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THE EFFECT OF BODY ARMOR ON PULMONARY FUNCTION AND REPEATED SPRINT PERFORMANCE

By

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A dissertation submitted in partial fulfillment
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The Graduate College

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Abstract

Introduction: Tactical athletes face the unique task of performing physically demanding occupational duties often while wearing torso-borne loads. While pulmonary function has been shown to decrease while wearing plate-carrier style body armor, there has yet to be a study using the more accurate measurement of plethysmography to determine exactly why. Additionally, the inspiratory muscle's pressure generation capabilities and how they respond to a repeated running sprint test while wearing body armor are unknown. Therefore, the purpose of this dissertation was to examine how body armor affects pulmonary function, inspiratory muscle strength, and athletic performance during repeated, high-intensity sprints.

Methods: Twelve college-aged males performed spirometry, plethysmography, maximal inspiratory pressure, and Running Anaerobic Sprint tests under three conditions (CNTL, unloaded plate carrier [UNL], and loaded plate carrier [LOAD]). Participants had their maximal inspiratory pressure recorded pre- and post-sprint tests.

Results: There was no significant difference among any of the conditions for inspiratory muscle strength pre-sprint test. Compared to CNTL, LOAD showed a small but statistically significant lower forced vital capacity ($p = 0.02$, $d = 0.3$) and a moderately lower total lung capacity ($p < 0.01$, $d = 0.5$). The LOAD condition also had a significantly higher total running anaerobic sprint test time ($p < 0.001$, $d = 1.5$).

Conclusion: A loaded plate-carrier body armor reduces pulmonary function and demonstrates similar reductions as obese individuals. Using the UNL, repeated sprint performance was ~10% slower than the CNTL but did not significantly differ in fatigue rate. Tactical athletes should aim to train with their style of body armor to reduce the negative effects of wearing body armor during repeated anaerobic activity.

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Dedication

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List of Acronyms

FVC = Forced vital capacity

FEV_1 = Force expiratory volume in one second

PEF = Peak expiratory flow

MVV = Maximal voluntary ventilation

TLC = Total lung capacity

FRC = Functional residual capacity

RV = Residual volume

VC = Vital capacity

IC = Inspiratory capacity

ERV = Expiratory reserve volume

IMF = Inspiratory muscle fatigue

IMT = Inspiratory muscle training

CNTL = Control condition consisting of regular athletic attire

UNL = Unloaded body armor condition

LOAD = Loaded body armor condition

1.0 Introduction

Most modern, life-threatening engagements by military and law enforcement occur in urban environments where running speed is a critical factor in potential injury and effectiveness. These "tactical athletes" are equipped in body armor to protect their vital organs from gunshots and shrapnel; however, the additional weight can increase the physiological demand of locomotion(26, 45). This increase in physiological demand decreases agility, soldier task performance, and can alter gait mechanics (26, 39, 45, 49, 54, 60, 75). With these decreases in performance, it is vital to better understand how tactical athletes wearing body armor perform bouts at high intensities in rapid succession, with minimal recovery between bouts.

Some research has indicated a decrease in pulmonary function from 2 – 6% with the use of a plate-carrier style of body armor, possibility limiting tactical athletes ability to optimally perform due to the restriction placed on the chest wall (4, 5, 20, 23, 39, 56). Greater loads increase this restriction, with some body armor styles that also restrict the thoracic cavity through the use of attachments such as cummerbunds and side plates (4, 5, 56). While previous research using body armor has shown decreases in forced vital capacity FVC by 2 – 6%, forced expiratory volume in one sec (FEV_1) by ~6%, and maximal voluntary ventilation (MVV) by ~7%, there is little-to-no research utilizing plethysmography (4, 56). Plethysmography can give a more accurate test of how pulmonary function are affected by body armor. It is possible that wearing a heavy and restrictive vest around the thoracic cavity could have similar restrictions to those seen in obese adults (17, 98). Excess fat on the thoracic cavity in the context of obesity creates a restrictive effect that is associated with a reduction in functional residual capacity (FRC) This reduction if FRC pushes breathing closer to the residual volume where there could be impairments with gas exchange and a higher risk of airway closure and expiratory flow limitation. These limitations may reduce exercise performance and increase exertional dyspnea

(6). This thoracic cavity restriction from body armor may compound with the increasing obesity rate with some tactical populations leading to even greater performance decreases (35, 84).

Body armor can decrease submaximal aerobic capacity by ~11% and perceived exertion by 1 or 2 points (26, 45, 54, 87). However, it is unclear how wearing body armor affects repeated high-intensity sprint performance. Increasing the total mass an individual has to move can increase the energy required for locomotion and leads to a decrease in occupational task performance (49, 88). In real-life operations, tactical personal may not have the ability to rest in between bouts of high-intensity exertions for more than a few seconds. Understanding how this short recovery time combined with body armor performance may help train these tactical populations to perform repeated bouts of high-intensity activity with minimal recovery periods.

While the inclusion of additional weight to the torso has shown an increase in tactical athletes' overall work rate, body armor also restricts the chest wall (4, 20, 56). This chest wall restriction has shown ~16% lower FVC, ~8% lower maximal oxygen uptake, and ~11% slower task completion time (4, 20, 22, 23, 26, 56). These performance and pulmonary function detriments linked to wearing body armor, which both restricts the chest and adds weight to the torso, have raised the question of how the respiratory muscles are affected while performing high-intensity physical tasks while wearing body armor. Therefore, the purpose of this dissertation was to examine how body armor affects pulmonary function, inspiratory muscle strength, and athletic performance during repeated, high-intensity sprints.

2.0 Review of Current Literature

2.1 Introduction

The term “tactical athlete” refers to members of the military, law enforcement, first responders, and fire & rescue. The name references the unique occupational demands required from the individuals in these fields. A tactical athlete must perform their occupational tasks to help serve and protect their country and community but must do so under physically demanding circumstances to achieve their objective, similar to an athlete. The training that tactical athletes go through is substantially different from individuals training for a sport or recreation. Most tactical athletes are tasked with performing at a high level while wearing various pieces of equipment such as body armor or other torso-borne loads (backpacks, rucksacks, oxygen tanks, etc.) These torso-borne loads can weigh more than 35% of the athlete’s body weight (12, 55, 57, 59, 63). Additionally, the professions and situations tactical athletes are involved in require high aerobic and anaerobic fitness levels. Not only is the physical performance of these athletes crucial to minimize the risk of injury to themselves on the job, but it is also to the safety of their fellow athletes and to those they are tasked to serve and protect.

It is common for military and law enforcement to wear some form of body armor during everyday duty. The style and weight of the body armor can range from a lightweight style (2.9 kg), mostly used by law enforcement, to a ballistic plate-loaded style that can weigh up to 15.3 kg when fully loaded with steel or ceramic plates (4, 26, 45, 54, 56, 60). The use of body armor impedes the chest wall from fully expanding, causing the diaphragm to work harder (20, 23, 93). This increased work done by the respiratory muscles during physical activity results in a metaboreflex, reducing the blood flow to the active limbs to maintain respiratory muscle function (42, 72, 78). The reduction of blood flow to the active limbs may lead to a higher rate of fatigue in the limbs and an increase in injury rate (26, 64, 68, 73, 97). Due to the restriction of the chest wall, the increased rate of diaphragmic fatigue, and the decrease in pulmonary function that it causes, it is essential to understand how tactical athletes may be at a higher risk of fatigue and injury when performing physical activity while wearing body armor (4, 22, 23, 54, 56, 87).

Many tactical athletes in the field will have to carry some form of torso-borne loads, such as a backpack or oxygen pack that can exceed 35% of a person's body weight. Additionally, torso-borne load carriage adds additional weight to the shoulders, limiting their movement, and increasing the diaphragm's work during ventilation (28, 30-33, 63). The additional demand placed on the diaphragm and the increase in the physical work rate needed to accommodate the additional weight causes all the inspiratory muscles to work harder, leading to decreased inspiratory pressure (30-32). This loss in inspiratory pressure leads to less air entering the lungs and is known as inspiratory muscle fatigue (IMF).

