contains a ketone functional group on carbon-8 of the 5-carbon ring making it more akin to urate rather than xanthine. These structural differences, albeit small, may explain differences observed in pharmacodynamic and pharmacokinetic data.

![Molecular structures of caffeine, methylliberine, and theacrine.](image)

**Figure 1.1.** Molecular structures of caffeine, methylliberine, and theacrine.

**Pharmacokinetics of caffeine and caffeine-derivatives**

One notable difference between these compounds is the pharmacokinetic profiles. Caffeine’s peak plasma concentration following oral consumption occurs within approximately 30-60 min with a half-life of approximately 4-5 hours (Kaplan et al., 1997; Research, 2001). Methylliberine has a shorter peak time of 0.6 and 0.9 hours with a half-life of 1.4 hours when consumed in doses of 25 mg and 100 mg, respectively (Mondal et al., 2021), while theacrine, on the other hand, has a longer peak time of about 1.8 hours and half-life of 16.5-26.1 hours when consumed in 25 mg and 125 mg doses (He et al., 2017). These studies also assessed pharmacokinetic profiles when consumed in
conjunction with caffeine. Mondal et al. (2021) tested the pharmacokinetic profile of 100 mg methylliberine and 150 mg caffeine and found methylliberine kinetics were largely unaffected by caffeine but caffeine half-life increased to 13.6 hours with minimal effect on peak time. Similarly, He et al. (2017) provided a combination of 125 mg theacrine and 150 mg caffeine and showed a shortened peak time of 1 hour for theacrine and a typical peak time of 1 hour for caffeine with no effect on half-life for either compound. These results suggest methylliberine may substantially increase the half-life of caffeine, and caffeine may shorten the peak time of theacrine.

A recent study assessed the pharmacokinetics of caffeine, methylliberine, and theacrine when consumed together (Wang et al., 2020). In a combination of 100 mg methylliberine, 150 mg caffeine, and 50 mg theacrine, pharmacokinetic data showed peak plasma concentration times of 0.8, 1.1, and 1.4 hours, respectively, with half-lives of 1.5, 21, and 30 hours, respectively (Figure 1.2). This shows the potential synergistic effect of supplementation with these compounds as the differential peak times allow for the anti-depressive and stimulatory actions to be maximized across a longer period than supplementing with one alone. Together, this can create a more sustained peak effect while also resulting in longer lasting time course.
Methylliberine and theacrine to improve performance

Based on this theoretical rationale and the demonstrated safety of these compounds (He et al., 2017; VanDusseldorp et al., 2020), the efficacy of a combination of caffeine with methylliberine and/or theacrine has been assessed in applied studies on various performance outcomes (Bello et al., 2019; Cesareo et al., 2019; Kuhman et al., 2015; La Monica et al., 2021). Cesareo et al. (2019) assessed measures of muscular performance following consumption of placebo, 300 mg caffeine, 300 mg theacrine, and a combination of 150 mg caffeine and 150 mg caffeine on in 12 recreationally trained males. No differences in muscular power, rate of force development, muscular strength, or muscular endurance were observed between conditions. The three other studies took a different approach and assessed performance with a cognitive component using within-subjects designs. Bello et al. (2019) tested the effects of placebo, 300 mg
caffeine, 300 mg theacrine, and a combination of 150 mg caffeine and 150 mg caffeine on physical and cognitive task performance as well as RT in 24 high level soccer players. SRT, CRT, and cognitive-load RT were assessed throughout a simulated soccer match. At half-time, all RTs were faster in caffeine only compared to placebo and theacrine only, and CRT was faster in the combination condition than placebo and theacrine only. Following the match, only CRT was faster in the combination condition compared to all others, suggesting a more sustained positive effect following this supplementation protocol. A time-to-exhaustion task was completed following the match and RT testing, and, though no statistical differences in performance were observed between conditions, the largest effect for improvement above placebo (d=0.51) was noted in the combination condition (Bello et al., 2019). Kuhman et al. (2015) compared the effects of placebo, 150 mg caffeine, and an undisclosed amount of theacrine with 150 mg caffeine on cognitive task performance and RT in 20 young males and females. No differences in performance were observed between any of the conditions. Lastly, La Monica et al. (2021) tested the effects of placebo, 125 mg caffeine, and 125 mg caffeine with 75 mg methylliberine and 50 mg theacrine on first-person-shooter gaming performance in 9 recreational gamers. Over the course of a 4-hour protocol, greater improvements from baseline were observed in caffeine compared to other conditions for RT, though the combination condition showed greater improvements in variances in RT, overall shooting accuracy, and time to eliminate target, suggesting the most positive improvement in both RT and accuracy was observed following the combination supplementation protocol. Though preliminary, the results of these few studies show
positive effects of combining caffeine with methylliberine and/or theacrine on cognitive
tasks, RT, and accuracy, corroborating past research on the effects of caffeine on these
outcomes.

Hemodynamic responses

One difference of particular interest between caffeine and these related
compounds is the acute effect on hemodynamic responses. Hemodynamics broadly
refers to pressures and flows through the circulatory system includes measurements
such as blood pressure and heart rate (Secomb, 2016). Numerous systematic reviews
have been published assessing the hemodynamic effects of caffeine at rest and during
exercise (Green et al., 1996; Myers, 1988). Generally, moderate-to-high doses of
caffeine ranging from one cup of coffee (approximately 125 mg caffeine) to 300 mg
caffeine acutely increase blood pressure and heart rate in normotensive individuals.
These effects vary between studies, with some showing increases in both systolic (SBP)
and diastolic (DBP) as well as mean arterial pressure, and others showing increases in
only SBP or DBP (Myers, 1988). Further, effects on resting heart rate differs across
studies, with some showing increases, decreases, or no change (Green et al., 1996). One
factor that appears to affect the acute hemodynamic response following caffeine intake
is whether participants are caffeine-naïve or caffeine-habituated, as non-caffeine users
tend to experience greater perturbations in blood pressure one hour following
consumption (Cheung et al., 2016). Though, however, it is important to note that the
ergogenic effects of caffeine do not appear to be attenuated by habituation (Van Soeren & Graham, 1998; Van Soeren et al., 1993).

This hemodynamic effect also extends to exercise, as studies have shown greater increases in SBP and DBP during aerobic exercise bouts following consumption of ≥360 mg caffeine compared to placebo (Daniels et al., 1998; Harber et al., 2021; Sung et al., 1990). This hemodynamic response appears to be mediated by catecholamines, as multiple studies have shown higher norepinephrine and epinephrine levels both at rest and during exercise following caffeine intakes ranging from 3 mg/kg to 9 mg/kg (Graham & Spriet, 1995; Jackman et al., 1996; Robertson et al., 1978; Sung et al., 1990). However, other studies have shown increases in epinephrine but not norepinephrine (Kamimori et al., 2000) suggesting caffeine may influence adrenomedullary activity to a greater extent than autonomic nervous system activity.

Based on the alterations in blood flow observed following caffeine ingestion, resting hemodynamic responses following methylliberine and theacrine supplementation have been investigated (Taylor et al., 2016; VanDusseldorp et al., 2020). Over eight weeks of daily supplementation of 200 or 300 mg theacrine in 60 healthy, young males, no differences in SBP or DBP from placebo were observed (Taylor et al., 2016). In a similar safety study, 125 males and females were randomized to daily supplementation for 4 weeks in accordance with one of five groups: placebo, 100 mg methylliberine, 100 mg methylliberine and 50 mg theacrine, 150 mg methylliberine, or 150 mg methylliberine and 25 mg theacrine (VanDusseldorp et al., 2020). No changes were observed in acute or chronic blood pressure responses in any group. Additionally,
a subsequent study investigated hemodynamic effects with low-to-moderate doses of caffeine added to methylliberine and/or theacrine as this more closely mimics protocols in which performance benefits have been observed (Bloomer et al., 2020). Supplementation protocols included placebo, 25 mg methylliberine, 100 mg methylliberine, 150 mg caffeine, 100 mg methylliberine and 150 mg caffeine, 100 mg methylliberine and 50 mg caffeine, and a combination of 100 mg methylliberine, 50 mg theacrine, and 150 mg caffeine, and it was found that all conditions in which caffeine was included resulted in an increase in both SBP and DBP compared to those in which caffeine was not ingested. Together, the results of these studies suggest that caffeine appears to be the primary driver of resting blood pressure increases following acute supplementation.

In protocols with physical or cognitive stressors, the effects of these supplements are mixed. For example, Kuhman et al. (2015) provided 150 mg caffeine with and without an undisclosed amount of theacrine before a 4-hour testing battery consisting of the trail making test, digit symbol substitution test, and computer-based RT test and found that the condition in which both compounds were consumed resulted in higher SBP compared to the caffeine-only and placebo conditions. However, LaMonica et al. (2021) compared a combination of 125 mg caffeine, 75 mg methylliberine, and 50 mg theacrine to 125 mg caffeine consumed before four 20-min bouts of first-person shooter video gaming and showed no differences between the two conditions, supporting the previous notion that caffeine appears to be driving these hemodynamic responses.
Arousal

Like blood pressure responses, caffeine has also been shown to alter levels of arousal. The construct of arousal refers to a broad level of physiological “activation” and has historically been measured using objective assessments, such as skin conductance, electroencephalography, hemodynamics, catecholamine levels, etc. (Duffy, 1957; Neiss, 1988). Barry et al. (2011; 2008; 2005) conducted a series of studies, all of which tested the effects of 250 mg caffeine compared to placebo in college-aged males and females. The results of these investigations all showed higher skin conductance levels and lower electroencephalogram alpha frequency activities, unequivocally indicating greater physiological arousal following consumption of 250 mg caffeine compared to placebo. Several studies have attributed these increases in arousal following caffeine consumption to its role as an adenosine antagonist, specifically through acting on the adenosine A2A receptors (Huang et al., 2005; Lazarus et al., 2011).

In the field of sport psychology, however, subjective scales have been used to assess the construct of perceived or felt arousal (Raedeke & Stein, 1994; Russell et al., 1989; Svebak & Murgatroyd, 1985). The felt arousal scale, however, is the only of these that solely assesses arousal without incorporating an affective component (i.e., unpleasant vs. pleasant feelings) and has been used in multiple studies testing the effects of caffeine in the context of exercise on felt arousal (Ali et al., 2016; Astorino et al., 2012; Backhouse et al., 2005; Clarke et al., 2015; Richardson & Clarke, 2016). Overall, these investigations have shown no effects of caffeine consumption ranging from 5 to 6 mg/kg on ratings of felt arousal compared to placebo in sample sizes of 8 to 15 young
males during and following both resistance and endurance training bouts. The effects of the tetramethylurates, methylxantine and theacrine, on arousal measured using objective or subjective methodologies have yet to be assessed.

Jitteriness and habituation

Another effect of caffeine that has been reported in the literature is increases in jitteriness, which is considered to be unfavorable and is commonly quantified via hand tremors. In a sample of 17 ophthalmic surgeons, acute supplementation of 200 mg caffeine resulted in a larger increase in magnitude of hand tremors compared to placebo (Humayun et al., 1997). Another study showed that 2.5 and 5 mg/kg caffeine decreased hand steadiness in females consuming <90 mg/kg/d but not >750 mg/kg/d (Jacobson & Thurman-Lacey, 1992). In studies looking at the effects of methylxamine and theacrine, it has been found that caffeine increased subjective feelings of jitteriness to a greater extent than the tetramethylurates (Kuhman et al., 2015; La Monica et al., 2021).

Another effect of caffeine to consider is habituation or an alteration to an individual’s responsiveness to a specific dose of caffeine. Research dating back to the 1930s shows there is an effect of habituation on physiological responses to caffeine consumption (Winsor & Strongin, 1933). More recent work shows this caffeine tolerance effect through categorizing individual as caffeine users or nonusers on sensitivity of the autonomic nervous system at rest (Izzo et al., 1983; Zahn & Rapoport, 1987) and during exercise (Van Soeren et al., 1993). However, results are mixed
regarding the effect of habitual caffeine content on different aspects of exercise performance, as Bell and McLellan (2002) showed greater improvements in a time-to-exhaustion task in nonusers compared to users following consumption of 5 mg/kg caffeine, while Goncalves et al. (2017) found no effect of habituation on time trial performance following consumption of 6 mg/kg caffeine. Regarding RT, Kuznicki and Turner (1986) observed no differences in RT following low doses of caffeine (≤160 mg) in users versus nonusers. This finding, however, may be attributed to the low caffeine doses used in this study.

Interestingly, theacrine does not appear to have the same habituation effects as caffeine. Taylor et al. (2016) provided 200 or 300 mg theacrine once daily for 8 weeks and tested the acute cardiovascular effects of each supplement at weeks 4 and 8. No group-by-time interactions were observed for blood pressure or electrocardiogram-derived markers, and the authors concluded no habituation took place over this period. Though this study lacked a caffeine-only comparator group, these findings suggest that theacrine, a tetramethylurate, may have different habituation effects than caffeine.

Purpose

Based on the known pharmacokinetics and pharmacodynamics of caffeine, methylliberine, and theacrine, it is speculated that co-ingestion of these compounds results in sustained peak times and half-lives which can improve physical and cognitive performance over a longer period compared to caffeine alone. Additionally, the more favorable hemodynamic responses and reduced jitteriness and habituation effects
associated with methylliberine and theacrine further support the idea of a synergistic
effect of combining these supplements rather than consuming caffeine alone.
Therefore, the primary purpose of this study is to compare the effects of a combination
of caffeine, methylliberine, and theacrine to caffeine alone and placebo on RT and
marksmanship in tactical personnel. The secondary purpose is to determine differences
in hemodynamic responses and felt arousal following consumption of a combination of
caffeine, methylliberine, and theacrine compared to caffeine alone and placebo.
CHAPTER 2
MINIMAL-EQUIPMENT RESISTANCE TRAINING WITH AND WITHOUT BLOOD FLOW RESTRICTION: A LITERATURE REVIEW

Training for tactical performance

The United States Department of Defense is made up of various military branches, the largest of which is the United States Army, consisting of 1,098,642 active-duty, national guard, and reserve service members as of 2019. Service members are expected to meet specific physical performance standards throughout their careers based on his or her military occupational specialty, with each branch implementing its own version of a physical fitness assessment to evaluate the achievement of these standards. Recently, the Army developed the Army Combat Fitness Test (ACFT), a six-event test that assesses muscular power, strength, endurance, anaerobic capacity, and aerobic capacity. This replaces the previous Army Physical Fitness Test, a three-event test that simply assessed muscular endurance and aerobic capacity. One clear benefit of this change is that the physical training and preparation of Army soldiers and other service members for assessments akin to the ACFT results in a more comprehensive approach that has the potential to produce well-rounded, more robust tactical athletes. Further, this test is gender-neutral, and males and females must reach the same standards according to military occupational specialty.
However, one concern that has arisen because of this change is the perceived reliance on heavy, non-portable, and expensive resistance exercise training (RET) equipment, such as power racks, barbells, discs, etc. The Army guidelines for training outlined in FM 7-22 published in October 2012, Army Physical Readiness Training, are concurrent in nature with an emphasis on endurance training and rely primarily on resistance via one’s own body mass (i.e., calisthenic training) with traditional RET comprising only a small portion in the format of low-load, circuit-style training. Thus, with the advent of the ACFT, it seems as though equipment required for training to improve muscular power and strength is cumbersome since previous research showing the efficacy of traditional RET on these aspects of muscular performance as typical field-based training does not appear to offer the same benefits.

The most studied program design in this population is concurrent in nature by combining both resistance and endurance training. Although the literature surrounding concurrent training shows a negative impact on improvements in muscular power and strength in resistance-trained individuals starting with the seminal work by Hickson (1980), this training modality is essential for concomitantly improving both anaerobic and aerobic performance outcomes (Wilson et al., 2012). As such, Knapik (1997), Harman et al. (1997), and Nindl et al. (2017) all showed improvements in military-specific task performance including 1-rep max box lifts, 15- or 18.1-kg box lifts and carries, and 3.2-km ruck time following 14-, 24-, and 24-week concurrent training programs, respectively. In a comprehensive comparison of traditional-equipment concurrent training to minimal equipment training in female Army soldiers and
recruitment age civilians, Kraemer et al. (2001) investigated differences between 24-week periodized programs focused on full-body power and strength, full-body strength and hypertrophy, upper-body power and strength, and upper-body strength and hypertrophy in addition to groups that underwent field-based plyometric, partner-resisted training and endurance training only. The endurance training that was prescribed to all groups consisted of approximately 30 min of running, cycling, or stair climbing which occurred immediately after resistance or field training sessions. Notable differences included larger improvements in 1-repetition maximum (RM) squat strength in the full-body power and strength and full-body strength and hypertrophy groups compared to all other groups, including field training, and greater improvements in 1RM bench press in full-body power and strength compared to field training (Kraemer et al., 2001). These results not only demonstrate the efficacy and importance of full-body RET with traditional equipment, but also suggest that field training, at least following the program prescribed in this study, do not confer similar benefits on improving muscular power and strength, which are important aspects of performance for the tactical athlete.

High-load versus low-load RET – Applied outcomes

One explanation for the greater benefits often observed with traditional equipment training compared to field-based training is the role of load, a RET program design variable. According to the National Strength and Conditioning Association (NSCA), load refers to “the amount of weight assigned to an exercise set” (Haff &
In other words, this is the amount of weight being lifted by the individual and is commonly expressed as a percentage of 1RM. Many studies have compared the effects of low-load compared to high-load RET on strength outcomes, 21 of which were included in a 2017 meta-analysis and systematic review (Schoenfeld et al., 2017). Overall, high-load training protocols in which participants train with loads ≥12-RM or ~67% 1RM results in more favorable improvements in 1RM isotonic strength and isometric strength but not isokinetic strength. Upon closer examination of the studies included in this meta-analysis, only two studies were conducted in resistance-trained individuals and were separate analyses of the same data (Au et al., 2017; Morton et al., 2016). Both studies reported significant Load-by-Time interactions for bench press, showing that 1RM bench press strength improved to a greater extent in the high-load group (75-90% 1RM) compared to the low-load group (30-50% 1RM). However, this effect was not observed for the three other exercises that were tested (1RM leg press, overhead press, and knee extension) as both groups improved similarly in these metrics. This potentially biases the conclusions drawn from the meta-analysis as the effect of load may be exercise specific.

In addition to muscular strength, another important outcome for tactical performance is muscular power. In physics, power is defined as the time rate of doing work (work divided by time) and, more colloquially in the strength and conditioning field, refers to explosive strength (Haff & Triplett, 2016). Muscular power can be demonstrated by an athlete leaping above a defender to catch a football or by a police officer diving to tackle a suspect. Research has suggested that maximal power
development occurs using submaximal loads, as maximal power output occurs around
30-60% of squat 1RM (Haff & Triplett, 2016). Training status appears to affect this,
however, as studies have shown trained strength and power athletes to express
maximal power output at higher percentages of 1RM than untrained athletes, reaching
as high as 63% of squat 1RM (Baker et al., 2001; Stone et al., 2003). As such, training
with low loads, which was defined as <67% of 1RM in the meta-analysis discussed
previously, would be thought to be similarly beneficial, if not more, for improving
muscular power compared to higher load training. This likely has to do with the speed of
movement possible with slightly lighter loads. The role of load does not appear to have
been directly tested on muscular power outcomes, though multiple speculative review
articles have been published on the topic (Haff & Nimphius, 2012; Hansen & Cronin,
2009; Kawamori & Haff, 2004; Taber et al., 2016). Generally, “explosive-type” training
seems to improve movement-specific muscular power compared to higher-load RET.
This is consistent with guidelines set forth by the NSCA, in which loads recommended
for developing muscular power are lower than those for muscular strength (80-90% for
single-effort events and 75-85% for multiple-effort events), albeit these loads would not
be considered “low.” Another important note is that the number of repetitions
performed at these lower loads are also lower (1-5 repetitions) compared to typical low-
load training (15-30+ repetitions). Thus, theoretically, it appears as though training with
loads considered to be low (<67% of 1RM) may confer benefits on muscular power
development compared to high-load training so long as the low loads are lifted at high
velocities for a submaximal number of repetitions.
Muscular endurance is another important aspect of tactical performance, particularly during tasks requiring service members to sustain low levels of force production through isotonic, isokinetic, or isometric muscle actions over an extended period. Muscular endurance is required for activities with sustained anaerobic and aerobic demands such as running, cycling, sprinting, skating, etc. For a tactical athlete, examples of muscular endurance would include repeated pushing of an opponent during man-to-man combat and crawling to keep a low profile. One of the studies included in the previously mentioned meta-analysis (Schoenfeld et al., 2017) also assessed muscular endurance (Campos et al., 2002). Contrary to the findings for muscular strength, an interaction was observed for muscular endurance favoring the low-load group. This is intuitive as muscular endurance is characterized by high-repetition, low-load efforts, and low-load exercises are commonly prescribed with higher repetitions per set compared to high-load exercises. This finding also falls in line with NSCA guidelines, suggesting lower loads with more repetitions confer greater benefits on muscular endurance compared to higher loads with fewer repetitions (Haff & Triplett, 2016).

Another major limitation to the current literature assessing the effects of low-versus high-load training is the lack of full-body training protocols used in research designs. Of the 21 studies included in the meta-analysis, only six followed a full-body training program. Though studies assessing the role of individual program design variables (i.e., training volume, intensity, load, etc.) through protocols using only 1-2 exercises are important to isolate the effects of these variables, the external validity of
the answers generated by this research is questionable as athletes typically train numerous movement patterns and muscle groups throughout the same micro-, meso-, and macrocycles.

In addition to the performance outcomes discussed, body composition may also be differentially affected by high- and low-load RET. The meta-analysis mentioned previously (Schoenfeld et al., 2017) also looked at muscle hypertrophy and found no effects of load on this outcome. In fact, much of the recent literature on this topic has shown that total volume performed is the biggest driver in the hypertrophy responses to RET (Figueiredo et al., 2018; Lasevicius et al., 2018; Schoenfeld et al., 2019; Sooneste et al., 2013). However, important factors that are seldom mentioned and tested in this research are the relationships between load, volume, rest periods, and total session duration. For instance, low-load training is typically performed with higher repetitions per set and shorter rest periods while high-load training is typically performed with lower repetitions per set and longer rest periods. As such, low-load and high-load training likely result in very different quantities of volume when maintaining a typical exercise session duration of 60 to 75 min. Therefore, much of the previous research has equated volume across high- and low-load groups, but it appears as though no studies have controlled for total exercise session duration.

Further, one aspect related to body composition that is often overlooked and is tied to musculoskeletal health and performance is tendon thickness. Tendons are the connective tissue that join skeletal muscle to bone and allow muscles to perform their actions (Marieb & Hoehn, 2019). A recent meta-analysis looked at the effects of
mechanical load on tendon adaptations and found load was significantly related to changes in tendon stiffness, Young’s modulus, and cross-sectional area (Bohm et al., 2015). A subgroup analysis in this study also concluded that higher loads, categorized as ≥70% 1RM, resulted in greater tendon adaptations than lower loads, suggesting high load training may provide a greater stimulus for improving overall musculoskeletal health and reducing risk of injury. One difficulty in assessing tendon dimensions is the instruments required for valid and reliable measurements (Hayes et al., 2019). Historically, computer tomography and magnetic resonance imaging were required (Rosenberg et al., 1988), but the development of portable, inexpensive ultrasound transducers has made these assessments much more accessible in recent years (Seynnes et al., 2015).

High-load versus low-load RET – Mechanisms

To further explain the effects of load on performance outcomes, researchers have investigated the molecular mechanisms that explain muscular force production and signaling responses that occur following training bouts. Force production in skeletal muscle is dependent on both morphological and neurological properties, and improvements in muscular strength following RET are contingent on adaptations to these properties (Folland & Williams, 2007). Skeletal muscle is a highly adaptable tissue, and adaptations are dependent upon the stressors to which it is exposed, resulting in mechanical changes that occur primarily within skeletal muscle itself. Additionally, connective tissues, such as tendons, ligaments, and bones, also adapt to RET (Kraemer
et al., 1988), and these changes are critical for improvements in performance following training.

The primary effect of load on skeletal muscle remodeling and adaptation occurs through a process called mechanotransduction, which is the process of a tissue sensing mechanical stress (i.e., via loading) and translating it to a biochemical signal (Ingber, 2006). In skeletal muscle, sarcolemmal transmembrane mechanosensors, predominantly integrins, sense mechanical stress and transduce an intracellular signal (Carson & Wei, 2000). Most of the research on this topic has focused on the outcome of muscular hypertrophy, and load appears to be at least one important mechanism by which skeletal muscle fibers increase in size (Wackerhage et al., 2019). Fry, Nicoll, and Olsen (2020) recently reviewed the role of mechanotransduction on adaptations to exercise. With regard to skeletal muscle, this process seems to be primarily responsible for inducing hypertrophy, predominantly through activation of focal adhesion kinase and the Akt/protein kinase B/mechanistic target of rapamycin signaling pathway (Olsen et al., 2019). However, the role of muscular hypertrophy on improvements in muscular power, strength, and overall performance is debated (Buckner et al., 2016; Hornsby et al., 2018; Loenneke et al., 2019; Nuzzo et al., 2019; Taber et al., 2019) but appears to be contingent on the specific adaptations that take place.