The training foci of tactical athletes often consist of both high-intensity intervals and long-duration bouts of exercise. As the world has seen an increase in urbanization, the tactical athlete's training has seen a greater need for short-burst of high-intensity activity (50). This increase in urbanization has given military and law enforcement agents environments densely populated with many structures to navigate. Navigating streets and alleyways during operations prioritize short bursts of high-intensity activity moving from cover to cover or building to building. These short bursts of activity while carrying torso-borne loads have not been extensively studied. While short burst of high-intensity activity utilizes the anaerobic phosphocreatine (PCr) system for energy, the resynthesis of PCr is an aerobic process requiring adequate O_2 availability (43, 53, 61, 74). The combination of needing adequate O_2 for optimal performance with the decrease in pulmonary function caused by load carriage emphasizes a need for more knowledge of how these impact tactical athletes. Therefore, this review will analyze the literature around the IMF, load carriage, and how these concepts can be applied to the tactical athlete, emphasizing short-duration, high-intensity physical activity.

2.2 Respiratory Muscle fatigue

In healthy adults, the respiratory system is more than adequate at meeting the O_2 and CO_2 demands of moderate exercise. However, performing high-intensity activities or increasing the average work rate may fatigue the respiratory muscles, leading to decreased pulmonary function (1, 13, 21, 27, 29, 41, 42, 65, 79, 85). Supinski et al. showed that respiratory muscle fatigue was associated with increased perceived exertion (r = 0.96) (85). Supinski used an airflow pressure gauge to determine the magnitude of pressure generated over the course of 5 - 7 minutes. Maximal inspiratory pressure (MIP) was recorded before testing and was used as the baseline to determine when the inspiratory muscles were fatigued. The pressure threshold for inspiratory muscle fatigue on day one was found to be 24%. It was adjusted on subsequent testing days to test respiratory muscle fatigue patterns using either a higher or lower pressure. Electromyography (EMG) was used to monitor diaphragm muscle activity via an esophageal electrode and an electrode placed on the sixth intercostal muscle. Borg's rate of perceived exertion (RPE) scale was used to measure effort. They found that breathing against a higher-pressure threshold significantly reduced MIP by 12%, diaphragm EMG by 17%, and an increase of 7.1 RPE (85). These results were critical in determining how IMF can increase RPE and how this fatigue translates to a decrease in the diaphragm's ability to maintain pressure while fatigued.

The work showing decreased diaphragm pressure and increased RPE due to the IMF led other researchers to examine how these effects differ between highly trained individuals and the untrained. Coast et al. studied the differences in MIP post-exercise between highly trained cross-country skiers (average VO_{2MAX} 71.8 ± 3.8 $mL{\bullet}kg^{-1}{\bullet}min^{-1}$) and untrained college students (42.0 ± 3.0 $mL{\bullet}kg^{-1}{\bullet}min^{-1}$) (21). After a maximal cycle ergometer test, MIP was measured 10, 20, 60, and 120-sec post-exercise. The researchers found that while both groups had similar baseline MIP, only the untrained group's MIP significantly decreased due to exercise. These decreases averaged 10, 17, and 13% at the 10, 60, and 120-sec measurements. The skiers did not significantly change MIP; in fact, MIP was slightly elevated post-exercise on average. The trained athlete's ability to maintain MIP, even slightly elevating it, after a maximal test may demonstrate how IMF may only occur after longer durations of time in highly trained athletes. However, untrained individuals experienced the IMF after the maximal test and for at least 120-sec post-exercise. This difference among trained and untrained athletes raises the question: To what extent does the IMF occur in different athletes, and how might this fatigue influence activities of different durations and intensities?

Segizbaeva et al. examined the differences in MIP between trained athletes from power and endurance sports and untrained individuals (76). The endurance athletes had a training background in middle and long-distance running, swimming, skiing, and multi-event athletics (pentathlon and triathlon). The power athletes' background was in weightlifting, arm-wrestling, boxing, and mixed-martial arts. Both groups of athletes had significantly higher MIP, MEP, and MVV compared to the control (Table 1). Additionally, the endurance group had significantly greater pulmonary function than the control, but no significant difference from the power athletes (Table 1). The increases in respiratory muscle strength and higher MVV in both athlete groups suggest different training intensities will increase respiratory muscle strength; however, endurance training may be the superior option when respiratory function is concerned.

Table 1. Segizbaeva and Aleksandrova pulmonary data

	Endurance n = 28	**Power n = 22**	**Control n =24**
MIP (cmH_2O)	162.6 ± 16.3*	150.5 ± 36.8*	115.3 ± 25.0
MEP (cmH_2O)	187.3 ± 31.4*	153.1 ± 49.4*	118.3 ± 23.5
MVV (L/min)	178.6 ± 16.7*	162.0 ± 19.22*	148.7 ± 19.0
FVC (L)	5.6 ± 0.7*	5.2 ± 0.8	4.9 ± 0.7
FEV_1 (L)	5.1 ± 0.5*	4.6 ± 0.5	4.6 ± 0.7
PEF (L/sec)	10.5 ± 1.0*	8.9 ± 1.3	8.7 ± 1.6

* indicates a significant difference compared to Control (effect size ranges from 0.7-2.5)

2.3 The Effects of Respiratory muscle fatigue on athletic performance

Aerobic exercise can last from a few minutes to hours and relies heavily on the respiratory system to provide oxygen and expel CO_2. Due to the high demand placed on the respiratory system during aerobic exercise, research has focused heavily on how long-duration exercise may affect the respiratory muscles. With a marathon race being one of the most prolonged aerobic activities performed by professional and recreational athletes, early respiratory muscle fatigue research, such as Chevrolet et al. (18), examined how much fatigue occurred and its effect on performance.

Chevrolet et al. examined the relationship between respiratory muscle force, lung mechanics, metabolic parameters, and performance variables after a marathon race (18). They used twenty-seven male marathon runners (average best time = 189 ± 19 minutes) and took measurements before and after a marathon race. To test reliability and whether the ambient temperature influenced results, measurements were taken from an additional six runners before and after a different marathon. The researchers found a significant decrease in MIP (~27%) and lower leg muscle force (~ 28%) after the race, which lasted more than 2.5-hours without changes in expiratory force or respiratory muscle endurance. Additionally, this decrease in MIP did not correlate with training status, metabolic parameters, or the subjective feeling of fatigue, and there was no alteration in lung mechanics after the race. The researchers concluded that the IMF achieved in the marathon runners was probably due to an insufficient energy supply to the respiratory muscles. Similar results were found in triathletes who competed in a 3.8 km swim, 180 km bike ride, and 42 km run (46).

Interestingly, MIP did not decrease after the swim, but it did after the bike (26%) and run (~17%). This difference between events is possibly due to the athletes using an intentionally slower pace during the first event to perform better on the longer-duration bike and run events. Researchers also found that forced vital capacity (FVC) (Cohen's $d = 1.7$) and forced expiratory volume in one second (FEV_1) ($d = 1.8$)were significantly reduced post-race, FEV_1 significantly reduced after 24-hours ($d = 1.4$). This decrease in pulmonary function may be caused by the respiratory muscles being fatigued and unable to generate the same pressure as they did before the race.

Respiratory muscle function and strength have also been shown to affect shorter duration aerobic exercise. Oueslati et al. measured respiratory function and muscle strength in elite cyclists and runners during an incremental test in their respective modes (66). The cyclists performed an incremental cycle test where the work rate was increased by 30 W every 2-minutes until their pedal speed dropped below 60 RPM. The runners performed an incremental running test on a treadmill with the speed starting at ten km/h and increasing by one km/h every 2 minutes until exhaustion. Initial MIP ($d = 0.98$) and maximal expiratory pressure (MEP) ($d = 0.86$) were both significantly higher in the runners along with maximal voluntary ventilation (MVV) (runners: 184 ± 23; cyclist: 166 ± 16 L/min). Additionally, there were moderate correlations between MIP and MEP at rest and VO_{2max} (MIP: r = 0.34, $p < 0.01$; MEP: r = 0.36, p

< 0.01). The runner's higher respiratory strength is an indication that respiratory muscle strength increases in response to increasing demand for ventilation. When body weight is supported by the legs rather than a bike, the oxygen demand and the increase in ventilation increases as a response to the higher work rate. Additionally, runners maintained a higher ventilation rate than cyclists after 20% of their time to exhaustion and maintained this elevated rate until both groups were 100%. The increased demand on the respiratory muscles may be further exacerbated with the addition of external loads. Tactical athletes who use external loads may have even greater respiratory training adaptions while training with loads as the ventilatory demand increases.