Recent publications by Haun et al. (2019) and Roberts et al. (2020) were the first to provide compelling evidence for differential hypertrophy observed in sarcoplasmic versus myofibrillar components of skeletal muscle, and it is speculated these differences may explain the relationship between hypertrophy and muscular performance (Taber et
Hypertrophy to the myofibrillar portion of muscle results in a greater quantity of contractile proteins, specifically actin and myosin, therefore allowing a greater number of cross-bridges to form at the level of the sarcomeres of the myofibril during contraction, ultimately resulting in greater force production. This same effect is unlikely with sarcoplasmic hypertrophy, as the adaptations that account for this are attributed to increases in bioenergetic enzymes responsible for adenosine triphosphate production and protein synthesis, specifically proteins responsible for ribosomal biogenesis, as well as a process referred to as “spatial priming,” which prepares the muscle fiber for myonuclear donation from satellite cells (M. D. Roberts et al., 2020). Therefore, sarcoplasmic hypertrophy does not appear to increase skeletal muscle’s ability to generate high quantities of force to the same degree as myofibrillar adaptations.

In addition to skeletal muscle hypertrophy, another example of the plasticity of this tissue is its ability to transition between fiber types. Classically, muscle fiber types can be broadly categorized as type I or type II, with the former exhibiting characteristics including low force production, high oxidative capacity, and low fatiguability and the latter exhibiting characteristics including high force production, high glycolytic flux, and high fatiguability (McArdle et al., 2014). In humans, type II muscle fibers can further be broken down into IIa and IIx, ranging from lower abilities to produce force and fatiguability to higher force outputs and fatiguability. Along this continuum of fiber types, intermediate or hybrid forms exist as well and are described as type I/IIa and IIa/IIx (Medler, 2019).
Aside from the effects on skeletal muscle hypertrophy, mechanical stress also appears to play a role in inducing adaptive responses in neural tissue (Fry et al., 2020), another important component of skeletal muscle force generation. Neural factors that affect muscular strength and force production include motor unit recruitment, motor unit firing frequency or rate coding, motor unit synchronization, and neuromuscular inhibition. Recently, Del Vecchio (2019) demonstrated changes in motor unit recruitment and rate coding patterns following just four weeks of RET at 75% of maximal voluntary force production. Specifically, it was observed that the threshold required to recruit high power output motor units was decreased, and the rate of action potential production, also referred to as rate coding or firing frequency, at the level of the motor unit was increased, suggesting these factors are important in improving muscular power production. Another important neurological component of force production is the synchronization of motor units, or the ability for multiple motor units to generate action potentials in a temporal pattern which allows for the coordination of simultaneous muscular contractions, resulting in a greater summated force production (Semmler, 2002).

Low-load RET with BFR – Applied outcomes

As has been demonstrated, load appears to play an important role in muscular adaptations, and low-load RET consisting of high amounts of repetitions per set typically results in less favorable improvements in muscular power and strength compared to high-load training (Haff & Nimphius, 2012; Schoenfeld et al., 2017). However, metabolic
stress is another major factor by which muscular adaptations occur. Metabolic stress refers to the accumulation of metabolic byproducts (i.e., lactate, H+, inorganic phosphate, etc.) in circulation caused by the metabolic demands incurred by skeletal muscle during exercise (de Freitas et al., 2017). Though low-load training with high repetitions alone can increase metabolic stress during exercise to a greater extent than high-load training with low repetitions, blood flow restriction (BFR) exercise has been shown to augment acute physiological responses to exercise which may bolster chronic adaptations regarding skeletal muscle hypertrophy and performance outcomes, such as muscular power, strength, and endurance.

Therefore, one apparent way to improve the effects of low-load training is through the addition of BFR. This method of training, also known as KAATSU or, formerly, occlusion training, involves the addition of a pneumatic cuff, knee wrap, torniquet, etc. to the proximal limb in an attempt to limit venous blood outflow from the limb without affecting arterial blood inflow (Sato, 2005). Most of the research on this topic has focused on the outcome of muscular hypertrophy, particularly showing type I muscle fiber hypertrophy (Bjornsen et al., 2019), with more limited research on the role of low-load RET with BFR on performance metrics. Though muscle size is thought to be related to muscular strength, as mentioned, this topic is highly debated, emphasizing the importance of testing the effects of BFR training on strength in a direct and applied manner. Recently, two meta-analyses have been conducted on the effects of low-load BFR training compared to traditional high-load RET on muscular strength (Gronfeldt et al., 2020; Lixandrao et al., 2018). The results of these separate analyses
were contradictory, as one revealed superior effects of high-load RET compared to BFR on muscular strength (Lixandrao et al., 2018; Lixandrao et al., 2021) and the other showed no significant differences in strength improvements between high-load RET and low-load RET with BFR (Gronfeldt et al., 2020).

A difficulty of taking a meta-analytical approach to the current body of literature is the vast differences in study designs. Research protocols range from single-exercise, often single-joint exercises, training interventions with and without BFR cuffs (Patterson & Ferguson, 2010; Takarada et al., 2002) to the addition of a few exercises with BFR following a moderate-to-high load RET bout (Bjornsen et al., 2019; Luebbers et al., 2019; Yamanaka et al., 2012). These factors limit the generalizability of the study findings since, as mentioned previously, athletes typically train multiple movements patterns and muscle groups simultaneously. Cook et al. (2014) took a unique approach to assessing the effects of BFR training on performance outcomes in rugby players. Using a within-subjects, counter-balanced, crossover design, athletes underwent 3 weeks of moderate-to-high-load RET (70%1RM) with or without BFR cuffs. The condition in which athletes underwent BFR resulted in greater improvements in countermovement jump peak power, 1RM back squat, 1RM bench press, and 40-m sprint time (Cook et al., 2014). This appears to be the only study that employed BFR with high-load training and shows the efficacy of BFR when used with high-load training, though this doesn’t appear to be the method in which this type of training is commonly employed in practice.

The most common design in assessing these applied performance effects compares low-load RET with BFR to traditional moderate-to-high-load training (Korkmaz
et al., 2020; Yasuda et al., 2011). Yasuda et al. (2011) showed high-load (75% 1RM) training resulted in greater improvements in 1RM bench press and isometric triceps extension strength compared to low-load (30% 1RM) RET with BFR over 6 weeks in 40 young recreationally trained males. However, Korkmaz et al. (2020) recently found greater improvements in leg extensor isokinetic strength following 6 weeks of low-load (30% 1RM) BFR training compared to high-load (80% 1RM) training in 23 male soccer athletes.

Together, the results of these studies suggest that the addition of BFR tends to lead to greater improvements in performance changes when loads are matched. However, the equivocal findings comparing high-load training to low-load training with BFR show the need for more research on this topic to determine if low-load BFR training can be as, if not more, effective than high-load training. An important consideration, however, is the potential impact BFR may play on load and the effort required to lift these loads resulting in different overall stress responses following load-matched exercise bouts.

Low-load RET with BFR – Mechanisms

As mentioned previously, BFR appears bolster adaptations to RET, and these effects appear to be mediated through the BFR-related production of an ischemic environment and higher degrees of extra- and intramuscular osmotic pressure which appear to have subsequent effects, causing greater degrees of metabolic stress and
larger increases in concentrations of circulating anabolic hormones and inflammatory cytokines (Rossi et al., 2018).

Ischemia is defined as an inadequate blood supply to a given tissue, and, though BFR cuffs do not fully occlude arterial blood flow, it is speculated that a degree of ischemia occurs within skeletal muscle during this type of training (Wernbom et al., 2020). As such, lack of blood supply results in reduced oxygen and nutrient delivery to the working muscles during exercise (Murthy et al., 2001; Tanimoto et al., 2005), resulting in greater metabolic stress (Hagberg, 1985; Harris et al., 1986; Larsson & Hultman, 1979; Marcinek et al., 2010; Sjostrom et al., 1982). Several studies have shown that BFR training increases metabolic stress to a greater extent than non-BFR training (Okita et al., 2019; Suga et al., 2009; Teixeira et al., 2018). Takada et al. (2012) showed a positive relationship between metabolic stress and increases in muscle cross-sectional area, and it has been proposed that metabolic stress is a stimulatory mechanism by which skeletal muscle hypertrophy occurs (Schoenfeld, 2010), though this effect appears to be mediated by the subsequent processes that occur as a result of high degrees of metabolic stress.

One such effect is the role of metabolic stress on endocrine responses. Goto et al. (2005) showed greater metabolic stress comparing moderate-load resistance exercise with and without rest periods and found greater acute lactate and growth hormone (GH) responses at 15- and 30-min post-exercise which corresponded with larger improvements in muscular strength and endurance following 12 weeks. In the context of increasing metabolic stress through ischemia due to BFR, several studies have
shown greater acute increases in blood lactate, cortisol, and GH in the 1-h period following low-load BFR compared to non-restricted exercise or an ischemic control session (Fujita et al., 2007; Pierce et al., 2006). However, Tanimoto et al. (2005) found no differences in acute blood lactate or GH responses between low-load BFR versus non-restricted exercise in the 30-min post-exercise period despite greater decreases in skeletal muscle oxygenation following BFR versus non-BFR. These differential findings may be explained by the use of slightly higher loads in the non-BFR group compared to the BFR group by Tanimoto et al. (2005) but not Fujita et al. (2007) or Pierce et al. (2006).

In the exercise literature outside of ischemia and BFR, it is well-established that GH is elevated during and immediately following both endurance and resistance exercise, which occurs in an intensity-dependent fashion (Godfrey et al., 2003; Wideman et al., 2002), and, as mentioned, this effect appears to be bolstered by exercise that results in high metabolic stress. One reason for this greater GH response may be explained by the increased metabolic demands. Early research showed that GH has direct effects on metabolism during exercise through increasing lipolysis in adipose tissue resulting in the release of non-esterified fatty acids into circulation which can be taken up and oxidized by working muscles (Hunter et al., 1965; Schalch, 1967). In addition, this acute GH response has also been used to explain the anabolic response that occurs following exercise as research shows increases in skeletal muscle protein synthesis following exposure to GH (Fryburg & Barrett, 1993), leading investigators to speculate that acute rises in GH, as well as other anabolic hormones (i.e., testosterone),
play an important role in hypertrophy following resistance exercise (Ahtiainen et al., 2005). However, some researchers have argued that GH, particularly acute increases with exercise, exerts minimal direct anabolic effects in adult skeletal muscle (Rennie, 2003; Schoenfeld, 2013; West & Phillips, 2010), and there are data supporting the hypothesis that acute increases in anabolic hormones do not relate to improvements in strength or hypertrophy following RET (Morton et al., 2016; West et al., 2010). Increases in basal GH levels, however, have been shown to be related to improvements in deadlift strength in female collegiate soccer players over the course of a competitive season (McFadden et al., 2020). As such, it appears as though GH’s anabolic effects may be dependent on greater total exposure of skeletal muscle to this hormone and may also be mediated through its role as a secretagogue for hepatic insulin-like growth factor-I release (Gibney et al., 2007), as part of the GH/insulin-like growth factor (IGF)-1 axis (Eliakim & Nemet, 2020).

Like GH, total IGF-1 concentrations increase acutely following exercise, as shown by a recent meta-analysis (de Alcantara Borba et al., 2020), with exercise itself acting as a stimulus for the release of muscle-derived IGF-1 expression as well as the GH-induced release of hepatic IGF-1 (McKay et al., 2008). Due to its release from both the liver and skeletal muscle, IGF-1 is said to have autocrine, paracrine, and endocrine actions (Philippou et al., 2007), and its primary effects on skeletal muscle are to increase muscle protein synthesis via activation of Akt and mammalian target of rapamycin signaling pathways (Barclay et al., 2019) as well as satellite cell differentiation, proliferation, and myonuclear donation (Machida & Booth, 2004). Together, based on the impact of BFR
training on metabolic stress and GH secretion, the role of IGF-1 on mediating the adaptative response is of interest, though limited data exist on this topic.

Along with GH and IGF-1, a recent review discussed the effects of BFR exercise on inflammation and circulating cytokines (Rossi et al., 2018). Inflammation during and following exercise is typically observed through increases in interleukin (IL)-6, IL-10, IL-1β, as well as C-reactive protein and tumor necrosis factor-α (Pedersen, 2000). Classically, the inflammatory response to exercise has been explained by exercise-induced muscle damage through cellular and subcellular disruptions (Clarkson & Hubal, 2002; Pyne, 1994). However, this explanation does not apply to BFR training as a 2014 review concluded that this method of training does not appreciably cause muscle damage assessed via decrements in performance, muscle swelling, ratings of muscle soreness, or blood biomarkers (Loenneke et al., 2014), though this has been debated as the current research has shown large variances in markers of muscle damage following BFR exercise (Burr et al., 2020; Wernbom et al., 2020). Regardless, this inflammatory response appears to be driven by ischemia and glycogen depletion (Febbraio & Pedersen, 2005; Gute et al., 1998). Together, this lends support to the idea that metabolic stress, particularly the heightened response observed during BFR exercise, and the endocrine and inflammatory responses result in a physiological environment conducive to bolstering adaptations to training and improving performance.
Low-load RET with BFR – Practical considerations

Practical methodological concerns also appear to be an issue in this body of literature and many articles on BFR training guidelines have been published (Patterson et al., 2021; Patterson et al., 2019; Pignanelli et al., 2021). One important variable in the prescription of BFR training is cuff pressure. This refers to how tightly the cuff is placed on the proximal limb and is often assessed as a percentage of arterial occlusion pressure and, as such, applies to pneumatic cuffs with manometers but not knee wraps, tourniquets, etc. Many features of the specific cuffs used for BFR training affect the pressure required to fully occlude arterial blood flow, including cuff width (Laurentino et al., 2016; Loenneke et al., 2012; Weatherholt et al., 2019) and material (Buckner et al., 2017; Loenneke, Thiebaud, et al., 2013). Generally, the pressure required to occlude arterial blood flow is greater for narrower, more elastic cuffs compared to wider, more rigid cuffs. It is, therefore, important to prescribe cuff pressures based on the measurement obtained from the same cuff that will be used in training, as pressures do not translate across different types of BFR cuffs (Jessee et al., 2016; Loenneke, Fahs, et al., 2013). Despite the effects of different types of cuffs, the percentage of arterial occlusion pressure used to induce BFR appears to translate well across studies. Recent reviews have concluded that appropriate pressures range from 40-80% of arterial occlusion pressure (Patterson et al., 2019), though 60-80% may be more effective (Patterson et al., 2021).

Assessment of the cuff pressure that fully occludes arterial blood pressure should be left for measurement in laboratories and clinics with specialized equipment by
trained personnel and limits accessibility of BFR training in field-based scenarios. As such, practitioners and individuals training with BFR cuffs must often rely on other methods of determining the sufficient cuff pressure if taken into a field setting. Many studies have assessed the effects of BFR training on subjective, perceptual responses, including perceived exertion (Lixandroa et al., 2019), cuff tightness (Bell et al., 2020), and, more commonly, discomfort or pain (Jessee et al., 2017; Lixandroa et al., 2019; Loenneke et al., 2011; Loenneke et al., 2015; Martin-Hernandez et al., 2017; Mattocks et al., 2017; Mattocks et al., 2019). In the BFR literature, discomfort or pain are typically used interchangeably and are assessed using the Borg CR10 scale, which ranges from 0 (no discomfort) to 10, corresponding with one’s previously experienced worst pain, making it possible for scores to exceed 10 (Borg, 1998; Hollander et al., 2003; Loenneke et al., 2011).

Several studies have measured both cuff pressures prescribed as percentage of arterial occlusion pressure and perceived discomfort simultaneously in young (18 to 35 years old), physically active or resistance trained males and females. Loenneke et al. (2015) assessed various combinations of load and cuff pressures on CR-10+ scores and found that 4 sets at 30% 1RM following a 30-15-15-15 repetition scheme over four sets at cuff pressures of 40%, 50%, and 60% of arterial occlusion pressure resulted in average discomfort scores of 6-8 with no statistical effects of cuff pressure observed. In a similar design, Jessee et al. (2017) showed discomfort scores ranging from 4.25 to 6.25 after set four with 40% of arterial occlusion pressure and 6.25 to 8 after set four with 80% of arterial occlusion pressure.
Low-load RET with BFR – Safety concerns and considerations

Another important consideration for BFR exercise is the potential for adverse responses to acute exercise and chronic training. Despite the findings suggesting BFR does not cause muscle damage (Loenneke et al., 2014), several case reports have been published on the onset of rhabdomyolysis following low-load BFR exercise sessions in young (27 to 37 years old) males after a session of BFR exercise (Clark & Manini, 2017; Iversen & Rostad, 2010; Krieger et al., 2018; Tabata et al., 2016). Rhabdomyolysis is a condition characterized by extremely rapid skeletal muscle breakdown (Sauret et al., 2002; Zutt et al., 2014). One common factor to each of these published case studies in the BFR literature is that this complication occurred following the first session of this type of training. This is consistent with exertional rhabdomyolysis associated with any type of unaccustomed exercise of high intensity (Sayers & Clarkson, 2002).

The generally-accepted primary diagnostic criterion is serum creatine kinase levels elevated above 10 times higher than upper limit of the reference range, and symptoms include myalgia, muscle weakness, and myoglobinuria (Torres et al., 2015). Several causes of rhabdomyolysis have been established, and, in relation to BFR exercise, the most pertinent are physical exertion and muscle ischemia. Other causes include direct muscular trauma, drugs, toxins, infections, electrolyte, metabolic, and endocrine disorders, genetic disorders, prolonged bed rest, and hyperthermia (Allison & Bedsole, 2003). This condition has the potential to result in acute renal failure and death, though this has not been reported following BFR exercise-induced rhabdomyolysis. Despite this cause of concern, only four case studies have reported
incidence of rhabdomyolysis following BFR training. Other forms of exercise and physical activity have also reported incidence rates of exertional rhabdomyolysis, and these rates appear to be similar, if not higher than those observed in BFR training (Alpers & Jones, 2010; Hopkins et al., 2019; Luetmer et al., 2020).

Another safety concern that has been discussed is the effect of BFR training on cardiovascular dynamics and the exercise pressor reflex (Spranger et al., 2015; Vanwye et al., 2017). The exercise pressor reflex consists of the muscle metaboreflex and mechanoreflex and is the mechanism by which increases in heart rate, contractility, and ventilation occur during exercise (Kaufman & Hayes, 2002). Both mechanical and metabolic stimuli affect these processes through neural impulses from group III and group IV muscle afferent neurons, respectively (McCord & Kaufman, 2010). BFR training appears to augment activity of both the pressure-and-stretch group III and metabolite-sensitive group IV muscle afferents. In fact, as mentioned, increases in intracellular osmotic pressure and cellular swelling and high degrees of metabolic stress are mechanisms by which BFR training appears to confer its benefits on adaptations to exercise. However, it has been argued that these factors may lead to a dysregulated baroreflex response during exercise, causing excessively large increases in arterial blood pressure which may ultimately result in cardiac arrhythmia, myocardial infarction, stroke, and sudden cardiac death in individuals with and without preexisting cardiovascular conditions (Kambic et al., 2021; Spranger, 2020; Spranger et al., 2015). These claims are based on studies that found larger increases in blood pressure during BFR exercise compared to non-restricted endurance (Prodel et al., 2016; Thomas et al., 2018). Downs
et al. (2014) and Libardi et al. (2017) conducted similar studies assessing changes in blood pressure responses during BFR resistance exercise compared to non-restricted exercise. Downs et al. (2014) found larger increases in systolic and diastolic blood pressures during low-load BFR exercise compared to low-load and high-load without BFR, however the researchers used unconventional BFR methods in which cuff pressures were relative to systolic and diastolic blood pressure rather arterial occlusion pressure. Libardi et al. (2017) used 50% of arterial occlusion pressure and showed lower increases in intra-exercise systolic and diastolic blood pressures in low-load BFR exercise compared to both low-load and high-load non-BFR exercise. Overall, more studies are needed on this topic, but the current findings do not support the idea that blood pressure increases excessively during BFR resistance exercise conducted with cuffs at 50% arterial occlusion pressure.

Though concerns for rhabdomyolysis and cardiovascular events are warranted, BFR can be performed safely to ameliorate negative outcomes. As mentioned, all rhabdomyolysis cases occurred during the first day of BFR training. Therefore, extra precautions must be taken on the first day, particularly beginning with low-to-moderate cuff pressures. Further, to reduce the risk of cardiovascular events, communication with the exercising individual regarding pain and discomfort at the level of the muscle as well as systemically is critical as the group III and IV muscle afferents that respond to mechanical and metabolic stimuli also transmit feelings of pain through nociceptive stimulation of the muscle (McCord & Kaufman, 2010).
Purpose

It is pivotal for military personnel to train during periods of limited access to traditional exercise equipment such as sustained operations to improve or maintain fitness. However, RET in field settings has been consistently shown to be inferior to traditional RET, likely attributed to the inability to use high loads, as load is a primary driver in performance and body composition adaptations to resistance exercise. However, heightened metabolic stress along with endocrinological and immunological responses to low-load high-repetition exercise also serve as important stimuli for inducing favorable performance adaptations, which can be further augmented through BFR. Therefore, the primary purpose of this investigation is to assess the efficacy of 6 week of minimal-equipment RET with and without BFR on the military-relevant performance tasks of the Army Combat Fitness Test compared to traditional-equipment RET in male and female Reserve Officers’ Training Corps (ROTC) cadets and midshipmen. The secondary purposes include the effects of minimal-equipment training with and without BFR on laboratory-based performance measures of muscular power, upper-body muscular strength, and aerobic capacity compared to traditional RET in ROTC cadets and midshipmen.
CHAPTER 3

CAFFEINE AND CAFFEINE-DERIVATIVES ON REACTION TIME AND MARKSMANSHIP:

METHODOLOGY

Specific Aims

The primary aim of this study is to compare the effects of a combination of caffeine, methylliberine, and theacrine to caffeine only and placebo on reaction time (RT) and marksmanship in tactical personnel, including military personnel and law enforcement officers. The secondary aim is to determine differences in hemodynamic responses and felt arousal following consumption of a combination of caffeine, methylliberine, and theacrine, caffeine alone, and placebo.

Design

This study will be a randomized, placebo-controlled, double-blind, between-subjects, clinical trial (ClinicalTrials.gov Registration: NCT03937687).

Participants

Participants (N=54) will be males currently employed as military personnel or law enforcement officers, currently enrolled in a Reserve Officers’ Training Corps (ROTC) program, or a military veteran or retired law enforcement officer who has completed
service within the past 18 months or is actively involved in tactical training or operations between the ages of 18 and 63 years (inclusive).

Inclusion Criteria:

• Participant is in good health as determined by a medical history questionnaire.

• Participant is between the ages of 18 and 63 (inclusive).

• Participant is a current member of a ROTC program, military branch, or law enforcement entity.

• Participant is a military veteran or retired law enforcement officer who has completed their service in the past 18 months.

• Participant is a military veteran or retired law enforcement officer who is actively involved in tactical training or operations.

• Participant has a body mass of ≥60 kg/132.3 lb.

• Participant has provided signed and dated written informed consent to participate in the study.

Exclusion Criteria:

• Participants who have injuries preventing them from completing the protocol.

• Participants who have migraines.

• Participants with a history of hepatorenal or neurologic disease.

• Participants with a history of caffeine sensitivity.

• Participants currently taking OTC products containing pseudoephedrine or other stimulants.
• Participants who drink more than four cups of coffee per day (or equivalent of 500 mg of caffeine).

Groups

Participants will be randomized to one of three groups: placebo (PLA), caffeine (CAF), or combination of caffeine, methylliberine, and theacrine (CMT). All pills will consist of an encapsulated white powder and will be identical across groups. The placebo capsule will contain 300 mg cellulose. The caffeine capsule will contain 300 mg caffeine. The combination capsule will consist of 150 mg caffeine, 100 mg methylliberine, and 50 mg theacrine. This dosing strategy was selected to equate for total purine alkaloid content between CAF and CMT. Capsules will be supplied by the study sponsor in packets labelled A, B, and C to ensure the study team is blinded along with a sealed envelope containing the information regarding capsule identification which will not be opened until the completion of data analysis.

Body composition

Height will be measured using a stadiometer, and body mass will be measured using a calibrated scale. Body composition will be assessed via air displacement plethysmography (BODPOD, COSMED Inc., Concord, CA, USA). This device has been previously shown to be valid and reliable (Dempster & Aitkens, 1995; McCrory et al., 1995). Participants will be instructed to arrive to the Sport Science Lab with non-padded compression shorts having refrained from food and water for ≥2 hours, caffeine for ≥12
hours, and moderate-to-vigorous physical activity or exercise for ≥24 hours. Prior to each testing day, the device will be calibrated according to manufacturer’s instructions. Similarly, each test will be conducted according to manufacturer’s guidelines. A prediction equation will be used to determine thoracic gas volume (McCrory et al., 1998), and the Brozek model will be used to determine body fat percentage from body density (Brozek, 1966).