While aerobic exercise increases the use of the respiratory muscles over a long time, anaerobic exercise occurs over a much shorter period. There is a shortage of research on anaerobic activities and how they affect respiratory function. In 2016, Ohya et al. examined the effects of running 400- and 800- meters on IMF and hypothesized that short-duration running exercise would induce IMF (65). The researchers recorded the MIP of eight female, collegiate-level, middle-distance runners before and after running a 400- and 800m run. Results showed a significant decrease in MIP after both running distances (400-m: 107.6 ± 25 vs. 97.6 ± 27 cmH_2O; $p = 0.01$, $d = 0.65$), with a greater decrease after the 800m run (108.6 ± 26 vs. 92.6 ± 27 cmH_2O; $p = 0.01$, $d = 0.74$). However, there was no correlation between running time and the IMF. This study demonstrates that the IMF does occur during short-duration exercise, but it does not affect running time. While this study showed a decrease in MIP after a single anaerobic bout of running, it is unclear how multiple bouts may affect MIP. Understanding how IMF changes through repeated high-intensity bouts of exercise may help researchers better understand its impact on performance and recovery during activities typically undertaken by tactical athletes.

During repeated sprinting, the body primarily utilizes PCr as the primary source of energy. The more sprints that are repeated, the higher the relative contribution to ATP production from PCr compared to anaerobic glycolysis (36). While the aerobic contribution to a single sprint's energy production is low, there is an increased demand for oxygen when the sprints are repeated (9, 36). In tactical populations that must utilize repeated sprinting in the increasing urban landscape, optimal performance is critical. Wearing personal protective equipment (PPE) may negatively impact the athletes' ability to properly recover in-between bouts of repeating physical exertion, leading to decreased performance. While there are many types of PPE worn by the various tactical athletes, body armor is the most common among law enforcement and military personnel. This PPE style may cause a decrease in pulmonary function, leading to a decrease in the athlete's ability to recover from the repeated bouts of anaerobic activity required during their occupational tasks.

2.4 Respiratory Muscle Fatigue Due to Chest Wall Restriction

Previous research has shown inspiratory and expiratory muscle fatigue to occur from several different activities. However, it is unclear how body armor's chest wall restriction may affect tactical athletes' ability to generate maximal inspiratory pressure. Legg was one of the earliest researchers to examine the effect body armor has on pulmonary function (56). That study investigated how different types of lightweight body armor (<10 kg) would affect pulmonary function. Three types of body armor were used; a bomb disposal searcher's suit (SS) weighing 6.2 kg that covered the trunk and lower abdomen, a fragmentation vest (FV) weighing 4.2 kg that only covered the chest, and basic lightweight body armor (LW) weighing 2.9 kg and covering the trunk down to the umbilical level. Thirty male soldiers participated in the study split into three groups based on body armor style. All pulmonary function testing was performed standing while using a spirometer. Statistically significant within-group reductions were seen in FVC (SS = 2.9%, FV = 2.4%), PEF (SS = 4.9%) and in MVV (LW = 10.4%). The study's main purpose was to compare the use of a "more restrictive" yet lighter body armor to previous work conducted on heavier backpacks. The 2-5% reduction is small, especially compared to a study before looking at backpacks weighing 35% of the participant's body weight (12% reduction) (55). Legg did mention the tightness of the body armor was not well controlled and may explain the anomalously large decrease in MVV with the LW body armor.

Cline et al. designed a chest wall restricting device to mimic the effects of skeletal and pulmonary disease and the mechanical restriction from occupational situations (20). The device was worn around the chest and contained an air bladder that increased the chest pressure. Five males and five females completed a pulmonary function test under four different restrictive loads. The lowest pressure used (20 mmHg) was enough to decrease FVC and FEV_1 during testing ($p < 0.001$). Higher pressures exacerbated this decrease in pulmonary function. These results are further evidence of the impact chest wall restriction had on pulmonary function. Unlike Legg's previous study, the device used in this study placed all the pressure on the chest wall with no added weight to the shoulder girdle. These results may indicate that body armor's main detriment to pulmonary function is the chest wall restriction rather than the weight added to the shoulders. A study using football shoulder pads had a similar conclusion that the reduction in pulmonary function was due to the restriction placed across the chest rather than the additional weight on the shoulders (22).

The use of a custom chest wall restricting device was further examined by Coast et al. (23). Rather than use a different pressure threshold, Coast used the same pressure as Cline (0, 20, 40, 60 mmHg) and found an average decrease in resting FVC of 1.2, 5.3, 7.3, and 11.9% (23). While under the effect of the chest wall restricting device, participants performed a graded maximal cycle test to determine their maximal oxygen uptake (VO_{2max}), minute inspired ventilation (V_{imax}), tidal volume (V_T), and breathing frequency. At a pressure of 20 mmHg, VO_{2max} was significantly reduced from baseline ($d = 0.7$), and V_{imax} ($d = 0.7$) were significantly reduced from baseline. The 40-mmHg condition, equal to a decrease in FVC of 7.3%, was enough to significantly reduce the time to reach exercise failure ($d = 1.3$), VO_{2max} (42.7 ± 1.1 . ml•kg^{-1}•min^{-1}

vs. 41.4 ± 1.0 . ml•kg^{-1}•min^{-1}, d = 1.2), and V_{imax} (d = 1.1) from baseline. The 60-mmHg condition had an even greater reduction from baseline as well as from the 40-mmHg condition. Considering there have been studies showing FVC reductions between 4-6% of various body armor styles, these results can be comparable to a tactical athlete performing a maximal effort test while wearing body armor (4).

When studied in practical applications, plate-loaded body armor has decreased VO_{2max} and sprint speed while increasing exercise RPE (26, 45, 54, 60, 87). Using a vest weighing 8.7 kg resulted in a decrease in VO_{2max}, repetitive box lift and carry task performance (20.5 kg), and an increase in 30-m sprint time (45). Additionally, obstacle courses have been used as a test of occupational proficiency, testing aspects related to tactical athletes such as balance, agility, speed, and power. Larsen et al. used an obstacle course that contained simulated shooting, army crawls, standing to prone repositioning, repetitive box lifts (20 kg), sprinting, and maneuvering around cones (54). The obstacle course was completed twice in succession while wearing ~20 kg PPE, including a training rifle and helmet. The circuit was repeated 11 times with a 2-minute rest period between circuits and a maximum of 44 minutes to complete the course. Two of the twelve participants did not meet the time requirement in the PPE condition. The PPE caused a significant increase in time in all event sections other than the box lift, resulting in a significant increase in mean circuit time (control: 66.8 ± 3.5; PPE: 74.1 ± 5.6 sec, d = 1.6). The researchers noted that PPE's use did not accrue more performance decrements over time; thus, the obstacle course may have been too short of causing an accumulating fatigue effect. It is still vital for tactical athletes and PPE developers to take into consideration the loads being carried. Occupational performance can be sacrificed for more protection but must be managed appropriately to accommodate the athlete's needs and occupational duty (54).

Over the years, body armor has evolved to include multiple variations, including both lightweight and multiple styles of plate-loaded variations. Armstrong and Gay examined the effect various styles of body armor have on pulmonary function (4). They hypothesized that impaired pulmonary function would be less when flexible body armor is worn than in-service body armor (ISBA). Eight active male infantry soldiers were selected to test four different styles of body armor. Along with the ISBA, which contained a front and rear monolithic ballistic plate, three separate flexible armors (FA) were chosen. The FA1 armor comprised of built-in flexible segments with no additional cummerbund; FA2 and FA3 both had flexible plates that could be removed and flexed differently. All of the body armor styles except for FA1 decreased FVC. These results show that plate loaded body armor's design influences pulmonary function and the inclusion of a cummerbund in the design. Due to the differing body armor styles used in this study, it is possible the inclusion of a cummerbund had a greater influence on the results rather than the style of the ballistic plate. However, it is also possible the weight of the body armors had an influence; the FAs weighted ~5kg less than ISBA. Previous research has shown the reduction of pulmonary function is directly proportional to the load carried (5, 28, 63).

Armstrong et al. found that body armor worn looser showed no difference to "battle-worn" tightened body armor (5). Twenty-four male infantry soldiers performed a 40-minute march on a treadmill under six conditions (control, wearing a body armor vest (10.9 kg), vest + 15 kg, vest + 25 kg, vest + 35 kg, and vest + 25 kg with a loose fit.) Participants wearing just the body armor vest (10.9 kg) showed no difference between the loose and tight fit loaded conditions. Instead, the study concluded that the weight of the load is the main factor in performance decreases. Only the vest + 35 kg condition had a significantly lower FVC (~8%) than the vest only condition. Under lighter loads, such as the PPE worn by law enforcement, weight may not be as much of a factor. Using PPE vests weighing 3 – 4.5 kg, male and female officers showed no significant lower body power output, Illinois Agility test results, or 20 m sprint performance (75). However, wearing loads of ~10 kg has been shown to significantly impair police officers' ability to change direction, with a 23% increase in 20-m sprint time when a change-of-direction was required (49). Additionally, there was a significant negative relationship (r = -0.4) between relative load and change-of-direction and a significant positive relationship (r = 0.4) with bodyweight and change-of-direction speed.

While the load may be the main antagonist to performance while wearing PPE, another possible issue may be the mechanical barrier it places on the thoracic cavity causing the respiratory muscles limited space to expand. This barrier can increase the diaphragm's work, possibly leading to a loss in diaphragmatic force production. Simultaneously, there is a significant positive relationship between inspiratory muscle strength and diaphragmatic movement in healthy non-smokers (r = 0.466; $p < 0.001$). Researchers have also found no changes in diaphragmatic pressure after inspiratory muscle training (67, 80). The perception of breathlessness resulting from diaphragmatic fatigue may be a larger contributor to performance declines than inspiratory pressure changes. Boyle et al. found that using a diaphragm-fatiguing protocol before a high-intensity cycle protocol significantly increased the participant's perception of dyspnea by 6% and rating of unpleasantness by 9% while not altering diaphragm EMG activity (10). Even though diaphragm EMG activity was unchanged in that study, there was still a 16% decrease in time to exhaustion from the control ($p = 0.023$).

The reduction of exercise capacity due to torso-borne loads could put a tactical athlete at a disadvantage while performing their duty or even put others at risk. The detriments to exercise capacity that are induced from the chest wall restriction needs to be studied further. The mechanical restriction may not allow for a training adaptation to occur in the respiratory system but rather increase the respiration's efficiency.

2.5 Torso-Borne Loads Effect on Respiratory Muscle Fatigue and Performance

Body armor has been shown to reduce pulmonary function by restricting the chest wall and adding additional loads to the shoulders (4, 5, 22, 39, 56, 62, 67). Torso-borne loads, such as a backpack, might affect pulmonary function by vertically restricting chest wall expansion through the additional load on the shoulders. This restrictive condition reduces end-expiratory lung volume and impairs the average increase in end-inspiratory lung volume, increasing the energy cost of breathing (15, 25, 28). These factors lead Faghy and Brown to examine the effect a 25 kg thoracic load has on respiratory muscle fatigue and pulmonary function during a 60-minute walk at a constant speed and a 2.4 km time trial (31). Prior studies found that backpack loads of ~30 kg decreased pulmonary function and performance, while lighter loads around 10 kg did not affect (63, 91). Nineteen healthy, physically active males participated in the study. Participants performed a 60 min walk both with and without the 25 kg load with one week's rest between trials. After each trial, participants were given 15 minutes' rest before beginning a 2.4 km time trial walk. Participants were instructed to adjust the treadmill's speed to complete the task in the shortest possible time (31). The researchers found the addition of a 25 kg thoracic load caused a 30% decrease in the 2.4km time trial's completion time. Additionally, MIP and MEP were reduced by 16-19%, and FVC and FEV_1 were reduced by 2-5%. These findings show the addition of a torso-borne load as light as 25kg can affect both time trial performance and pulmonary function (31). These results are beneficial to both the tactical athlete and anyone who actively carries torso-borne loads, such as hikers.

Due to tactical athletes carrying extra weight, leading to a higher work rate, a future study may examine the effect a torso-borne load has on a subject exercising in a "zero-gravity" treadmill. Since these treadmills reduce the subject's body weight at the hip, the participant could exercise with a torso borne load without the additional weight increasing work rate. The use of "zero gravity" treadmills may be the more practical method for examining the effects of torso-borne loads on performance. A cycle ergometer may yield similar results with the additional weight taken off the legs and placed solely on the torso. Using a cycle ergometer, Giuriato et al. examined how pulmonary function and aerobic capacity are affected by adding a weight vest equaling 10% (~8 kg) of the participant's body weight (39). Twenty-three healthy, college-aged males volunteered to participate in the study. Participants had their pulmonary function tested before and after a 5 km cycling time trial, both with and without the weight vest. The weight vest yielded similar, significant pulmonary function results (~2%) to previous studies looking at body armor (4, 5, 56). However, time-to-completion, HR, breath frequency, and VO_{2max} were not significantly different between the control and weight vest during exercise. There was a statistically significant difference in the power output during the first minute of exercise ($p < 0.01$, $d = 0.4$), but the peak power output was not different ($p = 0.088$). The additional weight possibly caused the participants to start at a lower intensity, which allowed them to pace themselves more efficiently, resulting in no significant difference in time-to-completion (control: 461 ± 59; weight vest: 470 ± 66 seconds, $p = 0.12$). Interestingly, blood lactate was significantly higher in the weight vest group post-exercise (10.7 ± 2.8 versus 12.2 ± 2.4 mmol/L, $p < 0.001$). The longer-duration exercise possibly lead to a difference in performance. The researchers also noted the weight vest had a minimal effect on chest wall restriction (V_T 125ml lower than control), and a more restrictive system may yield different results.

Weight distribution and fit have been critical variables considered by PPE manufacturers. Weight distribution may be one of the most crucial factors when it comes to performance. Researchers have found that an equal weight distributed in a rucksack versus a vest results in a faster fatigue rate with the rucksack in female participants (37). Using a modified Balke treadmill protocol where the speed started at 4.8 km/h and incline was increased by 2% every 2 minutes, participants had a significantly lower time to fatigue wearing the rucksack (6.6 ± 3.2 min) compared to both the weight vest (11.3 ± 1.7 min) and control (20.2 ± 1.2 min). Considering there was no difference in VO_{2max} between the loaded conditions, the rucksack most likely added additional work to the postural muscles leading to a quicker onset of the lactate threshold. Al-Khabbaz et al. found that increasing backpack weight up to 20% of body weight caused a significant increase in trunk backward inclination by 3.9° and erector spinae muscle activation by 19% (2). Rectus abdominis activation significantly increased by 3%, 4% and 6% at the lightest load (10% body weight), 15%, and 20% BW condition, respectively. Research on military load systems has also found that when the weight is evenly distributing and using a hip belt can lead to a lower overall perception of exertion (14%) and back pain (47%) during simulated operation tasks (77).

It's possible that utilizing a load system that lowers the perception of exertion and pain could lead to performance enhancements during extended load carriage. Multiple studies have shown an increase in RPE and dyspnea while wearing torso-borne loads. Still, participants' experience or respiratory muscle training may be affected by these subjective measures to lower the sensation of dyspnea (47, 54, 57, 77, 87, 88). Faghy and Brown conducted a training study to determine if IMT would increase inspiratory muscle strength, reduce the IMF, and improve time-trial performance while using torso-borne loads (33). Previous work on IMT had looked at how it can help strengthen the inspiratory muscles of the chest wall and the diaphragm leading to attenuation or no change in exercise-induced IMF but has only recently been studied with load carriage (11, 92). Nineteen healthy, non-smoking, and physically-active males with previous experience with torso-borne load carriage activities were separated into an IMT group and a control group. The training group participated in six weeks of IMT using an IMT device (POWERbreathe®). This device was selected as it targets both axes of the force-velocity relationship and is flow-independent. The training load for the IMT group was based around 50% MIP for the duration of the study. Participants used the IMT device to perform 30 dynamic breaths twice daily, identical to a previous study (31). After the six weeks of training, the IMT group increased MIP by 31% over the control group and had both a lower HR and RPE after the

2.4 km time-trial. Time to completion in the 2.4 km time-trial was also 8% lower in the IMT group compared to the control. This study was the first to show an ergogenic effect of IMT while carrying a torso-borne load. After six weeks of training, inspiratory and expiratory muscle strength increased and led to a decrease in time trial duration and a positive effect on the cardiovascular strain and the sensation of effort perception.