Vigilance task

The vigilance task will consist of a 30-min protocol using an interactive light board with 64 three-dimensional targets (D2, Dynavision International LLC, Cincinnati, OH, USA). This device has been previously shown to be reliable in assessing RT (Wells et al., 2014). Participants will stand ~12 inches from the board, and the board will be raised or lowered to a height ensuring that the LCD screen is at eye level and all lights can be reached. The protocol will be a go/no-go task with one of the 64 lights illuminating at a time (either red or green) and participants will be instructed to press the red lights as quickly as possible while avoiding the green lights. Each light will stay illuminated for 2 seconds unless it is pressed, in which case another light will be illuminated. Simultaneously, every 9 seconds, the digital screen will show 3-integer arithmetic problems for 1 second to which participants will be instructed to respond audibly before the next problem shows up. Responses to arithmetic problems will be scored. The blinds will be drawn, and lights will be turned off to reduce glare on the light board. Researchers will not provide feedback during the task. Participants will perform this task
for 5 minutes during the familiarization session and 30 minutes during the experimental session. During the experimental session, RT for red lights, correct go/no-go decisions, and correct arithmetic responses will be recorded.

Movement task

The movement task will be a 40-target task using a computer simulator with full-body optical sensing technology (Trazer, TRAQ Global Ltd., Westlake, OH, USA). This device has been previously shown to have strong test-retest reliability (Hogg et al., 2021). The simulator consists of a large digital screen and front-facing camera. The simulator will be placed in front of an open space where a 3-meter-by-3-meter grid with a mark in the center will be outlined on the floor using bright tape. Participants will stand on the mark in the center, the program will be started, and the simulator will self-calibrate for each assessment. The protocol will consist of targets appearing as pillars on the digital screen corresponding to locations 3 meters in front, behind, left, or right of center, and participants will be instructed to move to each target as quickly as possible and return to center after each target. Participants will be required to reach 20 targets for each of the 3 trials during the familiarization session and 40 targets for each of the 4 trials during the experimental session. During the experimental session, RT will be recorded.
Marksmanship task

The marksmanship task will be a 16-target task using a marksmanship simulator (Smokeless Range, Laser Ammo, Great Neck, NY, USA) with a laser-modified, gas blowback airsoft pistol (ATP-C, KWA, City of Industry, CA, USA). This device has been used in previous research (Buckley et al., 2021). The simulator consists of a computer connected to a short-throw projector, along with a short-throw high-speed camera pointed at the projector screen which allows the software to determine where the laser-modified pistol was pointed when the trigger was pulled. The protocol will consist of digital law enforcement training targets (B-27, National Rifle Association, Fairfax, VA, USA) projected onto the screen one at a time, and participants will be instructed to shoot each target as quickly and as accurately as possible. The round will begin with the participants holding the modified pistol at the hip, and participants will be instructed to not lift the pistol until the first target appears. The participant will continue shooting each target once until the middle of the round when a symbol comes up on the screen indicating a tactical reload, in which participants will release the magazine from the pistol and reload the second magazine from a belt-mounted holster that has been provided. Following the tactical reload, participants will shoot as quickly and accurately as possible at the remaining targets. Participants will shoot 8 targets scaled to 15 meters for each trial during the familiarization session and 16 targets scaled to 15 or 30 meters for each trial during the experimental sessions. During the experimental session, RT and distance from center of target will be scored.
Hemodynamic measures

Systolic and diastolic blood pressure will be measured using an automated blood pressure cuff (HEM 907XL, Omron Electronics LLC, Hoffman Estates, IL, USA). This device has been previously shown to be valid in adults (Ostchega et al., 2010). The participant will be seated in the upright position with the arm supported at heart level by a table before the researcher places the cuff snugly around the proximal portion of the right arm. The participant will be instructed to limit movement and refrain from talking during measurements. All blood pressure readings will be measured in duplicate with one minute between measurements. Blood pressure will be measured at baseline before the participant consumes the capsule and at 6 timepoints throughout the protocol. Blood pressure readings will be averaged across duplicate measurements at each timepoint.

Heart rate will be continuously monitored using a chest-strap heart rate monitor (H7, Polar Electro, Lake Success, NY, USA) connected via Bluetooth to a fitness monitor (V800, Polar Electro, Lake Success, NY, USA). This sensor has been shown to have high agreement with heart rate measured via electrocardiogram (Pasadyn et al., 2019). The monitor will not be worn by the participants but will be kept near participants to ensure proper transmission between the sensor and the watch. Heart rate data will be averaged across 6 blocks throughout the protocol.
Felt arousal

Felt arousal will be measured using the felt arousal scale (FAS), which ranges from 1 (low arousal) to 6 (high arousal) (Svebak & Murgatroyd, 1985). Felt arousal will be assessed at baseline before the participant consumes the capsule and at 12 timepoints throughout the protocol.

Protocol

Day 1: Screening, consenting and anthropometric testing, and familiarization

Participants will be recruited through local military and law enforcement offices and ROTC programs. Potential participants will be scheduled to arrive to the University of South Carolina Sport Science Laboratory for screening to determine eligibility. They will be instructed to arrive having refrained from food and water for ≥2 hours. A screening and medical history questionnaire will consist of questions relating to inclusion and exclusion criteria. Upon determination of eligibility to participate, an informed consent form will be given to the participant outlining the study protocols and procedures. This form will be read and explained to the participant according to the IRB requirements. Participants will also be given time to read the form and ask questions before providing written informed consent. Following screening and consenting, participants will continue with testing and familiarization.

First, participants will undergo body composition testing using air displacement plethysmography. Participants will then be familiarized with the testing protocols using the interactive light board (Dynavision D2), computer simulator with full-body optical
sensing technology (Trazer), and marksmanship simulator (Smokeless Range).

Participants will complete a shortened (5-min) version of the vigilance protocol on the interactive light board, three trials of spatial RT using the computer simulator with full-body sensing technology, and three trials of marksmanship assessment using the marksmanship simulator.

Day 2: Experimental session

Following the initial session, participants will be randomly assigned to the placebo (PLA), caffeine (CAF), or combination of caffeine, methylxanthine, and theacrine (CMT) groups. Prior to this session, participants will be asked to maintain a normal sleep schedule in the week leading up to their session, maintaining the same wake time each day. Participants will also be asked to refrain from caffeine for 24 hours and alcohol for 48 hours, with no major changes in food intake. Prior to the start of the session, verbal confirmation of adherence to the pre-visit instructions will be obtained. If participants do not adhere, the session will be rescheduled. This session will be scheduled to begin within 2 hours of waking and will be within 30 min of the time the participant arrived for the initial familiarization session. This 2-hour period was chosen to ensure consistency across participants since sleep and wake schedules can vary drastically in this population.

Participants will arrive and sit quietly for 5 min. Following quiet rest, blood pressure will be measured using the automated blood pressure cuff. Felt arousal also be assessed using the 6-point felt arousal scale. Participants will then complete the
multicomponent training distress scale. Next, participants will consume the randomized capsule orally with water provided ad libitum. Following this, participants will sit and read leisurely for 30 min. At the 25-min point of the 30 min quiet reading period, blood pressure and felt arousal will be measured.

After 30 min of quiet reading is completed, participants will move to the interactive light board to begin the 30-min vigilance task. Following completion of this task, participants will be asked to immediately return to a seated position while blood pressure and felt arousal are again assessed. Immediately following these measurements, participants will move to the computer simulator with full-body sensing technology to begin the 40-target movement task, which will then be immediately followed by the 16-target marksmanship task with 15-meter targets on the marksmanship simulator. This will again be immediately followed by the same movement task and 16-target marksmanship task with 30-meter targets. Felt arousal will be assessed between each of these tasks. Upon completion of these tasks at the ~75-min point, participants will return to a quiet, seated position and blood pressure and felt arousal will be assessed.

Participants will then repeat the protocol, beginning with sitting and reading leisurely for 30 min until the 105-min point. At the 25-min point of the quiet reading period, blood pressure and felt arousal will be measured. After the 30-min of quiet reading period, participants will move to the interactive light board to begin the 30-min vigilance task. Following completion of this task, participants will be asked to immediately return to a seated position while blood pressure and felt arousal are again
assessed. Immediately following these measurements, participants will move to the computer simulator with full-body sensing technology to begin the 40-target movement task, which will then be immediately followed by the 16-target marksmanship task with 15-meter targets on the marksmanship simulator. This will again be immediately followed by the same movement task and 16-target marksmanship task with 30-meter targets. Felt arousal will be assessed between each of these tasks. Upon completion of these tasks at the ~150-min point, participants will return to a quiet seated position, and blood pressure and felt arousal will be assessed. An overview of the protocol is depicted in Figure 3.3.

Figure 3.3: Overview of the experimental testing protocol.

Data analysis

One-way analyses of variance will be conducted to determine differences in baseline descriptive metrics between groups. For vigilance, movement, and marksmanship task variables, Z-scores will be computed to compare changes in group performance relative to the cohort mean at each respective timepoint. This method has been used previously in a similar study design (Doyle et al., 2016). Composite Z-scores for vigilance and marksmanship will be computed to create a score reflective of RT,
cognitive decision making, and accuracy. For these tasks, linear mixed-effects models with a random intercept to adjust for between-subject variability will be performed on each dependent variable to test for Group (PLA, CAF, and CMT)-by-Time (two rounds) interactions, as well as main effects of Group and Time. Mixed-effects models have recently been shown to be robust to distributional assumptions, such as the requirement of a normally distributed residuals, and more powerful alternative to more traditional statistical models of data with repeated observations on the same individual (Schielzeth et al., 2020). For hemodynamic variables and felt arousal, linear mixed-effects models with a random intercept to adjust for between-subject variability will be performed on each dependent variable to test for Group (PLA, CAF, and CMT)-by-Time (7 timepoints for SBP and DBP, 6 timepoints for HR, and 13 timepoints for felt arousal), as well as main effects of Group and Time. Significant interactions or main effects will be followed up with post-hoc pairwise comparisons with a Bonferroni adjustment to further explain the effects. Similarly, linear mixed-effects models with a random intercept to adjust for between-subject variability with post-hoc tests will be used to analyze hemodynamic and arousal data. An $\alpha$-level of 0.05 will be used to determine statistical significance. Post-hoc tests for all analyses will be followed with effect sizes using Cohen’s d to determine magnitude of change within groups. All analyses were conducted and figures were produced using commercially available open-source statistical software (R; version 4.1.0; Team, 2021) with the lme4 (version 1.1-27.1; Bates et al., 2015), emmeans (version 1.6.2-1; Lenth, 2021), effectsize (version 0.5; Ben-Shachar et al., 2020), and ggplot2 (version 3.3.5; Wickham, 2016) packages.
Limitations, delimitations, and assumptions

One limitation of this study is that participants will be recruited from law enforcement, military, and ROTC. Marksmanship training is likely different across these populations in terms of weapon preference and years of shooting experience. To address this, all participants experience the same familiarization protocol prior to the experimental testing and will be randomized into one of the three groups. Additionally, the marksmanship simulator and airsoft pistol used in this study do not match outdoor, live-fire conditions used in previous research, but the immediate feedback provided through the laser and high-speed camera as well as gas blowback of the pistol provided simulated conditions. A delimitation of the findings of this study will not necessarily extend to female tactical personnel. Based on inherent differences in RT between males and females (Silverman, 2006) as well as the fact that females make up less than 15% of law enforcement officers and active-duty military personnel, females will be excluded from participating in this study. Further, another delimitation that reduces consistency with previous research on tactical outcomes is the lack of a sleep deprivation protocol prior to supplementation. This will not be included in this study as law enforcement officers and military personnel do not always operate under sleep deprived conditions, and the purpose of the study is to determine the effects of the supplements provided under typical operating conditions. Therefore, participants will be instructed to maintain normal sleep and wake schedules during the week leading up to the experimental testing session.
CHAPTER 4

MINIMAL-EQUIPMENT RESISTANCE TRAINING WITH AND WITHOUT BLOOD FLOW RESTRICTION: METHODOLOGY

Specific Aims

The primary aim of this investigation is to assess the efficacy of 6 week of minimal-equipment resistance exercise training (RET) with and without blood flow restriction (BFR) on the military-relevant performance tasks of the Army Combat Fitness Test compared to traditional-equipment RET in male and female Reserve Officers’ Training Corps (ROTC) cadets and midshipmen.

Secondary aims include the effects of minimal-equipment training with and without BFR on laboratory-based performance measures of muscular power, upper-body muscular strength, and aerobic capacity compared to traditional RET in ROTC cadets and midshipmen.

Tertiary aims include the effects of minimal-equipment training with and without BFR on body compositions measures including body fat percentage, fat-free mass, and muscle thickness, musculoskeletal health assessed through tendon architecture, acute and chronic blood-based hormonal responses indicative of stress, inflammatory status, and anabolic status, and acute and chronic subjective responses indicative of training distress and muscle soreness compared to traditional RET.
Design

This study will be a randomized, parallel-group, between-subjects, clinical trial (ClinicalTrials.gov Registration: NCT05003778).

Participants

Participants will be enrolled in the University of South Carolina ROTC, which represents various military branches including Army, Navy, Marines, and Air Force. A total of 48 participants will be recruited for this study, 30 of which will be males and 18 of which will be females. To avoid undue coercion, an ombudsman will be present during recruitment, and the ROTC cadre will not be present. To account for attrition, up to 54 participants (37.5% female) will be recruited.

Inclusion Criteria:

• Males and females between the ages of 18 and 35 (inclusive) and enrolled in an ROTC program.

• Participant has provided written and dated informed consent to participate in the study.

• Participant is in good health as determined by medical history and is cleared for exercise.

• Participant will be asked about dietary supplement use within the past 6 months.
  
  o If participant began taking a supplement within the past month, subject will be asked to discontinue supplement use followed by a 2-week washout prior to participation.
In all other cases, we will request that participants maintain supplement use, and this will be verified verbally.

Exclusion Criteria:

- Participants with any musculoskeletal injuries that would prevent exercising.
- Participants with any metabolic disorder including known electrolyte abnormalities, diabetes, thyroid disease, adrenal disease, or hypogonadism.
- Participants with any inborn error of metabolism.
- Participants with a history of hepatorenal, musculoskeletal, autoimmune, or neurologic disease.
- Participants with a personal history of heart disease, high blood pressure (systolic >140 mm Hg & diastolic >90 mm Hg), psychiatric disorders, cancer, benign prostate hypertrophy, gastric ulcer, reflux disease, or any other medical condition deemed ineligible to participate in physical training by the ROTC athletic trainers.
- Participants currently taking thyroid, hyperlipidemic, hypoglycemic, anti-hypertensive, or anti-coagulant medications.
- Participants who are pregnant or lactating.

Groups

The three groups to which participants will be randomized are traditional-equipment RET (TRAD), minimal-equipment RET (MIN), and minimal-equipment RET with BFR (MIN+BFR).
Training interventions

Participants in the TRAD group will train 4 days per week for 6 weeks following a full-body routine. Exercises will include movements such as power clean, trap-bar deadlift, bench press, back squat, pull-up, overhead press, row, push-up, single-joint movements (i.e., leg curls/extensions, arm curls/extensions), and core movements (i.e., hanging leg raise, planks, pallof press, etc.). Progressive overload will be implemented following National Strength and Conditioning Association (NSCA) guidelines. RET prescription for TRAD is shown in Table 4.1.

Participants in the MIN group will train 4 days per week for 6 weeks following a full-body routine, and movement patterns will mimic those used in the TRAD protocol. However, all exercises will be performed using highly portable equipment that can be field-expedient. Exercises will be matched based on movement pattern to those exercises performed in TRAD and will include movements such as: sandbag power clean, resistance band deadlift, weight-vest suspension-trainer squat, weight-vest pull-up, sandbag overhead press, suspension-trainer row, resistance-band push-up or suspension-trainer chest press, single-joint movements (i.e., suspension-trainer and resistance-band leg and arm curls/extensions), and core movements (i.e., hanging leg raises, sandbag throws, planks). Progressive overload will be implemented following NSCA guidelines. Participants in the MIN+BFR groups training will follow the same prescription as MT in terms of exercise selection with only the additional BFR application. RET prescription for MIN and MIN+BFR is shown in Table 4.1.
BFR training will be performed using elastic, pneumatic cuffs (upper body width: 5.5 cm, lower body width: 7 cm; BStrong, Park City, UT, USA). This method combines the safety and accuracy of doppler-based cuff pressures used in clinical settings and the convenience of portable tourniquets and elastic wraps used in field settings. These cuffs have been used previously (Early et al., 2020; Stray-Gundersen et al., 2020). For the MIN+BFR group, lab personnel will place the appropriate cuff around the proximal portion of the participant’s arms and legs at the beginning of each training session. Cuffs will be inflated to appropriate pressures according to manufacturer and existing guidelines based on cuff size, limb girth, and participant tolerability (Bagley et al., 2015; Machek et al., 2020; Patterson et al., 2019). Participant comfort will be assessed subjectively throughout the training session, and cuff pressure will be adjusted accordingly. If participants report discomfort, each cuff will be deflated as requested. If tolerable, the cuffs will remain inflated for all working sets of the training session as suggested to be most effective for maximizing the training stimulus through increasing metabolic stress and intracellular osmotic pressure and altering local oxygen kinetics (Patterson et al., 2019). After every 2-3 exercises, the cuffs will be deflated and reinflated during the 1-min rest period to ensure the cuffs are inflated to the appropriate pressure.

Initial cuff sizes and pressures will be determined according to manufacturer’s guidelines, and cuff pressures will be adjusted throughout the 6-week training intervention using subjective ratings based on a combination of manufacturer guidelines and previous research (Table 4.2). If the participant experiences severe muscular
discomfort at any point, cuffs will be completely deflated before being reinflated to 50 mmHg lower than previous cuff pressure for the remainder of the session, if tolerable. Further, if the participant experienced nausea at any point, cuffs will be completely deflated before being reinflated to 100 mmHg lower than previous cuff pressure for the remainder of the session, if tolerable. For the subsequent session, cuff pressure will be reduced by 100 mmHg.

All training associated with this study will occur in addition to group-based ROTC training. As a group, ROTC cadets typically train 2-5 times per week which consists of mainly aerobic and field training. Though cadets do not follow specific training guidelines during the summer, they are expected to maintain physical training to maintain physical fitness testing standards. Potential participants will not be removed from typical ROTC training, but this additional RET will be consistent with their usual supplemental training performed outside of ROTC duties. Thus, this will not impact other aspects of ROTC training including the development of leadership and comradery among cadets.
Table 4.1. Exercise prescription for all groups.

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Equipment</th>
<th>Sets</th>
<th>Repetitions</th>
<th>RPE</th>
<th>Rest</th>
</tr>
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<tbody>
<tr>
<td><strong>Traditional-Equipment Resistance Training</strong></td>
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<td></td>
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<tr>
<td>Day 1</td>
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<td></td>
</tr>
<tr>
<td>High Pull / Hang Clean</td>
<td>BB</td>
<td>3</td>
<td>3</td>
<td>6-7</td>
<td>3 min</td>
</tr>
<tr>
<td>Trap-bar Deadlift</td>
<td>TB</td>
<td>3</td>
<td>6</td>
<td>8-9</td>
<td>3 min</td>
</tr>
<tr>
<td>Bench Press</td>
<td>BB</td>
<td>3</td>
<td>6</td>
<td>8-9</td>
<td>3 min</td>
</tr>
<tr>
<td>Goblet / Front Squat</td>
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<td>3</td>
<td>10</td>
<td>9-10</td>
<td>2 min</td>
</tr>
<tr>
<td>Cable Pulldown</td>
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<td>3</td>
<td>10</td>
<td>9-10</td>
<td>2 min</td>
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<tr>
<td>Pallof Press</td>
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<td>10</td>
<td>6-7</td>
<td>2 min</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push Press</td>
<td>BB</td>
<td>3</td>
<td>3</td>
<td>6-7</td>
<td>3 min</td>
</tr>
<tr>
<td>Back Squat</td>
<td>BB</td>
<td>3</td>
<td>6</td>
<td>8-9</td>
<td>3 min</td>
</tr>
<tr>
<td>Cable Row</td>
<td>Cable</td>
<td>3</td>
<td>6</td>
<td>8-9</td>
<td>3 min</td>
</tr>
<tr>
<td>Romanian Deadlift</td>
<td>BB</td>
<td>3</td>
<td>10</td>
<td>9-10</td>
<td>2 min</td>
</tr>
<tr>
<td>Military Press</td>
<td>DB, BB</td>
<td>3</td>
<td>10</td>
<td>9-10</td>
<td>2 min</td>
</tr>
<tr>
<td>Calf Raise</td>
<td>Machine</td>
<td>3</td>
<td>10</td>
<td>9-10</td>
<td>2 min</td>
</tr>
<tr>
<td>Stability Ball Crunch</td>
<td>DB</td>
<td>3</td>
<td>10</td>
<td>6-7</td>
<td>2 min</td>
</tr>
<tr>
<td><strong>Minimal-Equipment Resistance Training</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Clean</td>
<td>SB</td>
<td>3</td>
<td>3</td>
<td>6-7</td>
<td>3 min</td>
</tr>
<tr>
<td>Deadlift</td>
<td>SB, RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>8-9</td>
<td>1 min</td>
</tr>
<tr>
<td>Push-up</td>
<td>WV</td>
<td>3</td>
<td>30, 15, 15</td>
<td>8-9</td>
<td>1 min</td>
</tr>
<tr>
<td>RFE Split Squat</td>
<td>WV, SB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>TRX Row</td>
<td>WV</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>Leg Curl</td>
<td>RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>Biceps Curl</td>
<td>SB, RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>Calf Raise</td>
<td>WV, SB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>Deadbug</td>
<td>-</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>Day 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push Press</td>
<td>SB</td>
<td>3</td>
<td>3</td>
<td>6-7</td>
<td>3 min</td>
</tr>
<tr>
<td>Lunge</td>
<td>WV, SB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>8-9</td>
<td>1 min</td>
</tr>
<tr>
<td>Pull-up</td>
<td>RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>8-9</td>
<td>1 min</td>
</tr>
<tr>
<td>Romanian Deadlift</td>
<td>SB, RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>Overhead Press</td>
<td>SB, RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>Squat</td>
<td>WV, SB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>Bent Over Row</td>
<td>RB, SB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>Triceps Extension</td>
<td>RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>Plank with Shoulder Tap</td>
<td>-</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
</tbody>
</table>

BB = barbell, TB = trap-bar, KB = kettlebell, DB = dumbbell, SB = sandbag, RB = resistance band, WV = weight vest
Table 4.2. Guidelines used to adjust BFR cuff pressures.

<table>
<thead>
<tr>
<th>CR10</th>
<th>Weeks 1-2</th>
<th>Weeks 3-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Increase by 50 mmHg</td>
<td></td>
</tr>
<tr>
<td>3-4</td>
<td>Increase by 25 mmHg</td>
<td>If in this range for 2 consecutive sessions, increase 25 mmHg</td>
</tr>
<tr>
<td>5-7</td>
<td>Maintain</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Decrease by 25 mmHg</td>
<td>If in this range for 2 consecutive sessions, decrease 25 mmHg</td>
</tr>
<tr>
<td>≥9</td>
<td>Decrease by 50 mmHg</td>
<td></td>
</tr>
</tbody>
</table>

Blood sample collection, processing, and analysis

Blood samples will be collected using typical phlebotomy techniques.

Participants will sit in a designated chair for blood sample collection, and a trained phlebotomist will perform venipuncture of an antecubital vein using a 21-gauge needle (Becton Dickinson, Franklin Lakes, NJ, USA). Blood will be collected into plastic serum-specific vacutainer tubes (two spray-coated silica and two spray-coated silica with serum-separator polymer gel; Becton Dickinson, Franklin Lakes, NJ, USA). Samples will be allowed to stand at room temperature for 30 min to clot before being centrifuged at 1600 g for 10 min (642E, Drucker Diagnostics, Port Matilda, PA, USA). The supernatant will be transferred into 1.5-mL aliquots using disposable pipettes. Samples will be stored at -80 degrees Celsius until analysis.

Serum samples will be analyzed for cortisol, growth hormone (GH), insulin-like growth factor (IGF)-1, interleukin (IL)-6, IL-10, and IL-1β. Frozen samples will be shipped on dry ice to a clinical laboratory improvement amendments (CLIA)-certified lab (BioReference Laboratories, Elmwood Park, NJ, USA) for analysis of cortisol, GH and IGF-
1. Serum samples will be analyzed for IL-6, IL-10, IL-1β using commercially available magnetic-bead kits and magnetic analyzer (MAGPIX, Luminex, Austin, TX, USA).

Body composition

Height will be measured using a stadiometer and body mass will be measured using a calibrated scale. Body composition will be assessed via air displacement plethysmography (BODPOD, COSMED Inc., Concord, CA, USA). This device has been previously shown to be valid and reliable (Dempster & Aitkens, 1995; McCrory et al., 1995). Participants will be instructed to arrive to the Sport Science Lab with non-padded compression shorts (and non-padded sports bra for females) having refrained from food for ≥2 hours, caffeine for ≥12 hours, and moderate-to-vigorous physical activity or exercise for ≥24 hours. Prior to each testing day, the device will be calibrated according to manufacturer’s instructions. Similarly, each test will be conducted according to manufacturer’s guidelines. A prediction equation will be used to determine thoracic gas volume (McCrory et al., 1998), and the Siri model will be used to determine body fat percentage from body density (Siri, 1961).

Muscle and tendon thickness

Biceps brachii and quadriceps (rectus femoris and vastus intermedius) muscle and tendon (distal biceps and quadriceps tendon) thickness will be measured with a 10 MHz ultrasound transducer (iQ, Butterfly Network Inc., Guilford, CT, USA). The transducer will be set to B-mode on the musculoskeletal setting, which is recommended
for imaging muscles and tendons, with gain set to a constant 50% and depth optimized to capture the best image. Participants will lay supine on an elevated table. A trained ultrasound technician will measure the distance between the acromion of the scapula and the lateral epicondyle of the humerus and will make a mark at 60% of the distance from the acromion on the most anterior portion of the upper arm. The technician will apply ultrasound gel and will image directly perpendicular to the humerus from the skin to the bone to determine biceps brachii thickness. This method has been described previously (Ogasawara et al., 2012; Schoenfeld et al., 2016). The intra- and inter-rater reliabilities for assessing muscle thickness using this technique are high, as research has shown intraclass correlation coefficients of 0.96 and 0.98 for intra- and inter-rater reliability, respectively (Filippo et al., 2019). The technician will then image just above the anterior elbow, with the image partially obstructed by the trochlea of the humerus to determine distal biceps tendon thickness. The technician will then image just above the anterior elbow, with the image partially obstructed by the trochlea of the humerus to determine distal biceps tendon thickness.

Next, the technician will measure from the greater trochanter of the femur to the lateral epicondyle of the femur and will make a mark at 50% of the distance from the greater trochanter on the most anterior portion of the upper leg. The technician will apply ultrasound gel and will image directly perpendicular to the femur from the skin to the bone to determine biceps rectus femoris and vastus intermedius thicknesses. This method has been described previously (Blazevich et al., 2009; Loenneke et al., 2017;
Matta et al., 2017). The technician will then image just above the knee, with the image partially obstructed by the patella to determine quadriceps tendon thickness.

For muscle thickness, the ultrasound transducer probe will be oriented perpendicular to the bone (humerus or femur) to determine the proper image depth, and images will be taken. The probe will be turned 45 degrees to image the same muscle at the same depth. For tendon thickness, the ultrasound transducer probe will be oriented parallel to the bone (humerus or femur), and technician will move the probe distally until the image is partially obstructed by the olecranon or patella to image the tendon. Three images at each site will be obtained, and images will be labelled with subject ID number and measurement site. All thickness measurements will be determined using a straight line from the most superficial to the deepest aspect of the structure (muscle or tendon) in the center of the image. All images will be analyzed in triplicate using an image-processing program (ImageJ, National Institutes of Health, Bethesda, MD, USA), and an average of all three images at each site will be calculated.

Subjective measures of training distress, systemic fatigue, exertion, and discomfort

At the beginning of each training session, delayed onset muscle soreness (DOMS) will be assessed using a 100-mm visual analog scale to quantify recovery status and residual impacts of the previous session(s) (Arent et al., 2010). On the first day of each training week, multicomponent training distress scale (MTDS) will be completed to assess training distress and systemic fatigue. This 22-item questionnaire consists of adjectives and phrases that are rated based on frequency of feeling over the past 24
hours according to a 5-point Likert scale ranging from “not at all” to “extremely” and provides a total score and six subscale scores representing depressed moods, vigor, physical signs and symptoms, sleep disturbances, perceived stress, and general fatigue (Main & Grove, 2009). Following each set, participants will provide a rating of perceived exertion (RPE) according to Borg’s modified 10-point rating of perceived exertion scale (Borg, 1998). Following the completion of each training session, participants will be asked to provide an RPE using the same scale to reflect exertion throughout the entire session. Additionally, participants in MIN+BFR will provide rating of perceived pain or discomfort according to Borg’s CR10 scale (Borg, 1998) with the prompt originally described by Loenneke et al. (2011).

Metabolic measures

During all training sessions, heart rate will be continuously monitored using chest-strap heart rate monitors (TeamPro, Polar Electro Co., Woodbury, NY, USA). During the final training sessions in weeks 1, 3, and 6, blood lactate will be measured before, during, and immediately following the completion of the training session. The measurement during the session will occur immediately following an exercise as close to the middle of the session as possible, which will remain constant throughout the intervention. For MIN+BFR, the cuffs will remain inflated during this midpoint measurement. A lancet and lactate analyzer (Lactate Plus, Nova Biomedical, Waltham, MA, USA) will be used to measure blood lactate from the finger and the ear lobe at all timepoints due to the unknown effects of BFR on peripheral lactate concentrations.
Army Combat Fitness Test

The Army Combat Fitness Test is a 6-event test described in detail in the Army Combat Fitness Test Field Testing Manual (V 1.4 – 20180827). This assessment consists of the following tests (in order): 3-repetition maximum (RM) deadlift, standing power throw, hand release push-up, sprint-drag-carry, leg tuck, and 2-mile run. These events can be further broken down based on the physiological demands: 3RM deadlift assesses lower-body muscular strength, standing power throw assesses muscular power, hand-release push-up assesses upper-body muscular endurance, sprint-drag-carry assesses anaerobic capacity, leg tuck assesses upper body and abdominal muscular strength or endurance depending on fitness level, and 2-mile run time assesses aerobic capacity with a contribution of biological thresholds. Prior to the start of testing, participants will be sent the testing manual to review, and, upon arrival on the testing day, the test will be explained to the participants. To limit environmental effects, the first 5 events of this test will occur at an indoor climate-controlled facility (Prisma Health Apex Athletic Performance, 903 Huger Street, Columbia, SC, USA), and the last event will occur at an indoor climate-controlled track (Strom Thurmond Wellness and Fitness Center, 1000 Blossom Street, Columbia, SC, USA).

For the deadlift, participants will be provided a 10 min warm up with the trap bar (Diamond Bar, Sorinex Exercise Equipment, Lexington, SC, USA). After 10 min, participants will take the first attempt to complete a 3-repetition maximum. Upon completion, participants will have 2 min to rest before the second attempt. The greatest load lifted for 3 successful repetitions will be recorded. Attempts will be terminated if
hips are above the shoulders, back or shoulders round excessively, hands are released from the bar, or the bar is dropped. There will be a 2-min rest between deadlift and power throw.

For the standing power throw, participants will complete one warm-up attempt and two scored attempts. This test requires participants to stand facing away from the target and throw a 4.5-kg (10 lb) medicine ball over their head and behind them as far as possible. Each scored attempt will be measured using a measuring wheel and will be recorded. Faults will occur if the participants’ feet cross the start line, and two faults will count as one attempt. There will be a 3-min rest between power throw and push-up.

For the push-up, participants will complete as many hand-release push-ups as possible in 2 min. Participants will begin in the prone position, with feet no more than one boot’s width apart and index fingers directly below or medial to the lateral aspect of the shoulder. Upon the “get-set, go” command from the test administrator, the 2-min timer will begin, and participants will begin pressing up, ensuring that the hips and shoulder rise simultaneously. Once full extension of the elbows is achieved, participants will lower to the ground, ensuring the chest makes full contact with the ground and hands are lifted from the ground with a gap between hands and the floor that can be observed by the test administrator. Participants will be reminded to maintain hand and foot position, and repetitions will not count if the shoulders and hips do not raise simultaneously, the elbows are not fully extended at the top, or a gap between hands and the floor is not observed. Two administrators will count repetitions for this assessment. There will be a 3-min rest between push-up and sprint-drag-carry.
For the sprint-drag-carry, a 25-meter lane will be established and will be marked with cones. Participants will begin in the prone position with chest on the ground and the entire body before the start line. Upon the “get-set, go” command from the test administrator, the timer will begin, and participants will stand up and sprint to the end of the lane, touching the line with one hand and one foot before turning around and sprinting back to the start line. Next, participants will grab the handles of a nylon sled (Magic Carpet Dually Version, Spud Inc., Columbia, SC, USA) loaded with 40.8 kg (90 lb) and back pedal to the end of the lane, pulling the entire sled past the end of the lane before back pedaling to the start line, again pulling the sled beyond the line. Participants will then begin to lateral shuffle with arms fully extended, touching the line with one hand and one foot before lateral shuffling back to the start line facing the same direction. Participants will be instructed that their feet must face forward and cannot cross. Next, participants will pick up two 18.1-kg (40 lb) kettlebells in each hand and walk or jog to the end of the lane, touching the line with one foot before turning back and placing the kettlebells down beyond the start line. Participants will be instructed that kettlebells must be placed in the upright position and cannot be thrown down. If a kettlebell falls over, participants will have to go back and put it down correctly. Lastly, participants will sprint to the end of the lane, touching the line with one hand and one foot before turning around and sprinting back to the start line. Upon completion, the test administrator will end the timer. Two administrators will time this assessment. There will be a 4-min rest between sprint-drag-carry and leg tuck.
For the leg tuck, participants will complete as many leg tucks as possible in 2 min. Participants will begin in the dead-hang position from a bar so that feet are not touching the ground, elbows are fully extended, and hips are fully extended. Upon the “get-set, go” command from the test administrator, the 2-min timer will begin, and participants will pull themselves up on the bar to reach 90 degrees of elbow flexion while simultaneously flexing the hips and knees to touch both knees to both elbows before lowering to the start position. Repetitions will not count if the elbows do not reach 90 degrees of flexion and both knees do not touch both elbows. If the participant drops down from the bar at any point, the test will be terminated. There will be an extended rest beyond the 5-min prescribed in the manual between leg tuck and 2-mile run since participants need to travel to a different location.

For the 2-mile run, participants will run 2 miles as fast as possible. The test will occur on a climate-controlled 1/7-mile indoor track. Upon the “get-set, go” command from the test administrator, the timer will begin, and participants will begin running. The timer will end upon completion of 14 laps.

Anaerobic peak power

Anaerobic peak power will be assessed via countermovement vertical jump with the hands-on-hips method using a digital contact mat (Just Jump, Probotics, Huntsville, AL, USA). Participants will stand on the mat, perform a countermovement in the downward direction, and jump as high as possible vertically. The contact mat will measure flight time, which will be used to calculate jump height by the software.
Participants will complete three attempts with 30 seconds between. All three attempts will be recorded, and a maximum jump height will be used for analysis.

Upper-body muscular strength

Upper-body muscular strength will be assessed via a 3RM bench press. Participants will lay supine on a flat bench with a barbell at approximately eye-level and will be instructed to maintain five points of contact according to NSCA guidelines which includes head on the bench, shoulders on the bench, hips on the bench, and both feet on the floor. Following 2-3 warm-up attempts, participants will attempt loads assigned by a strength and conditioning specialist estimated to achieve a 3RM. If the set is performed successfully, load will be increased, and participants will be provided with 3-5 min of rest. Loads will continue to be increased until the participant cannot successfully perform three repetitions. All maximum attempts will be achieved within five attempts according to NSCA guidelines.

Maximal aerobic capacity

Maximal aerobic capacity will be assessed with a treadmill based (T170, HP COSMOS, Traunstein, Germany) graded exercise test following the Bruce protocol and a direct gas-exchange measurement using a indirect calorimeter (Quark RMR, COSMED, Concord, CA, USA). Participants will wear a chest-strap heart rate monitor (H10, Polar Electro Co., Woodbury, NY, USA) and will be asked to provide a rating of perceived exertion with 30 seconds remaining in each stage and immediately at the end of the
test. Participants will be instructed to continue until volitional fatigue and will be motivated by lab staff during the test. Prior to each testing day, the metabolic and respiratory analyzers will be calibrated according to manufacturer’s guidelines. The metabolic analyzer will use a breath-by-breath analysis through a gas sampling line to measure O\textsubscript{2} and CO\textsubscript{2} concentrations in expired gases. The respiratory analyzer, consisting of a flowmeter turbine and infrared sensors, will measure inspiratory and expiratory rates. Participants must achieve three of the following four criteria for a test to be considered valid: a plateau in VO\textsubscript{2} with an increase in external exercise intensity, a respiratory-exchange-ratio of 1.1 or greater, a rating of perceived exertion of 18 or greater, and a heart rate within 15 beats of age-predicted maximal heart rate. Following completion of the test, VO\textsubscript{2max} will be assessed as the highest 30-second average VO\textsubscript{2} achieved, and ventilatory threshold will be determined as the point at which VCO\textsubscript{2} increases nonlinearly from VO\textsubscript{2}.

Protocol
Day 1: Screening, consenting, questionnaire administration, blood sample collection, and anthropometric testing.

Participants will be recruited through local ROTC programs. Potential participants will be scheduled to arrive to the University of South Carolina Sport Science Laboratory to undergo screening to determine eligibility and will be instructed to arrive normally hydrated following an overnight fast. A screening and medical history questionnaire consisting of questions relating to inclusion and exclusion criteria will be
completed. Upon determination of eligibility to participate, an informed consent form will be read and explained to the participant outlining the study protocols and procedures. Participants will be given time to read the form in its entirety and ask questions before providing written informed consent. Following screening and consenting, participants will complete the MTDS. Next, participants will undergo a blood draw conducted by a trained phlebotomist. Following the blood draw, participants will undergo body composition testing via air displacement plethysmography, and muscle and tendon thickness will be assessed using ultrasound.

Day 2: Army Combat Fitness Test testing.

Participants will arrive in a normally hydrated state at least 24 h following Day 1 testing having refrained from caffeine for ≥12 h and tobacco for ≥48 h. Participants will undergo a standardized dynamic warm-up (Table 4.3) with the addition of three 10-m sprints at 60%, 75%, and 90% of perceived maximal sprint speed before beginning the 6-event test described previously. A heart rate monitor (Team Pro, Polar Electro Co., Woodbury, NY, USA) will be worn throughout this testing session.
Table 4.3. Standardized dynamic warmup.

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee hug</td>
<td>10 repetitions per leg</td>
</tr>
<tr>
<td>Quad stretch</td>
<td>10 repetitions per leg</td>
</tr>
<tr>
<td>Figure four</td>
<td>10 repetitions per leg</td>
</tr>
<tr>
<td>Frankenstein leg raise</td>
<td>10 repetitions per leg</td>
</tr>
<tr>
<td>Forward lunge</td>
<td>10 repetitions per leg</td>
</tr>
<tr>
<td>Lateral lunge</td>
<td>10 repetitions per leg</td>
</tr>
<tr>
<td>High knees</td>
<td>10 m</td>
</tr>
<tr>
<td>Butt kicks</td>
<td>10 m</td>
</tr>
<tr>
<td>Lateral shuffle</td>
<td>10 m each direction</td>
</tr>
<tr>
<td>Carioca</td>
<td>10 m each direction</td>
</tr>
</tbody>
</table>

Day 3: Laboratory performance testing.

Participants will arrive at the lab in a normally hydrated state at least 48 h following Day 2 testing having refrained from caffeine for ≥12 h and tobacco for ≥48 h.

Participants will complete a 5-min treadmill-based warm-up at a self-selected pace and will then undergo a standardized dynamic warm-up (Table 4.3) before beginning testing.

Next, participants will perform three attempts of countermovement vertical jump with hands fixed to the hips separated by 30 seconds of rest. After approximately 3 min of rest, participants will begin the 3-repetition maximum bench press assessment. After approximately 5 min rest, participants will begin the maximal aerobic capacity test.

Training intervention

Following completion of the three pre-testing days, participants will be randomly assigned into one of the three training groups and will complete 24 training sessions over 6 weeks. All training sessions will be approximately 60-75 min in duration for all groups. Upon arrival for all training sessions, participants will provide a subjective rating.
for DOMS. Participants will wear a heart rate monitor (Team Pro, Polar Electro Co., Woodbury, NY, USA) throughout all training sessions. At the start of each training week, participants will complete the MTDS. During training sessions in weeks 1, 3, and 6, blood lactate concentrations will be measured at the finger and ear at the beginning, middle, and end of the session.

Post-testing

Upon completion of the 6-week training program, participants will undergo post-testing following the same protocol as described for Day 1, Day 2, and Day 3 for pre-testing. The first day of post-testing will take place ≥48 hours following the final training session, and all testing will be completed within a 1-week period.

Data analysis

One-way analyses of variance will be conducted to determine differences in baseline descriptive metrics between groups. For performance, body composition, and blood biomarker assessments, linear mixed-effects models with a random intercept to adjust for between-subject variability will be performed on each dependent variable to test for Group (TRAD, MIN, MIN+BFR)-by-Time (pre-testing, post-testing) interactions, as well as main effects of Group and Time. Mixed-effects models have recently been shown to be robust to distributional assumptions, such as the requirement of a normally distributed residuals, and more powerful alternative to more traditional statistical models of data with repeated observations on the same individual (Schiezeth et al.,
For psychological responses to training, linear mixed-effects models with a random intercept to adjust for between-subject variability will be performed on each dependent variable to test for Group (TRAD, MIN, MIN+BFR)-by-Time (baseline, week 2, week 3, week 4, week 5, week 6) interactions, as well as main effects of Group and Time. For blood lactate responses, a linear mixed-effects model with a random intercept to adjust for between-subject variability will be performed to test for Group (TRAD, MIN, MIN+BFR)-by-Time (week 1, week 3, week 6) interactions, as well as main effects of Group and Time while adjusting for time within exercise session (pre-exercise, mid-exercise, and post-exercise). Post-hoc tests for all analyses will be followed with effect sizes to determine magnitude of change within groups. An α-level of 0.05 will be used to determine statistical significance. All analyses were conducted and figures were produced using commercially available open-source statistical software (R; version 4.1.0; Team, 2021) with the lme4 (version 1.1-27.1; Bates et al., 2015), emmeans (version 1.6.2-1; Lenth, 2021), effectsize (version 0.5; Ben-Shachar et al., 2020), and ggplot2 (version 3.3.5; Wickham, 2016) packages.

Limitations, delimitations, and assumptions

One limitation of this study is that the minimal equipment groups will be lifting loads in which 30 repetitions can be performed on the first set, which would be considered low-load exercise. Minimal equipment training, however, does not necessarily require individuals to use low loads. This program design was chosen to compare differences of this type of training with and without BFR cuffs, and this is
similar to the RET protocols used in previous BFR research. Therefore, the findings of this study will be delimited to minimal equipment RET used with moderate-to-high loads in lower repetition ranges. Another limitation is that ROTC cadets and midshipmen will continue to undergo prescribed or expected physical training according to ROTC duties in conjunction with the RET performed in the laboratory throughout the study. Training modalities and volumes of physical training may not be consistent across branches, and these training metrics will not be quantified by the researchers. However, it is assumed that randomization will evenly distribute participants in different military branches across each of the three groups.
CHAPTER 5

EFFECTS OF CAFFEINE, METHYLLIBERINE, AND THEACRINE ON VIGILANCE, MARKSMANSHIP, AND HEMODYNAMIC RESPONSES IN TACTICAL PERSONNEL: A DOUBLE-BLIND, RANDOMIZED, PLACEBO-CONTROLLED TRIAL

Abstract

Background: Tactical athletes require fast reaction times (RT) along with high levels of vigilance and marksmanship performance. Caffeine has been shown to improve these measures but also results in increased blood pressure and jitteriness. Research on other purine alkaloids, such as methylliberine and theacrine, has suggested they do not increase blood pressure or jitteriness to the same extent, but their impact on tactical performance is unknown. Methods: A between-subjects, randomized, placebo-controlled design was used to test the effects of placebo (PLA), 300 mg caffeine (CAF), and a combination of 150 mg caffeine, 100 mg methylliberine, and 50 mg theacrine (CMT) on RT and marksmanship along with hemodynamic and arousal measures following a sustained vigilance task in tactical personnel (N=48). Participants underwent a 150-min protocol consisting of two rounds. Each round began with leisurely reading followed by a 30-min vigilance task before beginning two trials of movement and marksmanship tasks. Hemodynamics and felt arousal were assessed throughout the protocol. Composite Z-scores were calculated for overall performance measures at each timepoint, and mixed-effect models were used to assess differences in RT, accuracy, and
composite Z-scores scores along with hemodynamics and felt arousal. An α-level of 0.05 was used to determine statistical significance, and Cohen’s d was used to quantify effect sizes. Results: A Group-by-Time interaction for vigilance RT (P=0.038) indicated improvements for both CAF and CMT from round 1 to round 2 (P<0.01) while PLA did not change (P=0.27). No Group main effects or Group-by-Time interactions were found for movement or marksmanship performance (P>0.20). Group main effects for systolic (SBP; P=0.001) and diastolic blood pressure (DBP; P=0.028) indicated higher SBP in CAF (P=0.003, d=0.84) and CMT (P=0.007, d=0.79) compared to PLA but only higher DBP in CAF (P=0.025, d=0.74). No Group-by-Time interaction or Group main effect was found for felt arousal (P>0.16). Conclusions: These findings suggest similar benefits on RT during a vigilance task between CAF, containing 300 mg caffeine, and CMT above PLA, though CAF resulted in slightly less favorable hemodynamic changes. This study is the first to provide data showing similar efficacy of combined caffeine, methylliberine, and theacrine compared to double the caffeine dose with CAF alone on vigilance RT but without a significant rise in DBP above PLA in tactical personnel.

Keywords: sports nutrition, dietary supplements, stimulants, reaction time

Background
Military and law enforcement personnel are required to possess sufficient physical and cognitive fitness to perform their official duties. As such, these populations have been deemed “tactical athletes” to emphasize these requirements. In a narrative review,
Scofield and Kardouni (2015) highlighted that tactical athletes must also have fast reaction times (RT), high levels of vigilance, defined as the ability to maintain alertness during extended periods, and proficient marksmanship capabilities. Most importantly, physical fitness and performance parameters have an effect on mission success in these populations (Austin & Deuster, 2015). Tactical athletes likely stand to benefit from the use of sports nutrition supplements, such as caffeine and caffeine-like purine alkaloids, to improve these aspects of performance.

Caffeine has been studied extensively, and a recent systematic review concluded that caffeine in the range of 3-6 mg/kg relative to body mass has positive ergogenic effects on both physical and cognitive performance (Guest et al., 2021). The primary mechanism of action by which caffeine exerts its ergogenic effects is central nervous system stimulation, primarily through adenosine receptor antagonism, attenuating feelings of drowsiness and fatigue (Faudone et al., 2021). Studies dating back to the 1930s have shown positive effects of caffeine on various measures of RT (Horst & Jenkins, 1935; Thornton et al., 1939), and more recent work has corroborated these findings (Doyle et al., 2016; Jacobson & Edgley, 1987; Kamimori et al., 2015; Kamimori et al., 2000; McLellan et al., 2007; Santos et al., 2014; Souissi et al., 2012). Overall, caffeine improves RT, movement time, and movement accuracy in healthy adults and athletes when consumed in moderate absolute doses of 300 mg or relative doses up to 6 mg/kg body mass, but higher doses of 600 mg or 7.5 mg/kg can be ergolytic (Doyle et al., 2016; Jacobson & Edgley, 1987; Santos et al., 2014; Souissi et al., 2012). In tactical populations, caffeine improves vigilance compared to placebo when consumed in doses ranging from
150 to 300 mg and has its largest effect when consumed in multiple consecutive doses during extended periods of sleep deprivation (Kamimori et al., 2015; Kamimori et al., 2000; McLellan et al., 2007). Marksmanship RT and accuracy are also improved by 200 to 300 mg caffeine (Gillingham et al., 2003; Gillingham et al., 2004; Johnson & Merullo, 1999; Tharion et al., 2003), though one study noted greater feelings of hand trembling and irritability following 5 mg/kg and 2.5 mg/kg caffeine doses separated by eight hours (Gillingham et al., 2004), both of which are commonly cited negative side effects of caffeine consumption (Humayun et al., 1997; Jacobson & Thurman-Lacey, 1992; Kaplan et al., 1997; Shirlow & Mathers, 1985).

Though caffeine is the most widely consumed and studied drug of the purine alkaloids, newly discovered compounds, such as methylliberine (Dynamine™) and theacrine (TeaCrine®) which are classified as tetramethylurates, exhibit structural similarities to caffeine and have similar pharmacodynamic effects. However, pharmacokinetic profiles of these compounds differ. Caffeine’s peak plasma concentration following oral consumption occurs within approximately 30-60 min with a half-life of approximately 4-5 hours (Kaplan et al., 1997). Methylliberine has a shorter peak time of 0.6-0.9 hours with a half-life of 1.4 hours when consumed in doses of 25 mg and 100 mg (Mondal et al., 2021), while theacrine has a longer peak time of about 1.8 hours and half-life of 16.5-26.1 hours when consumed in 25 mg to 125 mg doses (He et al., 2017). Recent pharmacokinetic data for a combination of 100 mg methylliberine, 150 mg caffeine, and 50 mg theacrine showed peak plasma concentration times of 0.8, 1.1, and 1.4 hours with half-lives of 1.5, 21, and 30 hours, respectively (Wang et al.,
This shows the potential synergistic effect of supplementation with these compounds as the differential peak times allow for the stimulatory actions to be maximized over a longer period rather than supplementing with one compound alone. Together, this can create a more sustained peak effect while also resulting in a more sustained time course of action.