Using an IMT device to improve physical performance and pulmonary function while wearing torso-borne loads may also improve performance while wearing body armor. However, these studies have not specifically been conducted. It is also possible IMT improvements may also influence the injury risk of tactical athletes. Studies analyzing the kinematic and kinetic variables of load carriage have found that the use of torso-borne loads significantly increased step-width variability ($d = 0.7$), as well as hip and trunk range of motion ($d = 0.9$) (12, 58, 69, 82). A tactical athlete's ability to have better control over ventilation may improve their ability to maintain the proper posture while wearing a torso-borne load leading to enhanced performance. Lowering perceptions of exertion and dyspnea during load carriage may also lower occupational task performance.

2.6 Conclusion

The unique training requirements of tactical athletes require aerobic and anaerobic training considering the type loads they may be wearing in the field. Respiratory muscle fatigue has been shown to occur in athletes of various sports (~27% reduction in marathon runners, 10% in elite rowers, 10-15% in short duration running) (18, 65, 95). However, there is little to no information on how repeated high-intensity sprinting may be affected. Expiratory muscle fatigue has also been shown to decrease performance by 33% in time to failure during a cycle test (86). When these effects on the respiratory muscles are compounded with the inclusion of PPE and torso-borne loads in tactical athletes during occupational tasks, performance has been shown to decrease (4, 5, 8, 26, 31, 37, 39, 54, 63, 91). With the increasing urbanization of the world, tactical athletes perform their occupational duty in smaller, more compact areas, requiring more reliance on quick bouts of speed and agility rather than long-duration marches (50). While there is promising research in utilizing IMT to improve load carriage performance during aerobic activity, it is still unclear how the respiratory muscles respond to repeated sprinting while wearing PPE (33, 34, 71, 80).

3.0 Methods

3.1 Participants

Fifteen college-aged men were recruited from the university student body. Participants were recreationally active for the past year with no lower body injuries six-months before testing. A sample size of 12 was estimated *a priori* using G*Power (version 3.1.9.2) using an effect size of d = 0.93, α = 0.05, and power of 0.8 for a two-tailed repeated-measures t-test. The effect size was calculated from the difference in MIP before and after exercise from Hartz et al. (44). Participants were required to be physically active for at least one year and be injury-free for six-months before participation. A Physical Activity Readiness Questionnaire (PAR-Q) and health history questionnaire were used to establish whether they met these qualifications. Three participants were excluded after their first visit due to their inability to achieve consistent pulmonary function test results. Twelve participants (age: 25.3 ± 4.0 years; height: 179.3 ± 7.5 cm; weight: 80.7 ± 21.2 kg) were included in the final data analysis. Ethical approval was granted by the Institutional Research Board at the University of Nevada, Las Vegas and all participants provided written informed consent before participation in the study.

3.2 Protocol

Day one consisted of the participant reading and signing the IRB approved informed consent, PAR-Q, and health history questionnaire filled out, having their anthropometric data collected, and practicing the pulmonary function test's protocols. Days 2-4 consisted of performing the pulmonary tests followed by an Anaerobic Running Test under three conditions. The control condition (CNTL) had participants wearing their basic athletic attire, body armor with no plates (UNL) had participants wearing a plate carrier style body armor (2.4 kg) (SBT Banshee elite 2.0 plate carrier, Shellback, Cayce, SC, USA) with no additional weight added to the vest, and the loaded condition (LOAD) (14 kg total weight). The LOAD conditions weight was provided by a front (3.7 kg), back (3.7 kg), and two side plates (1.1 kg each) (RMA Armament, Centerville, IA, USA) with an additional four dummy rifle magazines (0.5 kg) (AR15/M16/M4 30 RD. MAG. Weighted Blue Training Long Gun Magazine, Ring's Blueguns, Melbourne, FL, USA) placed in the side pouches (two on each side). Participants put on the fully loaded vest on day one to become familiar with the weight and fit. All three conditions were completed in a random order, which was counterbalanced to reduce potential order effects.

On day one, participants had their anthropometric data collected via scale and stadiometer (seca mBCA 514, seca North America, Chino, Ca, USA). Participants were then familiarized with the pulmonary function testing procedures and practiced the maneuvers. All pulmonary function tests followed the guidelines set by the American Thoracic Society (European & American Thoracic Society, 2002) and were performed on the Vmax Encore 229 PFT system with a V62J plethysmograph (Vyaire Medical, Yorba Linda, CA). Each maneuver was performed with a nose-clip to prevent airflow through the nose. The first maneuver consisted of performing a spirometry test in the seated position. While breathing through a mouthpiece, participants were asked to perform a deep, forceful inhalation, followed by a forceful exhalation, until prompted to take an additional deep inhalation. The researcher instructed the participant to take the second inhalation after they had reached their residual volume. This maneuver was repeated after a one-minute rest and continued until three tests with a forced vital capacity (FVC) within 150 mL of each other was achieved.

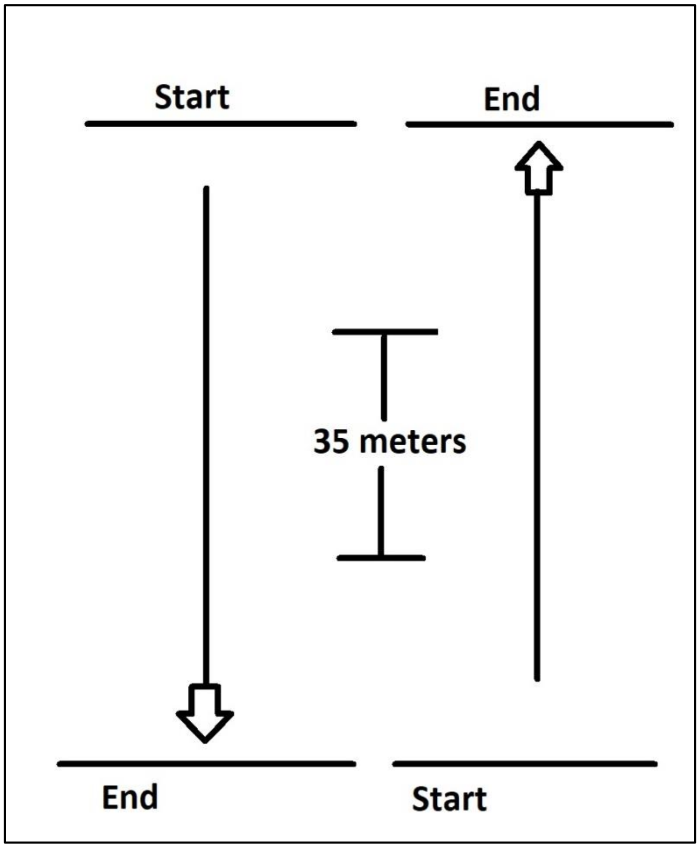
After meeting the completion guidelines for flow volume loops, participants performed a plethysmography test. Participants sat upright in the Vmax Encore Autobox with the door shut for one minute prior to the start of the test. Then participants breathed through the mouthpiece, similar to the previous test, with their hands placed gently over their cheeks. After breathing at their normal pace for at least three full breaths, they were instructed to pant at approximately 60 breaths per minute. After four pants were detected to have consistent values, the researcher initiated the test by blocking airflow via a balloon inflating in the mouthpiece. Participants continued to pant until four pants were detected to have consistent values. Once the four consistent pants were detected, the balloon deflated, and the participants were instructed to forcefully exhale until they had reached residual volume. After a verbal cue, the participant would forcefully inhale to their maximum, followed by another forceful exhalation to residual volume. This test was repeated three to seven times until three tests are within 5% for FRC.

After three acceptable maneuvers had been performed for the plethysmography test, participants performed a maximal voluntary ventilation (MVV) test. In an upright, seated position, participants formed an airtight seal around the mouthpiece and breathed normally. After a verbal cue from the researcher, participants would breathe as rapidly and deeply as possible while keeping their BPM between 90-110 for 12 seconds. The researchers gave verbal encouragement throughout the 12-seconds to help maintain an adequate breath frequency. After two tests were within 20% of MVV and breath frequency is between 90-110 BPM, the MVV test was concluded.