Based on this theoretical rationale and demonstrated safety (He et al., 2017; VanDusseldorp et al., 2020), the efficacy of a combination of caffeine with methylliberine and/or theacrine has been assessed in applied studies providing absolute rather than relative doses on various performance outcomes including RT (Bello et al., 2019; Kuhman et al., 2015; La Monica et al., 2021). Two studies showed no differences between caffeine only conditions compared to combinations of caffeine and theacrine (Bello et al., 2019; Kuhman et al., 2015), while another showed the largest improvement in both RT and accuracy following 125 mg caffeine with 75 mg methylliberine and 50 mg theacrine compared to 125 mg caffeine (La Monica et al., 2021). Though preliminary, the results of these few studies show positive effects of combining caffeine with methylliberine and/or theacrine on cognitive tasks, RT, and accuracy, corroborating past research on the effects of caffeine on these outcomes.

One difference of particular interest between caffeine and these related compounds is the acute effect on hemodynamics. Generally, moderate-to-high doses of caffeine ranging from one cup of coffee (approximately 125 mg caffeine) to 300 mg caffeine acutely increase blood pressure and heart rate in normotensive individuals (Green et al., 1996; Myers, 1988). This effect also extends to exercise, as studies have
shown greater increases in systolic (SBP) and diastolic blood pressure (DBP) during aerobic exercise bouts following consumption of ≥360 mg caffeine compared to placebo (Daniels et al., 1998; Harber et al., 2021; Sung et al., 1990). Based on these alterations observed following caffeine ingestion, resting hemodynamic responses following methylliberine and theacrine supplementation have also been investigated (Taylor et al., 2016; VanDusseldorp et al., 2020), and data show no changes in acute or chronic blood pressure responses following consumption in doses as high as 175 mg. However, when caffeine is included in combination with tetramethylurates, increases in hemodynamics appear to be attributed to caffeine content when compared to methylliberine or theacrine alone (Bloomer et al., 2020; La Monica et al., 2021). Law enforcement officers have been shown to experience increases in blood pressure throughout their career (Starosta & Earleywine, 2014), therefore this is an outcome of particular interest in this population. Similarly, caffeine increases levels of physiological arousal (Barry et al., 2011; Barry et al., 2008; Barry et al., 2005), though felt arousal, a subjective measure, has not been shown to be increased by caffeine above placebo in males (Astorino et al., 2012; Backhouse et al., 2005; Clarke et al., 2015; Richardson & Clarke, 2016). This response has never been assessed following tetramethylurate consumption.

Based on the known pharmacodynamics and pharmacokinetics of caffeine, methylliberine, and theacrine, it is speculated that co-ingestion of these compounds and sustained peak times and half-lives can improve physical and cognitive performance over a longer period compared to caffeine alone. Additionally, the more favorable hemodynamic responses along with data suggesting reduced jitteriness and habituation
Effects associated with methylliberine and theacrine (Kuhman et al., 2015; La Monica et al., 2021; Taylor et al., 2016) further support the idea of a beneficial effect of combining these supplements rather than consuming caffeine alone. Therefore, the purpose of this study was to compare the effects of a combination of caffeine, methylliberine, and theacrine to caffeine alone and placebo on RT and marksmanship following a sustained vigilance task along with hemodynamic responses and felt arousal in tactical personnel. It was hypothesized that the combination of these compounds would produce a synergistic effect, resulting in similar improvements in RT as caffeine alone above placebo, greater improvements in decision-making and accuracy compared to caffeine alone, and less pronounced hemodynamic responses and felt arousal compared to caffeine alone.

Methods

Experimental Approach

A between-subjects, randomized, placebo-controlled design was used to test the effects of caffeine, methylliberine, and theacrine on RT and marksmanship along with hemodynamic and felt arousal measures following sustained vigilance. Participants were randomized into one of three groups according to supplementation protocol: 300 mg cellulose placebo (PLA), 300 mg caffeine (CAF), or a combination of 150 mg caffeine, 100 mg methylliberine, and 50 mg theacrine (CMT). Following familiarization, participants arrived for the experimental testing session within two hours of waking, consumed the randomized supplement, and completed a 150-minute protocol consisting of two
rounds that each comprised vigilance, movement, and marksmanship tasks.

Hemodynamics and felt arousal were assessed throughout the protocol corresponding to each task. Participants were instructed to abstain from caffeine for ≥24 h and alcohol for ≥48 h while maintaining normal sleep and wake schedules over the one-week period before the experimental testing session. All protocols and procedures were approved by the Rutgers University and University of South Carolina Institutional Review Boards. This study was registered on ClinicalTrials.gov (NCT03937687).

Participants

Forty-nine males who were currently employed as military personnel or law enforcement officers, currently enrolled in a Reserve Officers’ Training Corps (ROTC) program, or military veterans or retired law enforcement officers who had completed service within the past 18 months or were actively involved in tactical training or operations were recruited to participate in this study. All participants were between the ages of 18 and 63 years (inclusive) and had a body mass of at least 60 kg. Individuals were excluded if they had injuries which would prevent completion of the protocol, experienced migraines, had a history of hepatorenal or neurologic disease, had a history of caffeine sensitivity, were currently taking over-the-counter products containing pseudoephedrine or other stimulants, or were currently consuming ≥500 mg caffeine per day. All participants provided written informed consent.
Groups

Participants were randomized to one of three groups: PLA, CAF, and CMT. All pills consisted of an encapsulated white powder and were identical across groups. The placebo capsule contained 300 mg cellulose, the caffeine capsule contained 300 mg caffeine, the combination capsule consisted of 150 mg caffeine, 100 mg methylxanthine, and 50 mg theacrine. Thus, total purine alkaloid content was matched at 300 mg for CAF and CMT, but total caffeine content differed.

Body Composition

Height was measured using a stadiometer, and body mass was measured using a calibrated scale. Body composition was assessed using air displacement plethysmography (BODPOD, COSMED Inc., Concord, CA, USA; Dempster & Aitkens, 1995; McCrory et al., 1995). Participants were instructed to arrive with non-padded compression shorts having refrained from food and water for ≥2 hours, caffeine for ≥12 hours, and moderate-to-vigorous physical activity or exercise for ≥24 hours. The device was calibrated, and each test was conducted according to manufacturer’s guidelines. A prediction equation was used to determine thoracic gas volume (McCrory et al., 1998), and the Brozek model was used to determine body fat percentage from body density (Brozek, 1966).
Vigilance Task

The vigilance task consisted of a 30-min protocol using an interactive light board with 64 three-dimensional targets and a digital screen (D2, Dynavision International LLC, Cincinnati, OH, USA; Wells et al., 2014). Participants stood approximately 12 inches from the board, and the board was raised or lowered to a height ensuring the digital screen was at eye level and all lights could be reached. The blinds were drawn, and lights were turned off to reduce glare on the light board. A go/no-go task in which one of the 64 lights illuminated (either red or green) at a time was used, and participants were instructed to press the red lights as quickly as possible while avoiding the green lights. Each light remained illuminated for 2 seconds or until it was pressed, in which case another light illuminated. Simultaneously, every 9 seconds, the digital screen showed a 3-integer arithmetic problem for one second to which participants were instructed to respond audibly to serve as a mental distraction before the next problem showed up. Researchers did not provide feedback during the task. Participants performed this task for 5 minutes during the familiarization session and 30 minutes during the experimental testing session. During the experimental testing session, RT for red lights and decision-making, quantified as a percentage of correct go/no-go decisions out of total decisions, were scored and recorded by the computer software.

Movement Task

The movement task was a 40-target protocol using a computer simulator with full-body optical sensing technology (Trazer, TRAQ Global Ltd., Westlake, OH, USA; Hogg et al.,
The simulator consists of a large digital screen and front-facing camera. The simulator was placed in front of an open space where a 3-meter-by-3-meter grid with a mark in the center was outlined on the floor using brightly colored tape. Participants stood on the mark in the center as the program was started, and the simulator self-calibrated for each assessment. The protocol consisted of targets appearing as pillars on the digital screen corresponding to locations 3 meters in front, behind, left, or right of center, and participants were instructed to move to each target as quickly as possible and return to center after each target. Participants were required to reach 20 targets for each of the three trials during the familiarization session and 40 targets for each of the four trials during the experimental testing session. During the experimental testing session, RT was scored and recorded by the computer software.

Marksmanship Task

The marksmanship task was a 16-target protocol using a shooting simulator (Smokeless Range, Laser Ammo, Great Neck, NY, USA) with a laser-modified, gas blowback airsoft pistol (ATP-C, KWA, City of Industry, CA, USA). This simulator has been used in previous research (Buckley et al., 2021). The simulator consists of a computer connected to a short-throw projector, along with a short-throw high-speed camera pointed at the projector screen which allows the software to determine where the laser-modified pistol was aimed when the trigger was pulled. The protocol consisted of digital law enforcement training targets (B-27, National Rifle Association, Fairfax, VA, USA) projected onto the screen one at a time, and participants were instructed to shoot each
target as quickly and as accurately as possible. The round began with the participant holding the modified pistol at his hip, and participants were instructed to not lift the pistol until the first target appeared. In the middle of the round, a symbol came up on the screen indicating a tactical reload, in which participants released the magazine from the pistol and loaded the second magazine from a belt-mounted holster that was provided. Participants shot 8 targets scaled to 15 meters for each of the four trials, two of which consisted of a tactical reload, during the familiarization session and 16 targets scaled to 15 or 30 meters for each trial during the experimental testing session. During the experimental testing session, RT was scored and recorded by the computer software, and accuracy, quantified as distance from center of target, was scored and recorded by a researcher using an image-processing program (ImageJ, National Institutes of Health, Bethesda, MD, USA).

Hemodynamic Responses

SBP and DBP were measured using an automated blood pressure cuff (HEM 907XL, Omron Electronics LLC, Hoffman Estates, IL, USA; Ostchega et al., 2010). The participant was seated in the upright position with his arm supported at heart level by a table before a researcher placed the cuff snugly around the proximal portion of the right arm ensuring legs were not crossed. The participant was instructed to limit movement and refrain from talking during measurements. All blood pressure readings were measured in duplicate with one minute between measurements. If measurements varied by >10%, a third measurement was taken, and the outlier measurement was removed. Blood
pressure was measured at baseline before the participant consumed the capsule and at 6 timepoints throughout the protocol. These timepoints occurred before and following specific tasks throughout the protocol (Figure 5.1). Blood pressure readings were averaged across duplicate measurements at each timepoint.

Throughout the experimental protocol, heart rate was continuously monitored using a chest-strap heart rate sensor (H7, Polar Electro, Lake Success, NY, USA; Pasadyn et al., 2019) connected via Bluetooth to a fitness watch (V800, Polar Electro, Lake Success, NY, USA). The watch was not worn by the participants but was kept near participants to ensure proper transmission between the sensor and the watch. Heart rate data were averaged across 6 blocks throughout the protocol.

Felt Arousal

Felt arousal was measured using the Felt Arousal Scale, which ranges from 1 (low arousal) to 6 (high arousal; Svebak & Murgatroyd, 1985). Felt arousal was assessed at baseline before the participant consumed the capsule and at 12 timepoints throughout the protocol.

Familiarization

Participants arrived at the Sport Science Laboratory having refrained from food and water for ≥2 hours, caffeine for ≥12 hours, and moderate-to-vigorous physical activity or exercise for ≥24 hours. Following screening and consenting, participants underwent body composition testing. Participants were then familiarized with the testing protocols
including the vigilance, movement, and marksmanship tasks. Participants completed a shortened (5-min) version of the vigilance task, three trials of the movement task, and four trials of the marksmanship task.

Experimental Testing Protocol

Prior to this session, participants were asked to maintain a normal sleep schedule in the week leading up to their session, maintaining the same wake time each day. Participants were also asked to refrain from caffeine for ≥24 hours and alcohol for ≥48 hours and maintain habitual dietary habits. Prior to the start of the session, verbal confirmation of adherence to the pre-visit instructions was obtained. If participants did not adhere, the session was rescheduled. This session was scheduled to begin within 2 hours of waking and was within 30 min of the start time of the initial familiarization session. This 2-hour period was chosen to ensure consistency across participants since sleep and wake schedules can vary drastically in this population.

Participants arrived and sat quietly for 5 min. Following quiet rest, blood pressure was measured and felt arousal was assessed. Next, participants consumed the randomized capsule orally with water provided ad libitum. Participants then sat and read a book about exercise leisurely for 30 min. At the 25-min point of the 30 min quiet reading period, blood pressure and felt arousal were measured.

After 30 min of quiet reading was completed, participants began the 30-min vigilance task. Following completion of this task, participants returned to a seated position while blood pressure and felt arousal were again assessed. Immediately
following these measurements, participants began the 40-target movement task, followed immediately by the 16-target marksmanship task with 15-meter targets on the marksmanship simulator. This was again immediately followed by the same movement task and 16-target marksmanship task with 30-meter targets. Felt arousal was assessed between each of these tasks. Upon completion of this first full round of testing at approximately the 75-min point, participants returned to a quiet seated position, and blood pressure and felt arousal were assessed. Participants then repeated the protocol in its entirety. An overview of the experimental testing protocol is shown in Figure 5.1.

Figure 5.1. Overview of the experimental testing protocol. BP = blood pressure, FA = felt arousal, HR = heart rate.

Data Analysis

One-way analyses of variance were conducted to determine differences in baseline descriptive metrics between groups, and chi-square tests were used to determine differences in felt arousal and participant occupations between groups. For vigilance, movement, and marksmanship task variables, RT, cognitive decision-making, and accuracy scores were analyzed. For composite vigilance and marksmanship task performance, Z-scores were computed for RT and cognitive decision-making (vigilance) or accuracy (marksmanship) to compare performance relative to the cohort mean at
each respective timepoint. The inverse of RT Z-score was calculated, and the product of RT and cognitive decision-making or accuracy Z-scores was used for composite score analyses. Linear mixed-effects models with a random intercept to adjust for between-subject variability were used to test for Group (PLA, CAF, and CMT)-by-Time (two rounds) interactions, as well as main effects of Group and Time. For hemodynamic variables, linear mixed-effects models with a random intercept to adjust for between-subject variability were used to test for Group (PLA, CAF, and CMT)-by-Time (7 timepoints for SBP and DBP, 6 timepoints for HR), as well as main effects of Group and Time. For felt arousal, a generalized linear mixed-effects model with a random intercept to adjust for between-subject variability was used to test for a Group (PLA, CAF, and CMT)-by-Time (13 timepoints) interaction, as well as main effects of Group and Time. Significant interactions or main effects were followed up with post-hoc pairwise comparisons with a Bonferroni adjustment to further explain the effects. An α-level of 0.05 was used to determine statistical significance. Effect sizes were calculated using Cohen’s d to determine magnitude of change within groups and differences between groups. All analyses were conducted and figures were produced using commercially available open-source statistical software (R; version 4.1.0; Team, 2021) with the lme4 (version 1.1-27.1; Bates et al., 2015), emmeans (version 1.6.2-1; Lenth, 2021), effectsize (version 0.5; Ben-Shachar et al., 2020), and ggplot2 (version 3.3.5; Wickham, 2016) packages.
Results

Participants

One participant was lost to follow-up, so total number of participants that completed
the protocol was 48. Participants consisted of 35% law enforcement officers, 19%
military personnel and veterans, and 46% ROTC cadets and midshipmen. A chi-square
test revealed no differences in participant occupation between groups (χ²=1.25,
P=0.868). One participant in CAF was not included the analysis of marksmanship
measures due to equipment technical malfunctions. One participant in the PLA group
was not included in the analysis of hemodynamic measures due to equipment technical
malfunctions.

Baseline Characteristics

Descriptive baseline statistics are shown in Table 5.1. One-way ANOVAs showed no
significant differences between groups in baseline metrics.

<table>
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<tr>
<th>Table 5.1. Baseline descriptive characteristics by group.</th>
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<tr>
<td>Group</td>
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<td>Felt arousal (au)</td>
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Data are presented as mean±SD. P-value shows result of one-way ANOVAs or chi-square test.

Vigilance Task

A Group-by-Time interaction was observed for RT ($F_{2,45}=3.52$, $P=0.038$), Time main effect for decision-making ($F_{1,45}=5.74$, $P=0.021$), and no effects for composite Z-score ($P>0.19$). For RT, post-hoc tests revealed significant improvements from round 1 to round 2 in CAF ($P<0.01; d=-0.37$) and CMT ($P<0.01, d=-0.32$), but not PLA ($P=0.27, d=-0.08$). Regardless of group, decision-making improved from round 1 to round 2 (PLA: $d=0.06$, CAF: $d=0.39$, CMT: $d=0.38$). Data are shown in Figures 5.2A-C.

![Figure 5.2](image_url)

Figure 5.2. Changes in (A) RT, (B) correct decisions, and (C) composite Z-score relative to PLA from round 1 to round 2 of the experimental testing protocol between groups during the vigilance task. “a” denotes a Group-by-Time interaction; “c” denotes a Time main effect.

Movement Task

No Group-by-Time interaction or Group main effect was found for RT ($P>0.22$). A Time main effect was observed for RT ($F_{1,141}=44.17$, $P<0.001$). Regardless of group, RT
improved from round 1 to round 2 for all groups (PLA: $d=0.38$, CAF: $d=0.65$, CMT: $d=0.46$). Data are shown in Figure 5.3.

Figure 5.3. Changes in RT from round 1 to round 2 of the experimental testing protocol between groups during the movement task. “c” denotes a Time main effect.

Marksmanship Task

No Group-by-Time interactions or Group main effects were found for RT, accuracy, or composite Z-scores during the marksmanship task ($P>0.20$). Time main effects were observed for accuracy during the 15-m ($F_{1,24.7}=18.83$, $P<0.001$) and 30-m trials ($F_{1,33.9}=6.00$, $P=0.020$). Regardless of group, accuracy improved from round 1 to round 2 for the 15-m (PLA: $d=-0.41$, CAF: $d=-0.27$, CMT: $d=-0.39$) and 30-m trials (PLA: $d=-0.50$, CAF: $d=-0.14$, CMT: $d=-0.38$). Data are shown in Figures 5.4A-F.
Figure 5.4. Changes in (A) 15-meter RT, (B) 15-meter accuracy, (C) 15-meter composite Z-score, (D) 15-meter RT, (E) 15-meter accuracy, and (F) 15-meter composite Z-score from round 1 to round 2 of the experimental testing protocol between groups during the marksmanship task. “c” denotes a Time main effect.

Hemodynamic Responses

Group and Time main effects were found for SBP ($F_{2,44}=7.87$, $P=0.001$; $F_{6,264}=54.32$, $P<0.001$) and DBP ($F_{2,44}=3.89$, $P=0.028$; $F_{6,264}=18.55$, $P<0.001$). For SBP, post-hoc tests showed higher values in both CAF ($P=0.003$, $d=0.84$) and CMT ($P=0.007$, $d=0.79$) compared to PLA, with no differences between CAF and CMT ($P=1.00$, $d=0.06$). For DBP, post-hoc tests showed higher values for CAF compared to PLA ($P=0.025$, $d=0.74$), with
no differences between CMT and PLA (P=0.947, d=0.29) or CAF and CMT (P=0.288, d=0.48). Regardless of group, SBP was higher than baseline at T3 (P<0.001) and T6 (P<0.001), and DBP was higher than baseline at T2 (P=0.002), T3 (P<0.001), and T6 (P<0.001). Heart rate responses exhibited a Time main effect (F\_5,\_156.8=247.7, P<0.001). Post-hoc tests revealed increases from T1 at all subsequent time points (P<0.001). Data are shown in Figures 5.5A-C.

![Figure 5.5](image-url)

Figure 5.5. Changes in (A) SBP, (B) DBP, and (C) heart rate throughout the experimental testing protocol between groups. “b” denotes a Group main effect; “c” denotes a Time main effect.

**Felt Arousal**

A Time main effect was found for felt arousal (χ\^2\_12=40.54, P<0.01). Regardless of group, felt arousal was higher than baseline at all timepoints (P<0.001) except T1, T7, and T8 (P>0.15). Data are shown in Figure 5.6.
Discussion

This is the first study to test the effects of caffeine in conjunction with methylliberine and theacrine on vigilance and marksmanship. The primary findings show a combination of 150 mg caffeine, 100 mg methylliberine, and 50 mg theacrine improves RT during a vigilance task from round 1 to round 2 to a similar extent as 300 mg caffeine alone while placebo does not. These findings support the hypothesis that CMT would exhibit improved RT similar to CAF when compared to PLA. However, it was also found that CMT did not improve decision-making or accuracy during vigilance or marksmanship tasks above caffeine alone or placebo, which does not support the hypothesis based on previous data suggesting less jitteriness as well as more sustained peak plasma concentrations associated with the combination of caffeine, methylliberine, and theacrine compared to a single dose of 300 mg caffeine. Over the same time course, CMT and CAF both resulted in increases of large effect sizes in SBP above PLA. Caffeine
alone, however, resulted in large elevations in DBP compared to placebo while the combination of caffeine, methylliberine, and theacrine did not. Though CAF was not statistically different from CMT, the difference in magnitude suggests a more favorable hemodynamic response in CMT compared to CAF as higher exercising blood pressures may contribute to cardiovascular death and myocardial infarction (Kjeldsen et al., 1997; Mundal et al., 1996). These data partially support the hypothesis that CMT would exhibit less severe perturbations in blood pressure than CAF. Further, the results showed no differences in movement RT between groups supporting the hypothesis that CMT and CAF would be similar, although lack of improvements in these groups above PLA do not corroborate previous research. Similarly, lack of differences in marksmanship performance across groups do not support the hypothesis that CAF but not CMT would result in decrements compared to PLA. Lastly, felt arousal was similar across all groups throughout the protocol, which does not support the hypothesis of a less pronounced response in CMT compared to CAF.

Maintaining vigilance is critical during sustained operations in tactical populations, and caffeine has consistently shown favorable effects on this task compared to placebo (Kamimori et al., 2005; Kamimori et al., 2015; Kamimori et al., 2000; McLellan et al., 2007). Though research designs vary greatly across studies on this topic in terms of caffeine dose, protocols, and outcome measures, this effect is consistent and is supported by the data presented here. The absolute dose of 300 mg or relative dose of 3.56 mg/kg based on the mean body mass in the sample of total caffeine or combined content provided in the current study would be considered a
A similar study by Kamimori et al. (2000) compared 2.1, 4.3, and 8.6 mg/kg caffeine to placebo on measures of choice RT during vigilance following 48 hours of sleep deprivation and found all caffeine conditions resulted in improved RT over placebo. Further, McLellan et al. (2007) provided multiple 200-mg caffeine doses during an overnight vigilance task which required soldiers to record all activities that occurred in an illuminated building situated 175-200 meters away for 120 min in 20 special operators and showed maintenance of vigilance in the caffeine condition while placebo resulted in decrements. The results presented here indicated no differences between the combination and caffeine only, suggesting the addition of methylliberine and theacrine provide similar ergogenic effects as caffeine alone perhaps due to the equivalent purine alkaloid content between groups.

Marksmanship performance, another crucial skill for the tactical athlete during and following periods of sustained vigilance, was unaffected by CMT or CAF compared to PLA. A recent systematic review concluded that marksmanship accuracy is improved by caffeine doses of 100-200 mg consumed every 2 hours (Torres & Kim, 2019), suggesting the dose provided in the current study may have been too large to improve marksmanship. However, a study conducted by Gillingham et al. (2003) in military reservists showed no differences in marksmanship performance between 300 mg caffeine and placebo conditions during periods of vigilance following sleep deprivation. This corresponds to the findings here and could be considered as a positive effect as caffeine consumption is often associated with jitteriness (Humayun et al., 1997; Jacobson & Thurman-Lacey, 1992; Kaplan et al., 1997; Shirlow & Mathers, 1985), but no
negative effects on marksmanship performance were observed. Interestingly, the lower
dose of caffeine along with methylliberine and theacrine did not result in improved
marksmanship despite the lack of jitters associated with this combination (Kuhman et
al., 2015; La Monica et al., 2021). Additionally, RT measured during the movement task
in this study also did not result in improvements over placebo following caffeine
consumption, which is contrary to much of the existing literature.

The improvement in vigilance above placebo and maintenance of marksmanship
accuracy observed in both CMT and CAF is even more substantial when considering the
hemodynamic responses observed in the current study. It is commonly cited that
moderate doses of caffeine increase blood pressure at rest (Green et al., 1996; Myers,
1988) and during exercise (Daniels et al., 1998; Harber et al., 2021; Sung et al., 1990).
This increase was observed in both supplement groups with regard to SBP, but DBP was
greater throughout the entire 150-min protocol in CAF compared to PLA with a
moderate-to-large effect size but was not elevated above PLA in CMT. This finding is
consistent with previous work as VanDusseldorp et al. (2020) observed no changes in
acute or chronic blood pressure responses following supplementation with
methylliberine alone, theacrine alone, or a combination of methylliberine and theacrine.
Similarly, Bloomer et al. (2020) recently showed increases in both SBP and DBP following
consumption of methylliberine and theacrine only when consumed with caffeine.
Though this slightly contradicts the current finding that SBP but not DBP was elevated
above placebo, it shows that caffeine appears to be the driver in altered hemodynamics
at rest and exercise and a lower dose of caffeine results in lesser perturbations in
hemodynamics. The observation of no differences in heart rate across groups is consistent with previous research as caffeine does not consistently affect this measure (Green et al., 1996).