The maximal inspiratory pressure (MIP) test was performed from a standing position using a POWERbreathe (POWERbreathe plus™, International Ltd, Warwickshire, United Kingdom). With a tight seal around the mouthpiece, participants would exhale to residual volume, followed by a maximal inhalation lasting between one and two seconds. This maneuver was performed three to seven times to ensure there was no decline in performance. A valid test required three maneuvers to be within 10% of each other.

On days 2-4, all pulmonary tests were performed before performing the Running Anaerobic Sprint Test. On the days including the plate carrier, the participant put it on before the pulmonary tests and wore it with no adjustments until the final MIP was performed. After the participants finished the pulmonary tests, they exited the lab to an outside, marked off course to perform the Running Anaerobic Sprint Test. Two lanes, set side-by-side on level pavement, were marked off (Figure 1). Laser timing gates (Dashr Timing System™, Dashr Motion Performance Systems, Lincoln, NE, USA) were placed at the start and stop lines set 35-m apart in both lanes. There was at least 20-m of additional space at both ends to allow for deceleration after the sprints. Participants were given 10-minutes to perform a self-selected warm-up before running two 35-m sprints at half speed with a 10-second rest between runs. Before running the test, temperature, humidity, and wind speed were collected using a portable barometer (Kestrel™ 3500 Weather Meter, Kestrel Meters, Boothwyn, PA, USA). After the participant had been given one-minute rest, they performed the Running Anaerobic Sprint Test. The test involved running six 35-m sprints with 10-seconds rest between each sprint. During every rest period, participants were given a verbal countdown to ensure they were back to the start line and ready for the next sprint. Researchers gave verbal encouragement during every sprint. After the sixth and final sprint was finished, the participant was taken back inside the lab to perform another MIP test. This post-sprint MIP took place between 1.5 – 2 minutes after the participants finished their sixth sprint.

Figure 1. Running Anaerobic Sprint Test setup



3.3 Statistical Analysis

A two-by-three analysis of variance (ANOVA) was used to compare the three conditions to pre- and post-run MIP. A one-way ANOVA was used to identify significant differences between the three conditions and Running Anaerobic Sprint Test performance and the lung function measurements. Statistically significant differences were accepted at a probability level of 0.05. Pairwise comparisons were used to identify the location of differences with Bonferroni adjustments for multiple comparisons.

Effect sizes were calculated using partial eta squared (η^2) for the main ANOVA effects, where 0.01 = small, 0.06 = moderate, and >0.14 = a large effect (70). Cohens-*d* was interpreted as <0.2 = trivial, 0.2 = small, 0.6 = moderate, 1.2 = large, 2.0 = nearly perfect, >4.0 = extremely large (48). All statistical analysis tests were performed using JASP (version 0.14).

4.0 Results

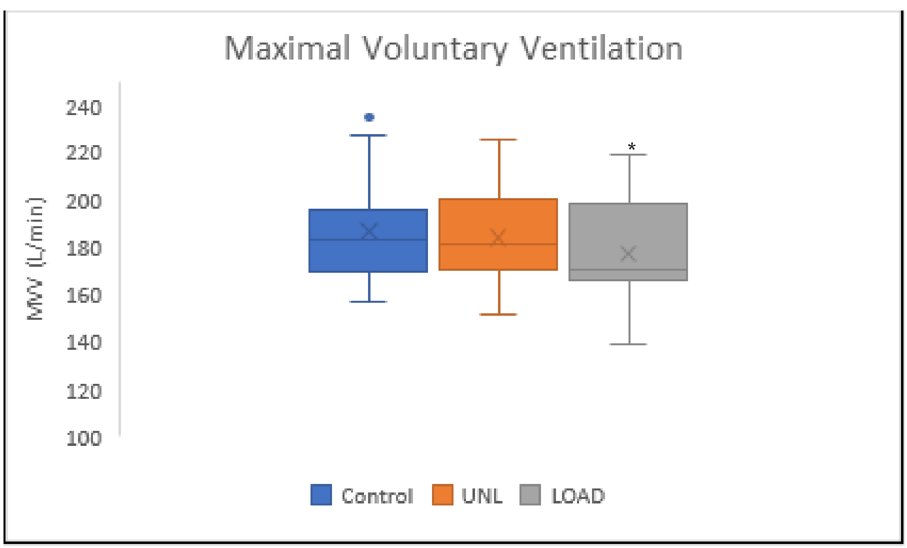
An analysis of variance showed body armor significantly affected: FVC ($F[2,22] = 4.473$, $p = 0.023$, $\eta^2 = 0.289$), PEF ($F[2,22] = 4.094$, $p = 0.031$, $\eta^2 = 0.271$), MVV ($F[2,22] = 3.894$, $p = 0.036$, $\eta^2 = 0.261$), TLC ($F[2,22] = 8.984$, $p = 0.001$, $\eta^2 = 0.450$), FRC ($F[2,22] = 17.388$, $p < 0.001$, $\eta^2 = 0.613$), VC ($F[2,22] = 5.889$, $p = 0.009$, $\eta^2 = 0.349$), IC ($F[2,22] = 3.740$, $p = 0.040$, $\eta^2 = 0.254$), and ERV ($F[2,22] = 7.908$, $p = 0.003$, $\eta^2 = 0.418$) (Table 2). Post hoc analyses using the Bonferroni post hoc criterion for significance indicated a lower FVC ($p = 0.02$, $d = 0.3$), MVV ($p = 0.04$, $d = 0.4$) (Figure 2), TLC ($p = 0.002$, $d = 0.5$), FRC ($p < 0.001$, $d = 0.8$), VC ($p = 0.016$, $d = 0.3$), and ERV ($p = 0.004$, $d = 0.7$) in the LOAD condition compared to CNTL. Post hoc also indicated a significantly lower FRC ($p < 0.001$, $d = 0.6$) and ERV ($p = 0.012$, $d = 0.6$) in UNL condition compared to the CNTL and a significantly lower TLC ($p = 0.013$, $d = 0.4$) and VC ($p = 0.019$, $d = 0.2$) during the LOAD condition compared to UNL.

Table 2. Spirometry and Plethysmography data

	CNTL	UNL	LOAD
FVC (L)	5.2 ± 0.7	5.1 ± 0.7	5.0 ± 0.7*
FEV_1 (L)	4.3 ± 0.6	4.2 ± 0.6	4.2 ± 0.6
FEV_1/FVC (%)	82.5 ± 4	82.3 ± 4.3	83.4 ± 5.2
PEF (L/sec)	11.2 ± 2.6	10.6 ± 2.3	11.2 ± 2.1
MVV (L/min)	186.9 ± 23.7	184.2 ± 21.2	177.3 ± 22.3*
TLC (L)	6.6 ± 0.9	6.5 ± 0.9	6.2 ± 0.8*†
FRC (L)	3.6 ± 0.7	3.1 ± 1.0*	3.0 ± 0.8*
RV (L)	1.4 ± 0.5	1.3 ± 0.5	1.3 ± 0.7
VC (L)	5.3 ± 0.7	5.3 ± 0.7	5.1 ± 0.7*†
IC (L)	2.9 ± 0.8	3.3 ± 1.1	3.4 ± 0.9
ERV (L)	2.1 ± 0.8	1.7 ± 0.9*	1.6 ± 0.7*†

* indicates a significant difference compared to CNTL ($p < 0.05$)
† indicates a significant difference compared to UNL of ($p < 0.05$)