Felt or perceived arousal was not different between any of the groups throughout the 150-min protocol. This finding is consistent with previous studies showing no effects of caffeine consumption ranging from 5 to 6 mg/kg on ratings of felt arousal compared to placebo in sample sizes of 8 to 15 young males during and following both resistance and endurance training bouts (Astorino et al., 2012; Backhouse et al., 2005; Clarke et al., 2015; Richardson & Clarke, 2016). This outcome, however, has not been assessed previously in studies providing methylliberine or theacrine. Therefore, this is the first study to show no further increases in physiological activation following consumption of caffeine, methylliberine, and theacrine compared to caffeine alone or placebo.

Overall, these findings show consistency with previous research, and there are several strengths, limitations, and delimitations to the current study. One strength is the protocol used as it mimics military and law enforcement tactics. The vigilance task simulated an overwatch scenario as it required participants to maintain mental acuity through using peripheral vision to see lights illuminate on the board and decide whether to press the button based on the color of the light while simultaneously remaining focused on the digital screening and performing mental math. Next, participants continued to the movement task which required physical movement resulting in elevations in heart rate and blood pressure before moving into the marksmanship task.
with a tactical reload. These tasks mimic undergoing a foot pursuit or physical
confrontation, identifying key activities and friend versus foe, and then engaging in a
firefight requiring accuracy and speed of decision-making. Additionally, the use of 300
mg purine alkaloids is a strength to the design as these supplements are often
consumed through capsules and beverages in absolute rather than relative doses.

One limitation, however, was that participants were recruited from law
enforcement, military, and ROTC. Marksmanship training is likely different across these
populations in terms of weapon preference and years of shooting experience. To be fair,
there is also considerable differences in skill and expertise within each of these
populations as well. To address this, all participants experienced the same
familiarization protocol prior to the experimental testing. It is important to note that
these categories of participants were evenly distributed across experimental groups.
Additionally, the marksmanship simulator and airsoft pistol used in this study do not
match outdoor, live-fire conditions used in previous research, but the immediate
feedback provided through the laser and high-speed camera as well as gas blowback of
the pistol provided simulated conditions. A delimitation is that these findings do not
necessarily extend to female tactical personnel. Based on inherent differences in RT
between males and females (Silverman, 2006) as well as the fact that females make up
less than 15% of law enforcement officers and active-duty military personnel, females
were excluded from participating in this study. Further, another delimitation that
reduces consistency with previous research on tactical outcomes is the lack of a sleep
deprivation protocol prior to supplementation. This was not included in this study as law
enforcement officers and military personnel do not always operate under sleep deprived conditions, and the purpose of the study was to determine the effects of the supplements provided under typical operating conditions. Therefore, participants were instructed to maintain normal sleep and wake schedules during the week leading up to the experimental testing session.

Together, the unique design of this study provides compelling evidence for the efficacy of combining a lower dose of caffeine with methylxanthines and theacrine for maintaining vigilance to a similar extent as caffeine alone and maintaining marksmanship without largely increasing DBP. Further, despite its distinct protocol compared to other literature on this topic, this study corresponds with previous findings regarding caffeine on measures of RT, vigilance, and marksmanship and on a combination of caffeine, methylxanthines, and theacrine on hemodynamics during exercise. Lastly, this study is the first to test the effects of this supplementation protocol on tactical performance outcomes and to report felt arousal responses following consumption of a combination of caffeine, methylxanthines, and theacrine.

Conclusions

Both CAF and CMT improved vigilance RT over the 150-min protocol while PLA did not, albeit no differences were observed in vigilance composite score between groups. CAF resulted in large increases in DBP above PLA while CMT did not, though CAF and CMT were not different from each other. Overall, these findings suggest similar overall effects on tactical performance measures between 300 mg caffeine alone and a
combination of 150 mg caffeine, 100 mg methylliberine, and 50 mg theacrine along with slightly more favorable hemodynamic responses following supplementation with the combination compared to caffeine alone. Tactical athletes including law enforcement officers and military personnel can use this supplementation strategy of combined caffeine, methylliberine, and theacrine prior to periods of overwatch to maintain vigilance without experiencing substantial adverse hemodynamic responses induced by caffeine alone.
CHAPTER 6

EFFECTS OF MINIMAL-EQUIPMENT RESISTANCE TRAINING WITH AND WITHOUT BLOOD FLOW RESTRICTION COMPARED TO TRADITIONAL-EQUIPMENT RESISTANCE TRAINING ON MILITARY-RELEVANT PERFORMANCE AND BODY COMPOSITION OUTCOMES

ABSTRACT

The purpose of this study was to compare the effects of minimal-equipment resistance exercise training (RET) with and without blood flow restriction (BFR) to traditional RET on body composition and performance changes following a 6-week training intervention. Fifty-four male and female Reserve Officers’ Training Corps cadets and midshipmen were randomized into one of three groups: traditional-equipment RET (TRAD; n=17), minimal-equipment RET (MIN; n=17), and minimal-equipment RET with BFR (MIN+BFR; n=18). Participants underwent performance and body composition testing pre- and post-training, and measures of intensity and overall workload were evaluated throughout the study. Performance assessments included the Army Combat Fitness Test (ACFT), countermovement vertical jump, 3RM bench press, and VO$_{2\text{max}}$, and body composition assessments included body fat percentage, fat-free mass, and muscle and tendon thickness. All groups trained four days per week following a full-body routine. Data were analyzed via mixed-effects models to test for Group-by-Time interactions, main effects of Group and Time, as well as the effects of Sex with an $\alpha$-
level of 0.05. Group-by-Time interactions were found for 3RM trap bar deadlift and 3RM bench press (P<0.004), and post-hoc tests revealed improvements from pre- to post-training on both tests in all groups (P<0.034) with the largest improvements for TRAD. Time main effects were found for all other performance variables, including ACFT score (P≤0.035). Time main effects were also found for body composition measures, including body fat percentage, fat-free mass, and muscle thickness (P≤0.017). A Sex-by-Time interaction was found for 3RM deadlift (P=0.008), and a Sex-by-Group-by-Time interaction was found for 3RM bench press (P=0.018). A Group-by-Time interaction for blood lactate (P<0.001), and Group main effects for heart rate (P<0.001) and workload variables (P<0.008) indicated higher intensity and overall workloads for MIN and MIN+BFR compared to TRAD. These findings show RET with minimal equipment improves multiple aspects of human performance and body composition over six weeks. The greater improvements in muscular strength for TRAD emphasize the importance of training specificity on this metric. The addition of BFR did not result in greater improvements in performance or body composition following minimal-equipment RET. Males made larger improvements in strength throughout the study compared to females. It was also found that MIN+BFR was more effective than MIN for improving 3RM bench press for males while the opposite was found for females. Differences in intensity and workloads indicate MIN and MIN+BFR trained at a higher exertion level than TRAD, though adaptations were similar between groups. In conclusion, the findings suggest military personnel can improve ACFT score along with other aspects of performance and body composition during periods of limited access to traditional RET
equipment by training with portable, field-expedient RET equipment, but the use of traditional equipment appears to bolster adaptations in muscular strength.

INTRODUCTION

The United States Department of Defense is made up of various military branches, the largest of which is the United States Army, consisting of over one million active-duty, national guard, and reserve service members as of 2019 (Army, 2019). Service members are expected to meet specific physical performance standards throughout their careers based on military occupational specialty, with each branch implementing its own version of a physical fitness assessment to evaluate the achievement of these standards. Recently, the Army replaced the Army Physical Fitness Test, which simply assessed muscular endurance and aerobic capacity, with the newly-developed Army Combat Fitness Test (ACFT) consisting of six events that assess muscular power, strength, endurance, anaerobic capacity, and aerobic capacity. Following this change, one concern that arose is the perceived reliance on heavy, non-portable, and expensive resistance exercise training (RET) equipment, such as power racks, barbells, discs, etc. This thought may stem from previous research showing the efficacy of traditional RET on these aspects of human performance while typical field-based training does not appear to offer the same benefits, as it is often performed with an emphasis on endurance training and relies primarily on resistance via one’s own body mass (Kraemer et al., 2001).
The most studied training program in this population is concurrent in nature by combining both resistance and endurance training. Although the literature surrounding concurrent training shows an attenuation of improvements in muscular power and strength in resistance-trained individuals starting with the seminal work by Hickson (1980), this training modality is essential for concomitantly improving both anaerobic and aerobic performance outcomes (Wilson et al., 2012). As such, Knapik (1997), Harman et al. (1997), and Nindl et al. (2017) all showed improvements in military-specific task performance including 1-repetition max (RM) box lifts, 15- or 18.1-kg box lifts and carries, and 3.2-km ruck time following 14-, 24-, and 24-week concurrent training programs, respectively. In a comprehensive comparison of traditional-equipment training to minimal equipment training in female Army soldiers and recruitment-age civilians, Kraemer et al. (2001) investigated differences between 24-week periodized programs focused on full-body strength training, field-based plyometric, partner-resisted training, and endurance training only. Notable differences included greater improvements in 1RM squat and bench press strength following full-body training compared to field training and endurance only training (Kraemer et al., 2001). These results not only demonstrate the efficacy and importance of full-body RET with traditional equipment, but also suggest that field training, specifically the program prescribed in this study, does not confer similar benefits on improving muscular power and strength, which are important aspects of performance for the tactical athlete.

One explanation for the greater performance benefits often observed with traditional equipment training compared to field-based training is the role of load,
which refers to “the amount of weight assigned to an exercise set” (Haff & Triplett, 2016). A 2017 meta-analysis and systematic review concluded that high-load training protocols in which participants train with loads ≥12RM or ~67% 1RM results in more favorable improvements in 1RM isotonic strength (Schoenfeld et al., 2017). Regarding muscular power, the role of load does not appear to have been directly tested, though multiple speculative review articles have been published on the topic (Haff & Nimphius, 2012; Hansen & Cronin, 2009; Kawamori & Haff, 2004; Taber et al., 2016). Generally, “explosive-type” training seems to improve movement-specific muscular power compared to higher-load RET. This is consistent with National Strength and Conditioning Association (NSCA) guidelines, in which loads recommended for developing muscular power are lower than those for muscular strength (80-90% for single-effort events and 75-85% for multiple-effort events), albeit these loads would not be considered “low.” Alternately, muscular endurance, another important aspect of performance, has been shown to improve by a greater extent following low-load training compared to high-load training (Campos et al., 2002).

In addition to load, metabolic stress is another major factor by which muscular adaptations occur (Wackerhage et al., 2019). Low-load training with high repetitions alone can increase metabolic stress during exercise to a greater extent than high-load training with low repetitions (Gonzalez et al., 2015). Blood flow restriction (BFR) exercise is a method of exercise which employs the use of cuffs placed snugly at the proximal limb, reducing arterial blood flow to the periphery and occluding venous return. This modality can further amplify the metabolic effect of low-load training and has been
shown to augment acute physiological responses to exercise (Suga et al., 2009). Ultimately, these effects may bolster chronic adaptations regarding skeletal muscle hypertrophy and performance outcomes, such as muscular power, strength, and endurance. Most of the research on this topic has focused on the outcome of muscular hypertrophy, particularly showing preferential type I muscle fiber hypertrophy (Bjornsen et al., 2019), with more limited research on the role of low-load RET with BFR on performance metrics. Recently, however, two meta-analyses were conducted on the effects of low-load BFR training compared to traditional high-load RET on muscular strength (Gronfeldt et al., 2020; Lixandrao et al., 2018). The results of these separate analyses were contradictory, as one revealed superior effects of high-load RET compared to low-load BFR on muscular strength (Lixandrao et al., 2018; Lixandrao et al., 2021) and the other showed no significant differences in strength improvements between high-load RET and low-load RET with BFR (Gronfeldt et al., 2020). Yasuda et al. (2011) showed high-load (75% 1RM) training resulted in greater improvements in 1RM bench press and isometric triceps extension strength compared to low-load (30% 1RM) RET with BFR over six weeks in 40 young recreationally trained males. However, Korkmaz et al. (2020) recently found greater improvements in leg extensor isokinetic strength following six weeks of low-load (30% 1RM) BFR training compared to high-load (80% 1RM) training in 23 male soccer athletes. These equivocal findings comparing high-load to low-load training with BFR show the need for more research on this topic to determine if low-load BFR training can be as, if not more, effective than high-load training.
BFR seems to bolster adaptations to RET through the production of an ischemic environment and higher degrees of extra- and intramuscular osmotic pressure which appear to have subsequent effects, leading to greater degrees of metabolic stress and larger increases in concentrations of circulating anabolic hormones and inflammatory cytokines (Rossi et al., 2018). Several studies have shown greater acute increases in blood lactate, cortisol, and growth hormone (GH) in the 1-h period following low-load BFR exercise compared to non-restricted exercise or an ischemic control session (Fujita et al., 2007; Pierce et al., 2006). Though some researchers have argued that GH, particularly acute increases with exercise, exerts minimal direct anabolic effects in adult skeletal muscle (Rennie, 2003; Schoenfeld, 2013; West & Phillips, 2010), increases in basal GH levels have been shown to be related to improvements in deadlift strength in female collegiate soccer players over the course of a competitive season (McFadden et al., 2020). Based on the impact of BFR training on metabolic stress and GH secretion, the role of insulin-like growth factor (IGF)-1 on mediating the adaptative response is of interest, though limited data exist on this topic. Along with GH and IGF-1, a recent review discussed the effects of BFR exercise on inflammation and circulating cytokines (Rossi et al., 2018). This inflammatory response may be driven by ischemia and glycogen depletion (Febbraio & Pedersen, 2005; Gute et al., 1998). Together, this lends support to the idea that metabolic stress, particularly the heightened response observed during BFR exercise, and the endocrine and inflammatory responses result in a physiological environment conducive to augmenting adaptations to training and improving performance.
Overall, it is pivotal for military personnel to train during periods of limited access to traditional exercise equipment to improve or maintain fitness. However, RET in field settings has been consistently shown to be inferior to traditional RET, likely attributed to the inability to use high loads, as load is a primary driver in performance and body composition adaptations to resistance exercise. However, heightened metabolic stress along with endocrinological and immunological responses to low-load high-repetition exercise also serve as important stimuli for inducing favorable performance adaptations, which can be further augmented through BFR. Ultimately, these stimuli and subsequent responses may hold greater relevance for multiple aspects of performance beyond strength and hypertrophy that have direct impact on tactical performance. Therefore, the primary purpose of this investigation was to assess the efficacy of six weeks of minimal-equipment RET with and without BFR on the military-relevant performance tasks of the ACFT compared to traditional-equipment RET in male and female Reserve Officers’ Training Corps (ROTC) cadets and midshipmen. The secondary purposes include examining the effects of minimal-equipment training with and without BFR on laboratory-based performance measures of muscular power, upper-body muscular strength, and aerobic capacity compared to traditional RET in ROTC cadets and midshipmen. Additionally, sex differences in these responses were also examined. It was hypothesized that minimal-equipment RET with BFR would produce similar adaptations in performance and body composition as traditional-equipment RET while minimal-equipment alone would result in lesser improvements.
METHODS

Participants

Fifty-four ROTC cadets and midshipmen (40.7% female) representing the United States Army, Navy, Marines, and Air Force were recruited to participate in this randomized, parallel-group, between-subjects, clinical trial. At the time of recruitment, all participants were between the ages of 18 and 35 years, were deemed in good health according to a medical history questionnaire with no metabolic disorders, hepatorenal, musculoskeletal, autoimmune, or neurological diseases, heart disease, not currently using thyroid, hyperlipidemic, hypoglycemic, anti-hypertensive, or anti-coagulant medications, and were not pregnant or lactating. All participants were cleared to participate in physical training with ROTC. To avoid undue coercion, an ombudsman was present during recruitment, and the ROTC cadre was not present. All participants provided written informed consent, and all protocols and procedures were approved by the University of South Carolina Institutional Review Board and the United States Department of Defense Human Research Protection Office. This study was registered on ClinicalTrials.gov (NCT05003778).

Training intervention

Participants were stratified by sex and randomly assigned to one of three groups: traditional-equipment RET (TRAD; n=17 [41.2% female]), minimal-equipment RET (MIN; n=17 [37.5% female]), and minimal-equipment RET with BFR (MIN+BFR; n=18 [37.5% female]). All groups trained four days per week for six weeks follow a full-body routine. Progressive overload was implemented following NSCA guidelines. Briefly, once
participants successfully completed all sets and repetitions at a rating of perceived exertion (RPE) below the desired target with proper technique, the load was increased. All sessions were led or supervised by an NSCA Certified Strength and Conditioning Specialist (CSCS).

TRAD exercises included movements such as power clean, trap-bar deadlift, bench press, back squat, overhead press, single-joint movements, core movements, etc. Rest periods lasted three minutes for exercises prescribed with six or fewer repetitions and two minutes for exercises prescribed with 10 or more repetitions. Participants alternated between two different workouts throughout the study. RET prescription for TRAD is shown in Table 6.1.

Participants in MIN and MIN+BFR followed exercise movement patterns that were matched to those used in the TRAD protocol. All exercises were performed using highly portable, field-expedient equipment. A single kit including an empty sandbag, empty weight vest, five resistance bands, and a suspension trainer weighed 5.5 kg. Exercises included movements such as sandbag power clean, resistance band deadlift, push-up, weight-vest suspension-trainer squat, sandbag overhead press, single-joint movements, core movements, etc. Rest periods lasted three minutes for exercises prescribed with three or fewer repetitions and one minute for the remaining exercises. To match for total exercise duration across groups, additional exercises were added to each workout. Participants in the MIN+BFR groups training followed the same prescription as MIN in terms of exercise selection with the addition of portable BFR cuffs (described below). Participants alternated between two different workouts throughout
the study. The prescribed repetition scheme was selected as this is commonly used in BFR research (Patterson et al., 2019). RET prescription for MIN and MIN+BFR is shown in Table 6.1.

All training associated with this study occurred in addition to group-based ROTC training. As a group, ROTC cadets typically train 2-5 times per week which consists of mainly aerobic and field training. Though cadets and midshipmen do not follow specific training guidelines during the summer, they are expected to maintain physical training and physical fitness testing standards. Participants in the current study were not removed from typical ROTC training, but this additional RET was consistent with their usual supplemental training performed outside of ROTC duties. Thus, participation in this study did not impact other aspects of ROTC training including the development of leadership and comradery among cadets and midshipmen.

Blood flow restriction

BFR training was performed using portable, elastic, pneumatic cuffs (upper body width: 5.5 cm, lower body width: 7 cm; BStrong, Park City, UT, USA). This method combines the safety and accuracy of doppler-based cuff systems used in clinicals settings and the convenience of portable tourniquets and elastic wraps used in field settings. A set of upper- and lower-body cuffs and a hand-held manometer weighed 0.5 kg. These cuffs have been used previously (Early et al., 2020; Stray-Gundersen et al., 2020). For the MIN+BFR group, lab personnel placed the appropriate cuff around the proximal portion of participants’ arms and legs at the beginning of each training session. Cuffs were
inflated to appropriate pressures according to manufacturer and existing guidelines based on cuff size, limb girth, and participant tolerability (Bagley et al., 2015; Machek et al., 2020; Patterson et al., 2019). Participant comfort was assessed qualitatively throughout the training session, and cuff pressure was adjusted accordingly. If tolerable, the cuffs remained inflated for all working sets of the training session as suggested to be most effective for maximizing the training stimulus through increasing metabolic stress and intracellular osmotic pressure and altering local oxygen kinetics (Patterson et al., 2019). After every 2-3 exercises, the cuffs were deflated and reinflated during the 1-min rest period to ensure the cuffs were inflated to the appropriate pressure. If participants reported extreme discomfort, each cuff was deflated as requested.

Initial cuff sizes and pressures were determined according to manufacturer’s guidelines, and cuff pressures were adjusted throughout the 6-week training intervention using subjective ratings including Borg’s CR10 scale based on a combination of manufacturer guidelines and previous research (Table 6.2). If the participant experienced severe muscular discomfort at any point, cuffs were completely deflated before being reinflated to 50 mmHg lower than previous cuff pressure for the remainder of the session, if tolerable. Further, if the participant experienced nausea at any point, cuffs were completely deflated before being reinflated to 100 mmHg lower than previous cuff pressure for the remainder of the session, if tolerable. For the subsequent session, cuff pressure was reduced by 100 mmHg.
Blood sample collection, processing, and analysis

Blood samples were collected from an antecubital vein using standardized phlebotomy techniques into plastic serum-specific vacutainer tubes (Becton Dickinson, Franklin Lakes, NJ, USA). Samples were allowed to stand at room temperature for 30 min to clot before being centrifuged at 1600 g for 10 min (642E, Drucker Diagnostics, Port Matilda, PA, USA). The supernatant was transferred into 1.5-mL aliquots using disposable pipettes and were stored at -80°C until analysis.

Serum samples were analyzed for cortisol, GH, and IGF-1. Frozen samples were shipped on dry ice to a clinical laboratory improvement amendments-certified lab (BioReference Laboratories, Elmwood Park, NJ, USA) for analysis of cortisol, GH, and IGF-1.

Body composition

Height was measured using a stadiometer, and body mass was measured using a calibrated scale. Body composition was assessed via air displacement plethysmography (BODPOD, COSMED Inc., Concord, CA, USA; Dempster & Aitkens, 1995; McCrory et al., 1995). Participants wore non-padded compression shorts (and non-padded sports bras for females) and refrained from food for ≥2 hours, caffeine for ≥12 hours, and moderate-to-vigorous physical activity or exercise for ≥24 hours. All calibrations and tests were conducted according to manufacturer’s guidelines. A prediction equation was used to determine thoracic gas volume (McCrory et al., 1998), and the Siri model was used to determine body fat percentage from body density (Siri, 1961).
Biceps brachii and quadriceps (rectus femoris and total quadriceps) muscle and quadriceps tendon thicknesses were measured with a 10 MHz ultrasound transducer (iQ, Butterfly Network Inc., Guilford, CT, USA). The transducer was set to B-mode on the musculoskeletal setting, which is recommended for imaging muscles and tendons, with gain set to 50% and depth optimized to capture the best image. Participants laid supine on a table. A researcher measured the distance between the acromion of the scapula and the lateral epicondyle of the humerus and made a mark at 60% of the distance from the acromion on the most anterior portion of the upper arm. A trained ultrasound technician imaged at this point with the probe perpendicular to the humerus to determine biceps brachii thickness (Ogasawara et al., 2012; Schoenfeld et al., 2016).

Next, an object was placed under the participant’s knee to achieve passive knee flexion of 20-30 degrees and ensure relaxation of the quadriceps. A researcher measured from the greater trochanter of the femur to the lateral epicondyle of the femur and made a mark at 50% of the distance from the greater trochanter on the most anterior portion of the upper leg. The technician imaged at this point with the probe perpendicular to the femur to determine rectus femoris and total quadriceps thicknesses (Blazevich et al., 2009; Loenneke et al., 2017; Matta et al., 2017). The technician then imaged just above the knee, with the image partially obstructed by the patella to determine quadriceps tendon thickness.

Three images at each site were obtained. All thickness measurements were determined using a straight line from the most superficial to the deepest aspect of the structure (muscle or tendon) in the center of the image. All images were analyzed in
triplicate using an image-processing program (ImageJ, National Institutes of Health, Bethesda, MD, USA), and mean thickness of all three images at each site was calculated.

Subjective measures of training distress, systemic fatigue, exertion, and discomfort

At the beginning of each training session, delayed onset muscle soreness (DOMS) was assessed using a 100-mm visual analog scale to quantify recovery status and residual impacts of previous training (Arent et al., 2010). During the first day of pre- and post-testing and on the first day of each training week, the multicomponent training distress scale (MTDS) was completed to assess training distress and systemic fatigue. This 22-item questionnaire consists of adjectives and phrases that are rated based on frequency of feeling over the past 24 hours according to a 5-point Likert scale ranging from “not at all” to “extremely” (Main & Grove, 2009). Following each set, participants also provided an RPE according to Borg’s modified 10-point RPE scale (Borg, 1998). Following each training session, participants provided an RPE according to Borg’s modified 10-point RPE scale to reflect exertion throughout the entire session. This was used to calculate a session RPE (sRPE) workload score as the product of RPE and duration (Haddad et al., 2017). Additionally, participants in MIN+BFR provided a rating of perceived pain or discomfort according to Borg’s CR10 scale (Borg, 1998) with the prompt originally described by Loenneke et al. (2011).
Metabolic measures

During all training sessions, heart rate was continuously monitored using recordable chest strap heart rate monitors (TeamPro, Polar Electro Co., Woodbury, NY, USA). Heart rate responses were used to calculate Edwards training impulse (TRIMP; Edwards, 1993). During the final training sessions in weeks 1, 3, and 6, blood lactate was measured before, during, and immediately following the completion of the training session. The measurement during the session occurred immediately following an exercise as close to the middle of the session as possible, which remained constant throughout the weeks. For the BFR group, the cuffs remained inflated during the mid- and post-exercise measurements. A lancet and lactate analyzer (Lactate Plus, Nova Biomedical, Waltham, MA, USA) were used to measure blood lactate from the finger and the ear lobe at all timepoints due to the unknown effects of BFR on peripheral lactate concentrations.

Army Combat Fitness Test

The ACFT is a 6-event test described in detail in the ACFT Field Testing Manual (V 1.4 – 20180827). This assessment consists of the following tests (in order): 3RM deadlift, standing power throw, hand release push-up, sprint-drag-carry, leg tuck, and 2-mile run. Each test is scored from 0-100 points, and the highest possible score on the ACFT is 600 points. A minimum score of 60 points is required for each test to pass the assessment, and a minimum score of 70 points is required for each test to achieve the standard for combat roles. The assessment was conducted by the researchers according to the
instructions outlined in the ACFT Field Testing Manual (V 1.4 – 20180827). To limit environmental effects, the first five events of this test occurred at an indoor climate-controlled facility, and the last event occurred at an indoor climate-controlled track.

Laboratory performance measures

Anaerobic peak power was assessed via countermovement vertical jump with the hands-on-hips method using a digital contact mat (Just Jump, Probotics, Huntsville, AL, USA). Participants stood on the mat, performed a countermovement in the downward direction, and jumped as high as possible vertically. The contact mat measured flight time, which was used to calculate jump height by the device. Participants completed three attempts with 30 seconds between efforts. All three attempts were recorded, and the maximum jump height was used for analysis.

Upper-body muscular strength was assessed via 3RM bench press. Participants laid supine on a flat bench with a barbell at approximately eye-level and were instructed to maintain five points of contact according to NSCA guidelines which includes head on the bench, shoulders on the bench, hips on the bench, and both feet on the floor. Following 2-3 warm-up attempts, participants attempted loads assigned by a CSCS estimated to achieve a 3RM. If the set was performed successfully, the load was increased, and participants were provided with 3-5 min of rest. Loads continued to be increased until the participant could not successfully perform three repetitions. All maximum attempts were achieved within five attempts according to NSCA guidelines.
Maximal aerobic capacity was assessed with a treadmill based (T170, HP COSMOS, Traunstein, Germany) graded exercise test following the Bruce protocol and direct gas-exchange (Quark RMR, COSMED, Concord, CA, USA). Participants wore a chest strap heart rate monitor (H10, Polar Electro Co., Woodbury, NY, USA) and were asked to provide an RPE according to Borg’s RPE scale with 30 seconds remaining in each stage and immediately upon completion of the test. Participants were instructed to continue until volitional fatigue and were motivated by lab staff during the test. All calibrations and tests were conducted according to manufacturer’s guidelines. Participants must have achieved three of the following four criteria for a test to be consider valid: a plateau in VO$_2$ with an increase in external exercise intensity, a respiratory-exchange-ratio of 1.1 or greater, a rating of perceived exertion of 18 or greater, and a heart rate within 15 beats of age-predicted maximal heart rate. Following completion of the test, VO$_{2\text{max}}$ was assessed as the highest 30-second average VO$_2$ achieved, and ventilatory threshold was determined as the point at which VCO$_2$ increases nonlinearly from VO$_2$.

Protocol

Day 1: Screening, consenting, questionnaire administration, blood sample collection, and anthropometric testing.

Participants were recruited through local ROTC programs. Potential participants were scheduled to arrive to the University of South Carolina Sport Science Laboratory to undergo screening to determine eligibility and were instructed to arrive normally hydrated following an overnight fast. A screening and medical history questionnaire
consisting of questions relating to inclusion and exclusion criteria was completed. Upon
determination of eligibility to participate, an informed consent form was read and
explained to the participant outlining the study protocols and procedures. Participants
were given time to read the form in its entirety and ask questions before providing
written informed consent. Following screening and consenting, participants completed
the MTDS. Next, participants underwent a blood draw conducted by lab personnel
trained in phlebotomy. Following the blood draw, participants underwent body
composition testing via air displacement plethysmography, and muscle and tendon
thickness was assessed using ultrasound.

Day 2: Army Combat Fitness Test testing.

Participants arrived in a normally hydrated state at least 24 h following Day 1 testing
having refrained from caffeine for ≥12 h and tobacco for ≥48 h. Participants underwent
a standardized dynamic warm-up consisting of 10 movements and several short-
distance sprints lasting ~10 min before completing the entire ACFT in the order specified
by Army regulations.

Day 3: Laboratory performance testing.

Participants arrived at the laboratory in a normally hydrated state at least 48 h following
Day 2 testing having refrained from caffeine for ≥12 h and tobacco for ≥48 h.
Participants completed a standardized dynamic warm-up consisting of 5 min at a self-
selected pace on the treadmill and 10 additional movements lasting ~10 min. Next,
participants performed three attempts of countermovement vertical jump with hands fixed to the hips separated by 30 seconds of rest. After approximately 3 min of rest, participants began the 3RM bench press assessment. After approximately 5 min rest, participants began the maximal aerobic capacity test.

Training intervention

Following completion of the three pre-testing days, participants were randomly assigned into one of the three training groups and completed 24 training sessions over 6 weeks. Upon arrival for all training sessions, participants provided a subjective rating for DOMS. Participants wore a heart rate monitor (Team Pro, Polar Electro Co., Woodbury, NY, USA) throughout all training sessions. At the start of each training week, participants completed the MTDS. During training sessions in weeks 1, 3, and 6, blood lactate concentrations were measured at the finger and ear at pre-, mid-, and post-exercise.

Post-testing

Upon completion of the 6-week training program, participants underwent post-testing following the same protocol as described for Day 1, Day 2, and Day 3 for pre-testing. The first day of post-testing took place ≥48 hours following the final training session, and all testing was completed within a 1-week period. An overview of the entire protocol is shown in Figure 6.1.
Data analysis

One-way analyses of variance were conducted to determine differences in baseline descriptive metrics between groups. For performance, body composition, and blood biomarker assessments, linear mixed-effects models with a random intercept to adjust for between-subject variability were performed to test for Group (TRAD, MIN, MIN+BFR)-by-Time (pre-testing, post-testing) interactions, as well as main effects of Group and Time. For MTDS scores, a linear mixed-effects model with a random intercept to adjust for between-subject variability was performed to test for Group (TRAD, MIN, MIN+BFR)-by-Time (pre-testing, week 2, week 3, week 4, week 5, week 6, post-testing) interactions, as well as main effects of Group and Time. For DOMS, a linear mixed-effects model with a random intercept to adjust for between-subject variability was performed to test for Group (TRAD, MIN, MIN+BFR)-by-Time (week 1, week 2, week 3, week 4, week 5, week 6) interactions, as well as main effects of Group and Time. For blood lactate responses, a linear mixed-effects model with a random intercept to adjust for between-subject variability was performed to test for a Group (TRAD, MIN, MIN+BFR)-by-Site (finger, ear) interaction followed by a Group (TRAD, MIN, MIN+BFR)-by-Time (pre-exercise, mid-exercise, post-exercise) interaction. To assess differences by Sex, mixed-effects models with a random intercept to adjust for between-subject variability were used to test for Sex (male, female)-by-Time (pre-testing, post-testing) and Sex (male, female)-by-Group (TRAD, MIN, MIN+BFR)-by-Time (pre-testing, post-testing) interactions as well as main effects of Sex on all dependent variables. Significant interactions or main effects were followed up with post-hoc pairwise comparisons with
a Tukey adjustment to further explain the effects. An α-level of 0.05 was used to
determine statistical significance. Effect sizes were calculated using Cohen’s d to
determine magnitude of change within groups and differences between groups. All
analyses were conducted and figures were produced using commercially available open-
source statistical software (R; version 4.1.0; Team, 2021) with the lme4 (version 1.1-
27.1; Bates et al., 2015), emmeans (version 1.6.2-1; Lenth, 2021), effectsize (version 0.5;
Ben-Shachar et al., 2020), and ggplot2 (version 3.3.5; Wickham, 2016) packages.
Table 6.1: Exercise prescription for all groups.

<table>
<thead>
<tr>
<th>Day</th>
<th>Exercise</th>
<th>Equipment</th>
<th>Sets</th>
<th>Repetitions</th>
<th>RPE</th>
<th>Rest</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Traditional-Equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Resistance Training</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>High Pull / Hang Clean</td>
<td>BB</td>
<td>3</td>
<td></td>
<td>6-7</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>Trap-bar Deadlift</td>
<td>TB</td>
<td>3</td>
<td>6</td>
<td>8-9</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>Bench Press</td>
<td>BB</td>
<td>3</td>
<td>6</td>
<td>8-9</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>Goblet / Front Squat</td>
<td>KB/DB, BB</td>
<td>3</td>
<td>10</td>
<td>9-10</td>
<td>2 min</td>
</tr>
<tr>
<td></td>
<td>Cable Pulldown</td>
<td>Cable</td>
<td>3</td>
<td>10</td>
<td>9-10</td>
<td>2 min</td>
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<tr>
<td></td>
<td>Pallof Press</td>
<td>Cable</td>
<td>3</td>
<td></td>
<td>6-7</td>
<td>2 min</td>
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<td>2</td>
<td>Push Press</td>
<td>BB</td>
<td>3</td>
<td></td>
<td>6-7</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>Back Squat</td>
<td>BB</td>
<td>3</td>
<td>6</td>
<td>8-9</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>Cable Row</td>
<td>Cable</td>
<td>3</td>
<td>6</td>
<td>8-9</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>Romanian Deadlift</td>
<td>BB</td>
<td>3</td>
<td>10</td>
<td>9-10</td>
<td>2 min</td>
</tr>
<tr>
<td></td>
<td>Military Press</td>
<td>DB, BB</td>
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<td>10</td>
<td>9-10</td>
<td>2 min</td>
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<tr>
<td></td>
<td>Calf Raise</td>
<td>Machine</td>
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<td>10</td>
<td>9-10</td>
<td>2 min</td>
</tr>
<tr>
<td></td>
<td>Stability Ball Crunch</td>
<td>DB</td>
<td>3</td>
<td></td>
<td>6-7</td>
<td>2 min</td>
</tr>
<tr>
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<td>Minimal-Equipment</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>Power Clean</td>
<td>SB</td>
<td>3</td>
<td></td>
<td>6-7</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>Deadlift</td>
<td>SB, RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>8-9</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Push-up</td>
<td>WV</td>
<td>3</td>
<td>30, 15, 15</td>
<td>8-9</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>RFE Split Squat</td>
<td>WV, SB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>TRX Row</td>
<td>WV</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Leg Curl</td>
<td>RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Biceps Curl</td>
<td>SB, RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Calf Raise</td>
<td>WV, SB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Deadbug</td>
<td>-</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td>2</td>
<td>Push Press</td>
<td>SB</td>
<td>3</td>
<td></td>
<td>6-7</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>Lunge</td>
<td>WV, SB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>8-9</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Pull-up</td>
<td>RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>8-9</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Romanian Deadlift</td>
<td>SB, RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Overhead Press</td>
<td>SB, RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Squat</td>
<td>WV, SB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Bent Over Row</td>
<td>RB, SB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Triceps Extension</td>
<td>RB</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td>Plank with Shoulder Tap</td>
<td>-</td>
<td>3</td>
<td>30, 15, 15</td>
<td>9-10</td>
<td>1 min</td>
</tr>
</tbody>
</table>

BB = barbell, TB = trap-bar, KB = kettlebell, DB = dumbbell, SB = sandbag, RB = resistance band, WV = weight vest
Table 6.2. Guidelines used to adjust BFR cuff pressures throughout the 6-week intervention.

<table>
<thead>
<tr>
<th>CR10</th>
<th>Weeks 1-2</th>
<th>Weeks 3-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Increase by 50 mmHg</td>
<td></td>
</tr>
<tr>
<td>3-4</td>
<td>Increase by 25 mmHg</td>
<td>If in this range for 2 consecutive sessions, increase 25 mmHg</td>
</tr>
<tr>
<td>5-7</td>
<td>Maintain</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Decrease by 25 mmHg</td>
<td>If in this range for 2 consecutive sessions, decrease 25 mmHg</td>
</tr>
<tr>
<td>≥9</td>
<td>Decrease by 50 mmHg</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.1. Overview of the experimental protocol.
RESULTS

Participants

Fifty-four (40.7% female) ROTC cadets and midshipmen were enrolled in this study and were randomized into one of the three groups. Participants represented Air Force ROTC (52%), Army ROTC (26%), and Naval ROTC (22%). A chi-square test revealed no differences by military branch between groups ($\chi^2_{4}=5.092, \ P=0.278$). Two participants attritted: one due to COVID-19 isolation and one due to personal reasons. Three participants completed the intervention but were unable to complete performance assessments during post-testing due to injuries sustained during ROTC physical training that occurred between completing the intervention and post-testing. These individuals were included in body composition, metabolic, workload, DOMS analyses (N=52) but not performance, training distress, or endocrine and immune marker analyses (N=49) due to the inability to complete performance testing and potential effects of acute injury on these biomarkers and training distress, especially responses pertaining to physical signs and symptoms. Sample sizes by group and sex for each measure are shown in Table 6.3.

Baseline characteristics

Descriptive baseline statistics for demographic, anthropometric, and performance variables are shown in Table 6.4. One-way ANOVAs showed no significant differences between groups for baseline metrics.
Army Combat Fitness Test

A generalized linear mixed-effects model failed to reveal a Group-by-Time interaction ($\chi^2_{2}=0.623$, $P=0.732$) but showed a Time main effect for ACFT score ($\chi^2_{1}=32.56$, $P<0.01$). Post-hoc tests showed improved ACFT scores in all groups ($P<0.001$; TRAD: $d=0.43$, MIN: $d=0.34$, MIN+BFR: $d=0.31$). Data are shown in Figure 6.2.

ACFT events

When looking at individual ACFT events, a Group-by-Time interaction was observed for 3RM deadlift ($F_{2,46}=5.25$, $P<0.001$). All groups improved from pre- to post-training ($P<0.017$), with the largest improvement for TRAD ($d=0.47$) followed by MIN ($d=0.26$) and MIN+BFR ($d=0.18$). Time main effects were found for 3RM deadlift ($F_{1,46}=58.78$, $P<0.001$), standing power throw ($F_{1,46}=12.16$, $P=0.001$), hand-release push-up ($\chi^2_{1}=4.95$, $P=0.026$), sprint-drag-carry ($F_{1,46}=51.69$, $P<0.001$), leg tuck ($\chi^2_{1}=7.87$, $P=0.005$), and 2-mile run ($F_{1,46}=10.01$, $P=0.003$). Data and effect sizes are shown in Table 6.5.

Laboratory performance

A Group-by-Time interaction was found for 3RM bench press ($F_{2,46}=6.12$, $P=0.004$). All groups improved from pre- to post-training ($P<0.034$), and the largest improvement was found for TRAD ($d=0.24$) followed by MIN+BFR ($d=0.10$) and MIN ($d=0.09$). Time main effects were observed for CMJ height ($F_{1,46}=13.58$, $P<0.001$), 3RM bench press ($F_{1,46}=44.20$, $P<0.001$), and VO$_{2\text{max}}$ ($F_{1,46}=4.70$, $P=0.035$). Data and effect sizes are shown in Table 6.6.
Body composition

Group-by-Time interactions were not found for any body composition variables (P>0.31). Time main effects were found for body mass (F_{1,49}=14.70, P<0.001), body fat percentage (F_{1,49}=65.67, P<0.001), and fat-free mass (F_{1,49}=126.90, P<0.001).

Coefficients of variation (CV) were calculated for all thickness measurements (biceps brachii: CV=2.2%; rectus femoris: CV=1.7%, quadriceps: CV=1.1%, quadriceps tendon: CV=6.0%). Time main effects were found for biceps brachii thickness (F_{1,49}=6.05, P=0.017), rectus femoris thickness (F_{1,49}=14.44, P<0.001), quadriceps thickness (F_{1,49}=33.59, P<0.001), but not quadriceps tendon thickness (F_{1,49}=1.51, P=0.225). Data and effect sizes are shown in Table 6.7.

Metabolic and workload measures

When testing blood La⁻ data for a Group-by-Site interaction, a main effect of Site was found indicating higher values for finger compared to ear regardless of group (F_{1,872.26}=8.47, P=0.004). As such, mean values were calculated for finger and ear blood La⁻ at each timepoint. A Group-by-Time interaction was found for La⁻ (F_{4,406.19}=54.989, P<0.001). Post-hoc tests showed increases from pre- to mid-exercise in all groups (P<0.001) with a further increase at post-exercise in TRAD (P<0.001) and decreases at this timepoint in MIN (P=0.011) and MIN+BFR (P=0.001). MIN and MIN+BFR were both greater than TRAD at mid- and post-exercise (P=0.001) but not pre-exercise (P>0.96). Data are shown in Figure 6.3.
A Group main effect was not observed for session duration ($F_{2,49.03} = 2.71$, $P > 0.076$) or daily RPE ($\chi^2 = 0.283$, $P = 0.868$). Group main effects were found for average heart rate ($F_{2,49.03} = 9.49$, $P < 0.001$), session RPE ($F_{2,49.06} = 7.34$, $P = 0.002$), and Edwards TRIMP ($F_{2,49.02} = 11.84$, $P < 0.001$). Post-hoc tests revealed higher values in MIN and MIN+BFR compared to TRAD for average heart rate ($P < 0.017$), sRPE ($P < 0.008$), and Edwards TRIMP ($P < 0.001$). In all measures, MIN and MIN+BFR were not different from each other ($P > 0.3$). Data are shown in Table 6.8.

MTDS score and DOMS

A Time main effect was found for MTDS score ($\chi^2_{6} = 20.60$, $P = 0.002$). Post-hoc tests showed increases above baseline at week 5 ($P < 0.005$) regardless of group. Data are shown in Figure 6.4. A Group-by-Time interaction was observed for DOMS ($\chi^2_{10} = 40.49$, $P < 0.001$). For TRAD, post-hoc tests showed decreases from baseline at weeks 2 ($P = 0.018$) and 3 ($P = 0.006$) but not weeks 4, 5, or 6 ($P > 0.46$). For MIN, post-hoc tests revealed no changes from baseline throughout the intervention ($P > 0.65$). For MIN+BFR, post-hoc tests showed DOMS was lower in week 2 compared to baseline ($P = 0.005$) and higher in week 6 compared to baseline ($P < 0.001$). No differences were found between groups within any week ($P > 0.21$). Data are shown in Figure 6.5.

Basal endocrine and immune markers

No Group-by-Time interactions were found for basal cortisol, GH, or IGF-1 ($P > 0.09$). A Time main effect was found for IGF-1 ($F_{1,46} = 12.69$, $P < 0.001$) but not cortisol or GH.
Regardless of group, basal IGF-1 levels decreased from pre- to post-training (P<0.001). Data and effect sizes are shown in Table 6.9.

Sex differences

A three-way Sex-by-Group-by-Time interaction was found for 3RM bench press (F_{2,43}=4.41, P=0.018). To explain this interaction, post-hoc tests were conducted on males and females separately. For males, improvements from pre- to post-testing were observed for TRAD (P<0.001, d=0.41) and MIN+BFR (P=0.002, d=0.26) but not MIN (P=0.575, d=0.05). For females, improvements from pre- to post-testing were observed for TRAD (P<0.001, d=0.74) and MIN (P=0.005, d=0.49) but not MIN+BFR (P=1.00, d=0.00). Data are shown in Figure 6.6. A Sex-by-Time interaction was found for 3RM deadlift (F_{1,43}=7.86, P=0.008). Regardless of group, post-hoc tests revealed improvements from pre- to post-testing in males (P<0.001, d=0.49) and females (P=0.007, d=0.45), albeit the magnitude of this improvement was greater in males (Δ=12.2 kg; d=0.49) compared to females (Δ=5.6 kg; d=0.45). Further, Sex main effects were observed for all performance (P<0.001) and body composition variables (P≤0.03) with the exception of quadriceps tendon thickness (P=0.705). Post-hoc tests showed males had a higher ACFT score, 3RM deadlift, standing power throw, hand-release push-up, leg tuck, CMJ height, 3RM bench press, VO2max, body mass, fat-free mass, biceps brachii muscle thickness, rectus femoris thickness, and quadriceps thickness as well as lower sprint-drag-carry, 2-mile run time, and body fat percentage compared to females regardless of time (P<0.05).
A Sex-by-Time interaction was observed for La\textsuperscript{−} (F\textsubscript{2,400}=10.59, P<0.001). Post-hoc tests showed differences between males and females at mid- (P<0.001) and post-exercise (P<0.001) regardless of group. No Sex-by-Group interactions were found for any workload variables (P>0.80). No Sex-by-Group or Sex-by-Group-by-Time interactions were found for MTDS (P>0.89). A Sex-by-Group-by-Time interaction was found for DOMS (χ\textsuperscript{2}\textsubscript{10}=40.49, P<0.001). For females, post-hoc tests showed lower DOMS compared to week 1 in weeks 2 (P<0.001) and 3 (P=0.060) for TRAD, higher DOMS compared to week 1 in weeks 2 (P=0.013) and 5 (P=0.025) for MIN, and no changes over time for MIN+BFR (P>0.77). For males, no changes were observed for TRAD (P>0.11), lower DOMS compared to week 1 was found in week 2 (P=0.05) for MIN, and lower DOMS compared to week 1 was found in week 2 (P=0.003) along with higher DOMS compared to week 1 in week 6 (P<0.001) in MIN+BFR.

A Sex-by-Time interaction was found for cortisol (F\textsubscript{1,43}=7.17, P=0.010), and post-hoc tests showed females exhibited a decrease from pre- to post-testing (P=0.003) while males did not (P=0.793). Females also exhibited higher cortisol levels than males at pre- (P<0.001) and post-testing (P=0.047). No Sex-by-Group or Sex-by-Group-by-Time interactions were found for GH (P>0.487) or IGF-1 (P>0.626). A Sex main effect was found for GH (F\textsubscript{1,35}=20.54, P<0.001) indicating females exhibited higher GH than males regardless of group and time.
Table 6.3. Sample sizes by group and sex.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Sex</th>
<th>TRAD</th>
<th>MIN</th>
<th>MIN+BFR</th>
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<tr>
<td></td>
<td>Overall</td>
<td>17</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>7</td>
<td>6</td>
<td>6</td>
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<tr>
<td></td>
<td>Overall</td>
<td>17</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>10</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td></td>
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<td>Performance, MTDS, Endocrine Markers (n)</td>
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<td></td>
</tr>
<tr>
<td>Body Composition, Metabolic and Workload Measures, DOMS (n)</td>
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Table 6.4. Baseline anthropometric and performance characteristics by group and sex.

<table>
<thead>
<tr>
<th>Measure</th>
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<th>MIN</th>
<th>MIN+BFR</th>
<th>p-value</th>
</tr>
</thead>
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<tr>
<td>Age (y)</td>
<td>Overall</td>
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<td>20.3±1.3</td>
<td>20.1±1.7</td>
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</tr>
<tr>
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<td>20.6±1.5</td>
<td>21.0±1.2</td>
<td>20.4±2.0</td>
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<tr>
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<td>Height (cm)</td>
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<td>164±8</td>
<td>163±9</td>
<td>0.910</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>Overall</td>
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<td>73.6±13.6</td>
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</tr>
<tr>
<td></td>
<td>Male</td>
<td>81.7±12.3</td>
<td>77.4±11.1</td>
<td>82.6±9.1</td>
<td>0.499</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>62.7±7.0</td>
<td>66.6±16.0</td>
<td>63.6±12.3</td>
<td>0.837</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>Overall</td>
<td>21.2±7.8</td>
<td>21.1±10.1</td>
<td>21.6±8.9</td>
<td>0.994</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>18.3±7.5</td>
<td>15.5±4.6</td>
<td>18.1±8.8</td>
<td>0.589</td>
</tr>
<tr>
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<td>Female</td>
<td>25.3±6.6</td>
<td>31.5±9.3</td>
<td>27.1±6.0</td>
<td>0.319</td>
</tr>
<tr>
<td>ACFT Score (points)</td>
<td>Overall</td>
<td>399±98</td>
<td>395±103</td>
<td>390±97</td>
<td>0.972</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>457±80</td>
<td>462±59</td>
<td>436±88</td>
<td>0.737</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>315±45</td>
<td>284±42</td>
<td>314±52</td>
<td>0.440</td>
</tr>
<tr>
<td>CMJ Height (cm)</td>
<td>Overall</td>
<td>46.3±7.7</td>
<td>48.8±11.4</td>
<td>45.7±8.3</td>
<td>0.621</td>
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<td>Male</td>
<td>50.3±6.6</td>
<td>54.7±8.2</td>
<td>48.5±8.4</td>
<td>0.208</td>
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<tr>
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<td>Female</td>
<td>40.7±5.5</td>
<td>38.9±8.9</td>
<td>41.1±6.3</td>
<td>0.843</td>
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<tr>
<td>3RM Bench Press (kg)</td>
<td>Overall</td>
<td>62±26</td>
<td>60±25</td>
<td>62±23</td>
<td>0.970</td>
</tr>
<tr>
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<td>Male</td>
<td>81±15</td>
<td>76±16</td>
<td>77±16</td>
<td>0.791</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>36±9</td>
<td>33±10</td>
<td>37±6</td>
<td>0.702</td>
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<tr>
<td>VO₂max (mL/kg/min)</td>
<td>Overall</td>
<td>47.8±9.1</td>
<td>46.0±8.0</td>
<td>47.4±8.0</td>
<td>0.831</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>50.6±9.3</td>
<td>50.4±5.3</td>
<td>50.8±8.2</td>
<td>0.993</td>
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<td>Female</td>
<td>43.6±7.7</td>
<td>38.8±6.6</td>
<td>41.8±3.6</td>
<td>0.411</td>
</tr>
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</table>

Data are presented as mean±SD. P-value shows result of one-way ANOVAs.
Figure 6.2. Changes in ACFT performance across groups.
Table 6.5. Changes in individual ACFT event performance by group and sex.