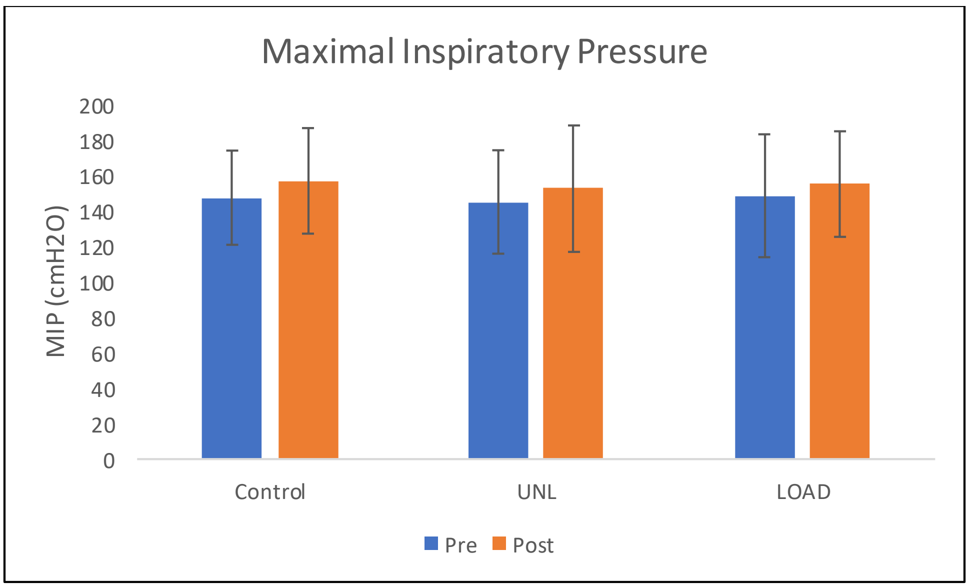
Figure 2. Maximal Voluntary Ventilation



* indicates a significant pairwise difference compared to CNTL ($p < 0.05$)

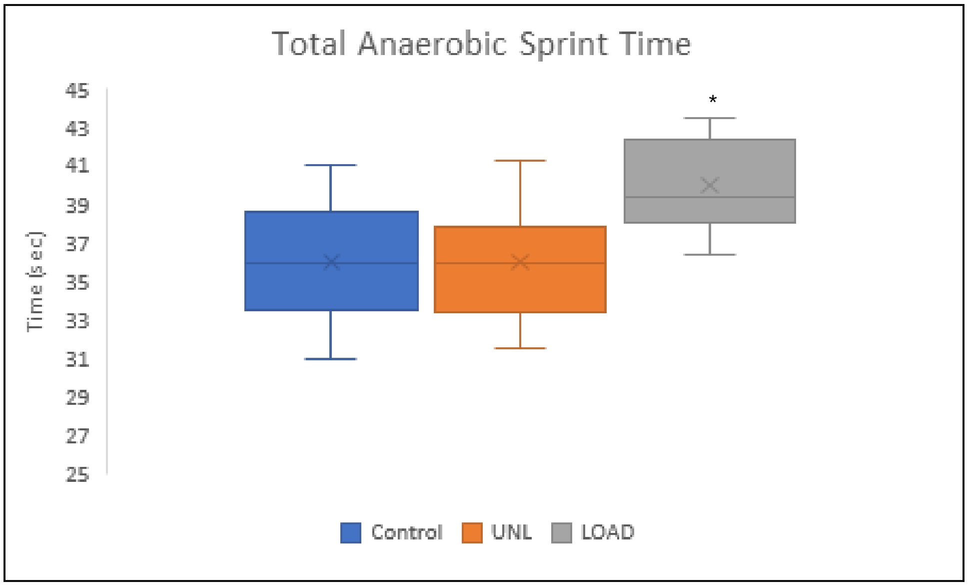
A two-way analysis of variance yielded no significant main effects for MIP x condition, $F(2,22) = 1.049$, $p = 0.367$, $\eta^2 = 0.022$. MIP performed pre- and post- Running Anaerobic Sprint Test did not significantly differ between the three conditions (Figure 3). There was a main time effect for MIP, $F(1,11) = 10.25$, $p = 0.008$, $\eta^2 = 0.126$, such that post-run MIP was significantly greater (155.0 ± 31.0 cmH_2O) than pre-run (147.2 ± 29.5 cmH_2O).

Figure 3. Maximal inspiratory pressure pre- and post- sprint test



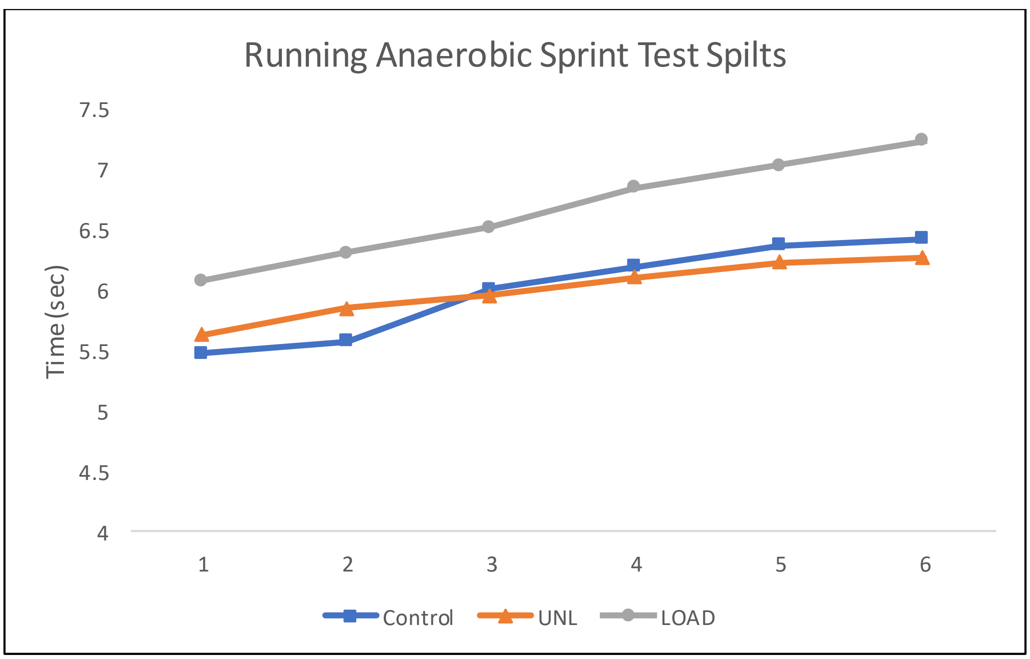
An analysis of variance of total run time was significant, $F(2,22) = 54.76$, $p < 0.001$, $\eta^2 = 0.833$. Post hoc analyses using the Bonferroni post hoc criterion for significance indicated that total running time was significantly higher in the LOAD condition (40.0 ± 2.3 sec) than in both the CNTL (36.0 ± 3.0 sec, $p < 0.001$, $d = 1.5$), and UNL (36.0 ± 3.0 sec, $p < 0.001$, $d = 1.5$) (Figure 4 & 5).

Figure 4. Running Anaerobic Sprint test total time



* indicates a significant pairwise difference compared to CNTL ($p < 0.05$)

Figure 5. Running Anaerobic Sprint test split times



5.0 Discussion

The purpose of this dissertation was to examine how body armor affects pulmonary function, inspiratory muscle strength, and athletic performance during repeated, high-intensity sprints. Results indicated using a plate-carrier style body armor with a load reduced FVC by ~4%, MVV ~5%, TLC ~6%, FRC ~ 17%, VC ~4%, and ERV ~24%. There was also an increase in the MIP post-sprint test independent of the condition. Running Anaerobic Sprint performance was ~10% slower in the LOAD condition compared to the CNTL.

5.1 Pulmonary Function and Lung Capacity

The current study's pulmonary function results are similar to previous research using plate-carrier style body armor (4, 5, 39, 56). Legg conducted one of the earliest studies to look at body armor's effect on pulmonary function. Body armor was found to have a small yet significant decrease in FVC of 2-3 % using a relatively light armor vest (4.2 kg) (56). Considering the weight of modern armor is closer to 14 kg with both front and back plates plus side plates, our findings of a 4% decrease in FVC are more in line with modern research looking at various body armor styles (4, 39). However, unlike previous research, our participants did not have a significant reduction in FEV_1. The difference between our studies may have been due to our participants sitting rather than standing, allowing for less movement of the thorax. Townsend found that standing allows for a significantly greater FVC and FEV_1 than when sitting (90). It is also possible that our body armor system's weight slightly assists in expiration due to the increased descending forces applied to the thoracic cavity. Armstrong and Gay found a decrease of 6% in FEV_1 using a body armor system with a similar style to ours, but with a flexible plate and about half the weight (4). However, when using a non-flexible plate and similar weight to our system, they found no significant difference in FEV_1. The style of flexible plates used by Armstrong and Gay may have provided enough chest restriction to decrease pulmonary function. Still, the weight of the system was also heavy enough to assist in expiration. Armstrong and Gay also utilized a standing position during their spirometry testing (4). Our results may indicate that extra weight may aid in expiration, but thoracic restriction may hinder inspiration.