<table>
<thead>
<tr>
<th>Measure</th>
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<th>MIN+BFR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>d</td>
</tr>
<tr>
<td>Deadlift 3RM (kg)</td>
<td>Overall</td>
<td>105±29</td>
<td>120±34</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>124±21</td>
<td>142±24</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>78±14</td>
<td>88±14</td>
<td>0.71</td>
</tr>
<tr>
<td>Standing Power Throw (m)</td>
<td>Overall</td>
<td>7.4±2.4</td>
<td>7.8±2.3</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>8.9±1.5</td>
<td>9.2±1.8</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>5.2±1.3</td>
<td>5.9±0.8</td>
<td>0.60</td>
</tr>
<tr>
<td>Hand-release Push-up (count)</td>
<td>Overall</td>
<td>30±12</td>
<td>34±11</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>36±11</td>
<td>40±10</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>20±6</td>
<td>25±6</td>
<td>0.84</td>
</tr>
<tr>
<td>Sprint-Drag-Carry (s)</td>
<td>Overall</td>
<td>128±27</td>
<td>117±23</td>
<td>-0.44</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>110±12</td>
<td>101±10</td>
<td>-0.82</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>152±23</td>
<td>138±19</td>
<td>-0.67</td>
</tr>
<tr>
<td>Leg Tuck (count)</td>
<td>Overall</td>
<td>4±5</td>
<td>6±6</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>6±5</td>
<td>9±6</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>1±2</td>
<td>1±2</td>
<td>-0.34</td>
</tr>
<tr>
<td>2-mile Run Time (min)</td>
<td>Overall</td>
<td>17.8±2.8</td>
<td>17.4±2.8</td>
<td>-0.12</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>17.1±3.0</td>
<td>16.7±2.3</td>
<td>-0.14</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>18.8±2.4</td>
<td>18.5±3.2</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

Data are presented as mean±SD. Cohen’s d represents magnitude of change within each group.
Table 6.6. Changes in laboratory performance measures by group and sex.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Sex</th>
<th>TRAD</th>
<th></th>
<th>MIN</th>
<th></th>
<th>MIN+BFR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>d</td>
<td>Pre</td>
<td>Post</td>
<td></td>
<td>d</td>
</tr>
<tr>
<td>CMJ Height (cm)</td>
<td>Overall</td>
<td>46.3±7.7</td>
<td>0.38</td>
<td>48.8±11.4</td>
<td>0.09</td>
<td>45.7±8.3</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>50.3±6.6</td>
<td>0.57</td>
<td>54.7±8.2</td>
<td>0.01</td>
<td>48.5±8.4</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>40.7±5.5</td>
<td>0.40</td>
<td>38.9±8.9</td>
<td>0.29</td>
<td>41.1±6.3</td>
<td>0.07</td>
</tr>
<tr>
<td>3RM Bench Press (kg)</td>
<td>Overall</td>
<td>62±26</td>
<td>0.24</td>
<td>60±25</td>
<td>0.09</td>
<td>62±23</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>81±15</td>
<td>0.41</td>
<td>76±16</td>
<td>0.05</td>
<td>77±16</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>36±9</td>
<td>0.74</td>
<td>33±10</td>
<td>0.49</td>
<td>37±6</td>
<td>0.00</td>
</tr>
<tr>
<td>VO₂ max (mL/kg/min)</td>
<td>Overall</td>
<td>47.8±9.1</td>
<td>0.05</td>
<td>46.0±8.0</td>
<td>0.31</td>
<td>47.4±8.0</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>50.6±9.3</td>
<td>0.00</td>
<td>50.4±5.3</td>
<td>0.30</td>
<td>50.8±8.2</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>43.6±7.7</td>
<td>0.13</td>
<td>38.8±6.6</td>
<td>0.57</td>
<td>41.8±3.6</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Data are presented as mean±SD. Cohen’s d represents magnitude of change within each group.
Table 6.7. Changes in body composition measures by group and sex.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Sex</th>
<th>TRAD</th>
<th>MIN</th>
<th>MIN+BFR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>Overall</td>
<td>73.9±14.1</td>
<td>74.4±14.4</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>81.7±12.3</td>
<td>82.2±12.4</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>62.7±7.0</td>
<td>63.3±7.2</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>21.2±7.8</td>
<td>19.0±7.5</td>
<td>-0.28</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>18.3±7.5</td>
<td>16.0±6.8</td>
<td>-0.32</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>25.3±6.6</td>
<td>23.4±6.6</td>
<td>-0.29</td>
</tr>
<tr>
<td>Fat-free Mass (kg)</td>
<td>Overall</td>
<td>58.1±11.5</td>
<td>60.2±11.8</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>66.1±5.8</td>
<td>68.4±6.2</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>46.8±6.8</td>
<td>48.5±6.7</td>
<td>0.25</td>
</tr>
<tr>
<td>Biceps Brachii Thickness (cm)</td>
<td>Overall</td>
<td>2.6±0.5</td>
<td>2.7±0.6</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>2.9±0.4</td>
<td>3.1±0.5</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>2.2±0.4</td>
<td>2.3±0.3</td>
<td>0.16</td>
</tr>
<tr>
<td>Rectus Femoris Thickness (cm)</td>
<td>Overall</td>
<td>2.2±0.4</td>
<td>2.4±0.3</td>
<td>0.55</td>
</tr>
<tr>
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<td>Male</td>
<td>2.3±0.4</td>
<td>2.6±0.3</td>
<td>0.95</td>
</tr>
<tr>
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<td>Female</td>
<td>2.1±0.4</td>
<td>2.2±0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>Quadriceps Thickness (cm)</td>
<td>Overall</td>
<td>4.3±0.8</td>
<td>4.9±0.8</td>
<td>0.80</td>
</tr>
<tr>
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<td>Male</td>
<td>4.7±0.8</td>
<td>5.4±0.7</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>3.7±0.4</td>
<td>4.3±0.3</td>
<td>1.37</td>
</tr>
<tr>
<td>Quadriceps Tendon Thickness (mm)</td>
<td>Overall</td>
<td>6.1±0.9</td>
<td>6.2±1.0</td>
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<td>Male</td>
<td>5.9±1.0</td>
<td>6.1±1.0</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>6.3±0.8</td>
<td>6.4±1.1</td>
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</tr>
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</table>

Data are presented as mean±SD. Cohen’s d represents magnitude of change within each group.
Figure 6.3. Average changes in La⁻ during a typical training session by group.
Table 6.8. Average session workload metrics by group and sex.

<table>
<thead>
<tr>
<th>Measure</th>
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<th>MIN</th>
<th>MIN+BFR</th>
<th>p-value</th>
</tr>
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<tbody>
<tr>
<td>Duration (min)</td>
<td>Overall</td>
<td>72±9</td>
<td>74±10</td>
<td>77±12</td>
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</tr>
<tr>
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<td>Male</td>
<td>71±9</td>
<td>73±9</td>
<td>76±12</td>
<td>0.222</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>72±10</td>
<td>76±10</td>
<td>77±13</td>
<td>0.323</td>
</tr>
<tr>
<td>Daily RPE (au)</td>
<td>Overall</td>
<td>6±1</td>
<td>7±1</td>
<td>7±1</td>
<td>0.868</td>
</tr>
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<td>7±1</td>
<td>7±1</td>
<td>0.931</td>
</tr>
<tr>
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<td>Female</td>
<td>6±2</td>
<td>7±1</td>
<td>7±1</td>
<td>0.934</td>
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<tr>
<td>Average HR (bpm)</td>
<td>Overall</td>
<td>122±13</td>
<td>139±13</td>
<td>134±15</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>119±15</td>
<td>137±11</td>
<td>130±12</td>
<td>0.003</td>
</tr>
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<td>Female</td>
<td>127±15</td>
<td>143±15</td>
<td>139±17</td>
<td>0.056</td>
</tr>
<tr>
<td>sRPE (au)</td>
<td>Overall</td>
<td>446±122</td>
<td>545±110</td>
<td>532±140</td>
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</tr>
<tr>
<td></td>
<td>Male</td>
<td>461±118</td>
<td>543±102</td>
<td>533±136</td>
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</tr>
<tr>
<td></td>
<td>Female</td>
<td>427±124</td>
<td>547±125</td>
<td>532±146</td>
<td>0.032</td>
</tr>
<tr>
<td>Edwards TRIMP (au)</td>
<td>Overall</td>
<td>130±44</td>
<td>193±55</td>
<td>188±55</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>120±44</td>
<td>178±41</td>
<td>171±42</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>146±39</td>
<td>219±66</td>
<td>212±63</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Data are presented as mean±SD. P-value shows result of one-way ANOVAs.
Figure 6.4. Changes in MTDS scores throughout the intervention by group.
Figure 6.5. Changes in DOMS throughout the intervention by group.
Table 6.9. Changes in endocrine markers by group and sex.

<table>
<thead>
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<th>Measure</th>
<th>Sex</th>
<th>TRAD</th>
<th></th>
<th>MIN</th>
<th></th>
<th>MIN+BFR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>d</td>
<td>Pre</td>
<td>Post</td>
<td>d</td>
</tr>
<tr>
<td>Cortisol (nmol/L)</td>
<td>Overall</td>
<td>498±135</td>
<td>426±89</td>
<td>-0.63</td>
<td>515±113</td>
<td>508±124</td>
<td>-0.04</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>428±89</td>
<td>421±64</td>
<td>-0.08</td>
<td>488±86</td>
<td>485±93</td>
<td>-0.03</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>598±129</td>
<td>432±122</td>
<td>-1.33</td>
<td>579±138</td>
<td>570±154</td>
<td>-0.06</td>
</tr>
<tr>
<td>GH (ug/L)</td>
<td>Overall</td>
<td>1.7±3.1</td>
<td>1.1±1.9</td>
<td>-0.41</td>
<td>0.8±1.4</td>
<td>0.9±1.5</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>0.6±1.4</td>
<td>0.2±0.3</td>
<td>-0.32</td>
<td>0.1±0.0</td>
<td>0.2±0.2</td>
<td>0.80</td>
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<tr>
<td></td>
<td>Female</td>
<td>3.8±4.2</td>
<td>2.2±2.7</td>
<td>-0.47</td>
<td>1.9±2.0</td>
<td>2.1±2.0</td>
<td>0.10</td>
</tr>
<tr>
<td>IGF-1 (nmol/L)</td>
<td>Overall</td>
<td>28.7±6.0</td>
<td>26.6±7.6</td>
<td>-0.30</td>
<td>26.6±5.3</td>
<td>23.5±5.4</td>
<td>-0.60</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>28.8±5.9</td>
<td>26.2±5.4</td>
<td>-0.46</td>
<td>25.2±5.7</td>
<td>22.5±5.6</td>
<td>-0.48</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>28.4±6.7</td>
<td>27.2±10.4</td>
<td>-0.14</td>
<td>27.9±4.4</td>
<td>23.9±5.1</td>
<td>-0.84</td>
</tr>
</tbody>
</table>

Data are presented as mean±SD. Cohen’s d represents magnitude of change within each group.
Figure 6.6. Changes in 3RM bench press performance across groups by sex.
DISCUSSION

The primary purpose of this study was to assess the effects of six weeks of RET using minimal equipment with and without BFR on ACFT performance and to compare those results to traditional-equipment RET. The results show that all training approaches improved ACFT score along with other aspects of performance to a similar degree. This finding is meaningful and suggests that field-expedient minimal-equipment RET can improve military-relevant composite performance to the same extent as traditional-equipment RET, providing evidence against the idea that training for tactical performance requires access to heavy, non-portable, and expensive RET equipment. However, when looking at individual performance outcomes, a difference between groups was found in isotonic muscular strength. Despite improvements from pre- to post-training in both MIN and MIN+BFR, this effect was greater for both 3RM trap-bar deadlift and bench press following traditional-equipment RET. Further, no differences in any performance or body composition measures were observed between MIN and MIN+BFR as both groups improved similarly from pre- to post-intervention, though this effect may be sex specific. These findings do not support the hypothesis as traditional-equipment RET improved muscular strength to a greater extent than minimal-equipment with BFR, and minimal-equipment with BFR did not outperform minimal-equipment RET on any measures.

To the authors’ knowledge, this is the first study to compare the effects of minimal-equipment, field-expedient RET to traditional-equipment RET on multiple aspects of muscular and human performance. Compared to previous findings, the use of
minimal equipment as an external load rather than body mass alone bolstered the effects of field training methods (Kraemer et al., 2001). However, Harman et al. (2008) found no differences in improvements in muscular power or aerobic capacity when comparing the effects of a traditional-equipment based RET program to the Army’s Standardized Physical Training program. An explanation for these dichotomous findings is the duration of the training programs. Participants in the Kraemer et al. (2001) trained for 24 weeks, while the Harman et al. (2008) study and the present study lasted eight and six weeks, respectively. Further, one difference between these findings was the greater improvement in muscular strength measures in the current study compared to Harman et al. (2008). This may be explained by the method of RET employed, as Harman et al. (2008) prescribed circuit-based training two days per week compared to the traditional power and strength training prescribed four days per week in the current study.

Contrary to the hypothesis, the implementation of BFR training in the current study did not confer additional benefits for performance or body composition adaptations above minimal-equipment RET alone. Additionally, though improvements were observed, MIN+BFR did not improve in muscular strength to the same extent as TRAD. Previous findings in studies of similar durations have shown comparable or greater improvements following BFR compared to traditional RET in all aspects of performance, including strength (Cook et al., 2014; Early et al., 2020; Korkmaz et al., 2020; Luebbers et al., 2019), though others have found differences in improvements in muscular strength akin to the current study (Bjornsen et al., 2019; Yasuda et al., 2011).
An explanation for these differences may be due to specificity as it is well established that improvements in muscular strength are largely predicated on this concept, including both movement and load specificity (Haff & Triplett, 2016). In the current study, all groups performed the exercises during training that were used for testing strength, though only TRAD used the same equipment. Similarly, TRAD performed sets of six repetitions during training while MIN and MIN+BFR performed sets of 15-30 repetitions. Therefore, TRAD trained more specifically for the strength assessments than MIN and MIN+BFR, which may partially explain the findings for trap-bar deadlift and bench press strength in this study. Though the current study used higher repetitions for MIN and MIN+BFR to allow for comparisons to previous BFR research, future studies should consider the efficacy of higher-load BFR given the patterns of improvement seen in this study across the three groups.

With regard to body composition, the current study showed improvements in FFM, %BF, and biceps brachii, vastus lateralis, and total quadriceps thicknesses with no changes in BM or quadriceps tendon thickness across all groups and no differences between groups. These findings are consistent with research comparing low- versus high-load RET (Au et al., 2017; Fink et al., 2016; Mitchell et al., 2012; Morton et al., 2016; Schoenfeld et al., 2015; Tanimoto et al., 2008) as well as a meta-analysis conducted on this topic (Schoenfeld et al., 2017). However, it is worth noting that the minimal-equipment RET program consisted of more sets and repetitions (i.e., volume) than the traditional-equipment RET which has been described as the most important program design variable in RET to enhance hypertrophy (Figueiredo et al., 2018;
Schoenfeld et al., 2019), but all groups still experienced similar hypertrophic responses. The addition of BFR did not augment hypertrophy in this study, which is consistent with those comparing BFR to higher load training (Lixandrao et al., 2015; Martin-Hernandez et al., 2013; Yasuda et al., 2011) but contrary to previous research comparing BFR to a load-matched control (Fahs et al., 2015). One explanation for this may be differences in study design as Fahs et al. (2015) used a contralateral limb model three days per week while the current study prescribed full body training four days per week. Additionally, though not quantified, the total volume performed by MIN may have been slightly greater than MIN+BFR since total repetitions and RPE were matched between groups, but the use of BFR may have limited the absolute loads lifted.

The sex differences found in this study show males exhibit greater levels of muscular power, strength, endurance, anaerobic capacity, and aerobic capacity as well as higher body mass, fat-free mass, muscle thickness, and lower body fat percentage. This is consistent with previous research (Bishop et al., 1987). Further, the impact of sex on changes in strength in this study showed greater improvements for males on 3RM trap-bar deadlift as well as differential patterns of change by group between males and females on 3RM bench press. The former effect suggesting larger improvements in lower-body strength for males compared to females contradicts recent meta-analytical findings which shows no sex differences (B. M. Roberts et al., 2020), but this finding has been observed previously in a sample of undergraduate students previously (Fernandez-Gonzalo et al., 2014). The latter finding was explained by greater improvements in males following BFR training compared to non-BFR and greater improvements in females.
following non-BFR training compared to BFR. This sex-specific effect of training does not 
appear to have been observed in the literature previously and warrants further 
investigation. Despite sex differences in muscular strength adaptations throughout this 
study, it is worth emphasizing the lack of differential patterns between males and 
females on other performance outcomes and body composition. These findings suggest 
males and females adapt similarly to RET with and without BFR and can expect 
improvements of similar magnitudes over six weeks of training.

In addition to performance and body composition, differences in exercise 
intensity and overall workload were observed between groups. Blood La⁻ was greater 
mid- and post-exercise in MIN and MIN+BFR compared to TRAD. Overall workload 
scores quantified using RPE- and heart rate-derived methods were also greater for MIN 
and MIN+BFR, but no differences in session duration or daily RPE were found between 
groups. Despite differences in exertion during training, no differences were observed for 
weekly MTDS score or DOMS between groups. Similarly, previous studies have assessed 
differences in RPE following each set, rather than the overall session, and have found 
higher RPE following resistance exercise with BFR (Dankel et al., 2019; Loenneke et al., 
2011; Loenneke et al., 2015; Spitz et al., 2020). Though the current study did not find 
differences in daily RPE, the differences in sRPE workload scores between groups 
follows a similar pattern to these previous findings. MTDS score has not been assessed 
in previous research on this topic, but the current results show overall low MTDS scores 
compared to previous data in team sports (McFadden et al., 2022) with no fluctuations 
over six weeks of training. DOMS exhibited different patterns of change between groups
over the 6-week intervention. TRAD and MIN+BFR exhibited higher DOMS in week 1 compared to week 2, and, during week 6, TRAD returned to baseline while MIN+BFR increased above baseline. MIN did not experience any changes in DOMS. Though not statistically significant, DOMS was higher during the first week of MIN compared to TRAD and MIN+BFR, potentially explaining the differential pattern observed, particularly since DOMS was not different between groups during any week. Previous research has shown higher DOMS following resistance exercise with BFR compared to both low- and high-load exercise (Brandner & Warmington, 2017; Umbel et al., 2009). These studies, however, looked at effects in the 24-72-hour period following a single bout of exercise, while the present study looked at daily DOMS ratings over six weeks of training. The lack of differences between groups may be attributed to the repeated bout effect (Hyldahl et al., 2017). Future studies should assess MTDS score and DOMS over longer periods of time in similar interventions. Further, there were not differences in relative RPE- and heart rate-derived workloads between males and females, providing support for the similar changes in performance and body composition changes between sexes throughout the study. However, while different in females, sRPE was not statistically different between groups when looking at males alone, though HR-derived workload followed the same pattern as the overall sample. This may indicate sex differences in perceptual and objective responses to this type of training. Lastly, the unique patterns in DOMS across groups between sexes suggests males and females may respond differently to the types of training prescribed here.
Chronic endocrine responses have been shown to be related to levels of stress and anabolic status as well as overreaching and overtraining syndrome (Lee et al., 2017; McFadden et al., 2020; Walker et al., 2019). There were no differential patterns of change between groups in any blood-based biomarker assessed in this study. Basal cortisol, a biomarker of stress and the final product of the hypothalamic-pituitary-adrenal axis, remained stable from pre- to post-training in the current study. This marker has previously been used as an indicator of overreaching or overtraining syndrome (Cadegiani & Kater, 2017), thus the lack of change during this 6-week intervention suggests the participants did not exhibit physiological signs of overreaching over this time period. However, when looking at males and females separately, this lack of change was consistent with males but not females. A decrease in cortisol from pre- to post-training in females was found, which is likely favorable when assessed in the basal state. No effects were observed for basal GH which is consistent with previous research (Kraemer et al., 1999; McCall et al., 1999). Basal IGF-1, however, exhibited decreases of small to moderate magnitudes from pre- to post-testing across all groups which contradicts recent meta-analytical findings across all modalities of exercise training (Jiang et al., 2020). This effect has been observed previously during a RET intervention, though significant reductions were not observed until week 11 of the 16-week study in participants training to momentary muscular failure (Izquierdo et al., 2006). It is also worth noting that females had higher cortisol and GH levels than males regardless of time and group. This has been shown previously and corroborates research in athletes (Tsai et al., 1991; Walker et al., 2017). The findings of the current study, particularly with
the highest magnitude of decrease in IGF-1 for MIN, may indicate a progression towards a state of overreaching and suggests periodization of this method of training may be required over durations longer than six weeks to balance stress and recovery.

One strength of this research study is the training frequency and overall workload prescribed during the intervention. Previous RET interventions in military populations or focused on military-relevant performance outcomes have trained participants three or fewer days per week (Harman et al., 2008; Heinrich et al., 2012; Knapik, 1997; Kozinc et al., 2021; Kraemer et al., 2001), while the current study trained participants four days per week following a full-body routine. Another strength of this study is that all training sessions were led or supervised by an NSCA CSCS. This improves both the internal and external validity of this study as exercise technique and progression were maximized, and, with the introduction of the Holistic Health and Fitness initiative in 2021, this mimics typical training procedures, as the Army employs strength and conditioning coaches to train soldiers for improved health and performance. Another strength of this study was the population from which the sample was recruited as ROTC cadets and midshipmen have previous RET experience and have been shown to have average to above average fitness levels (Thomas et al., 2004). Additionally, the inclusion and comparison of males and females in this study is unique and provides external validity as both male and female service members are required to meet ACFT and other physical fitness standards. Lastly, the use of both the ACFT along with laboratory performance measures is a strength, and similar patterns in field- and
laboratory-based assessments of different muscular and metabolic demands between groups were observed.

A limitation of this study is the lack of quantification and control of total training volume. RET volume is often expressed as the product of sets, repetitions, and load, but it was not possible to use this calculation for the current study due to the difficulty in quantifying load using band-resisted exercises, suspension trainer exercises, etc. in the minimal-equipment groups. However, it is evident that MIN and MIN+BFR performed more total reps than TRAD, albeit at lower loads. In fact, the authors intentionally designed the RET sessions to last approximately 60-75 min. Thus, with the shorter rest periods prescribed for minimal-equipment training, the groups following this protocol inevitably performed more total repetitions than TRAD. Lastly, a limitation of the current study was the lack of control of ROTC group-based physical training prescription. The specific modalities and workloads of training the participants performed during ROTC training is unclear, but this effect should not have impacted the results since participants from the various branches were randomized and evenly distributed into the three RET groups.

Overall, these findings show that minimal-equipment RET is an effective method of training tactical personnel to improve military-relevant performance. In fact, based on the current data, individuals can expect ACFT score improvements of 30-40 points or 8-12% in six weeks of RET similar to that prescribed here. Therefore, in times of limited access to typical exercise equipment, this type of field-based RET can be implemented to improve military-relevant performance in tactical athletes. Further, the data
presented here suggest males experience greater improvements in upper-body strength with BFR compared to non-BFR training. Moreover, the findings also suggest that the minimal equipment groups trained with objectively and subjectively greater exertion compared to TRAD. When coupled with the performance and body composition changes throughout the intervention, it can be inferred that TRAD experienced greater increases in strength and similar improvements in other performance metrics and body composition with less total effort than MIN and MIN+BFR. In conclusion, military personnel can expect similar improvements in ACFT score, muscular power, muscular endurance, anaerobic and aerobic capacity, and body composition, albeit an attenuation in muscular strength, during periods of limited access to traditional RET equipment.

Future research should investigate periodizing traditional- and minimal-equipment RET with and without BFR, the potential use of BFR with higher loads than those used here to further bolster adaptations in strength with this type of training, as well as sex differences in performance, body composition, and physiological responses to minimal-equipment and BFR training.
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