While the additional load may assist in the expiration due to higher depressing forces on the thoracic cavity, it appears the restrictions on inspiration outweigh the expiration benefits. Our results found a decrease in MVV by ~5% in the LOAD condition compared to the CNTL. This difference in MVV would indicate that the use of body armor hinders the more active action of inspiration. Our findings of a decrease in MVV agree with most of the literature involving body armor and heavier torso-borne loads such as backpacks (4, 5, 39, 55, 56, 63). Considering how well MVV results correlate with dyspnea and exercise capacity, it is an important variable to consider when balancing body armor weight with performance and protection. Armstrong et al. found using a looser-fit rucksack resulted in an 11% greater MVV compared to the same load in a tighter configuration (5). Other studies have found body armor systems that add restriction to the abdomen or reduce the system's elasticity, such as including a cummerbund or side plates, also contribute to reducing pulmonary function (4, 57, 60). Considering pulmonary function has been shown to decrease both with chest wall restriction and torso-borne loads, it is vital to consider the tightness of the torso-borne weight, whether it be a body armor vest or a rucksack. When the chest wall restriction is isolated through specialized equipment, pulmonary function is significantly reduced by 5-16% in proportion to the pressure applied (20, 23). A similar inverse relationship has been shown with torso-borne loads and pulmonary function, indicating a need to balance loads and tightness (5, 14, 31, 32, 38).

While there have been numerous studies examining body armor and other torso-borne loads using spirometry, to the researcher’s knowledge, this is the first-time plethysmography has been used with body armor. Plethysmography with lung volume measurement offers a more detailed and comprehensive picture of pulmonary function than spirometry alone. Our results indicated a 6% decline in TLC and a 17% decline in FRC in the LOAD condition compared to the CNTL.

Our results indicate a mechanical reduction in total lung capacity due to wearing a plate-carrier style body armor. Reductions in TLC are typically seen in obese individuals and restrictive lung disorders (24). Having a lower total lung capacity while wearing body armor may increase respiratory muscle work due to increased respiration rate (96). A significantly lower VC in LOAD compared to both the CNTL and UNL indicates that participants wearing body armor have access to a lower volume of air, leading to an increase in respiratory rate. This increase could be exacerbated by the increased workload of carrying more weight during physical activity. We know that energy expenditure increases with torso-borne loads, but it has also been shown to increase the IMF (25, 27, 32, 55, 85). All of these variables can compound to decrease performance in tactical athletes while wearing torso-borne loads. Some research has shown benefits in training the respiratory muscles to become strong under loads; however, these studies have only focused on load carriage performance using a rucksack (33, 34, 80, 81). It is unclear if the same benefits could be gained by a more restrictive system such as plate-carrier style body armor.

Unlike the loads applied to the torso via a backpack, body armor surrounds the whole thoracic cavity, and some systems may extend further down, adding additional resistance to the abdomen. This restriction could be comparable to the thoracic restriction seen in obese populations (7, 98). Our results are similar to those found by Watson et al., comparing lung capacity in obese men to men with a BMI lower than 27.5 kg/m^2 (98). Watson found that the obese group had significantly lower TLC (~17%), FRC (~36%), and ERV (~58%) compared to the CNTL group. While these decreases to lung capacity were smaller in our study, TLC (~6%), FRC (~27%), and ERV (~24%), the same values were also found to be significantly lower between the LOAD and CNTL group.

Interestingly, our LOAD condition did have a significantly lower VC (d = 0.3), unlike Watson et al., whose VC value in the obese group had a larger effect size than ours (p = 0.063, d = 0.9). It should also be mentioned that while FRC and ERV were significantly lower in our study in both LOAD and UNL conditions, only the LOAD condition had a significantly lower VC compared to both the CNTL and UNL. This difference between our studies may be due to the obese group being more accustomed to the added restriction, where our participants were unaccustomed to the loaded and restrictive condition. These similarities between wearing body armor and obesity may be of particular importance to some tactical populations seeing an increase in obesity rates (3, 19, 83). Adding a restriction on top of an already restrictive thoracic cavity may lead to even further performance decreases. Considering these layers of potential performance decreases, facilitators working with tactical athletes should strive to maintain healthy body composition, especially when the athlete is required to wear heavier torso-borne loads. Performance decreases due to poor pulmonary function in the tactical athlete can lead to the failure of their occupational duty leading to injury or loss of life of the athlete or individuals around them.

5.2 Maximal Inspiratory Pressure

Research has extensively studied the IMF in various physical activity events over long periods (1, 18, 21, 27, 46, 51, 89, 94). Due to the high demand for oxygen and the elimination of CO_2, the prolonged increase in respiratory rate during aerobic activity should be the most common activity for IMF to occur. However, anaerobic activity, especially when a torso-borne load is involved, may still elicit IMF in a shorter period of time due to an increase in respiratory rate to eliminate CO_2 and provide oxygen for the resyntheses of PCr (9, 36, 43, 61). A small number of studies have examined anaerobic activity and the IMF and little to no research on how a torso-borne load may influence anaerobic activity. Ohya et al. found that a single 400-meter sprint was enough to significantly decrease MIP in elite female runners by 10%, with an even greater decrease of 15% during an 800-m sprint (65). Ohya et al. is one of the few studies that has demonstrated a decline in MIP after an anaerobic activity; however, it is unclear if these results would change after repeated bouts of shorter duration sprints.

Based on our results, the IMF does not appear to occur after a short, high-intensity repeated sprint protocol. MIP significantly increased independent of the condition ($\eta^2 = 0.13$). This increase may be caused by a slight post-activation potentiation (PAP) effect in the inspiratory muscles. The increased performance from doing a short, non-fatiguing activity immediately before another activity has been well established in many different anaerobic and resistance training activities. However, to our knowledge, this is the first instance observed in the respiratory muscles (16, 52, 99). This increase in MIP post-exercise may indicate anaerobic activity eliciting a training response to the respiratory muscles. Previous literature has shown that while endurance athletes have higher MIP compared to untrained and power athletes, power athletes also had significantly higher MIP compared to untrained individuals ($d = 1.12$) (76). Incorporating any style of training may increase inspiratory muscle strength, but for tactical athletes, incorporating both may have the most benefit.

Maximizing ventilation between bouts of activity assists in oxygen uptake and maintaining blood pH homeostasis to maximize performance. However, when tactical athletes carry additional loads but have their pulmonary function decreased due to the load and restriction placed on the thoracic cavity, understanding the IMF's role may lead to training protocols to aid in respiration. It is possible that incorporating some form of IMT into tactical athletes' training could assist with performance while wearing body armor. Faghy et al. have shown IMT to significantly increase performance while wearing a 25 kg backpack ($d = 0.9$) (33, 34). It is still unclear if IMT can be an effective training style for improvements while wearing body armor due to the different restrictions on the thoracic cavity. Considering the increase in MIP after repeated sprints, it is possible merely wearing body armor during training will elicit enough training adaption for tactical athletes to perform at a high-level during their occupational duties.

5.3 Running Anaerobic Sprint Performance

Using a plate carrier style body armor decreased repeated-sprint performance by ~10%. This decreased performance was only experienced while wearing the loaded body armor, not in the UNL condition. Decreased performance has been shown in similar studies involving body armor and task performance (26, 45, 54, 60). Larsen et al. found a similar 10% reduction to task completion while running a circuit course in full combat loads (helmet, training rifle, body armor); however, this performance decrease did not progress after repeated runs of the course (54). In addition to a decrease in task performance, there is a demonstrated inverse relationship between body armor weight and physical performance (87). The load used in the current study (14 kg) is heavier than many previous studies but did not exceed the weight used by Larsen (4, 26, 54, 56, 77). An interesting result from our study showed no significant difference between the individual split times independent of the condition. This lack of difference between a condition and split times could indicate that body armor was not enough to increase the test's sprint fatigue rate. A decrease in overall performance without an increase in fatigue rate while wearing body armor has been demonstrated before in the literature during short-duration occupational tasks and athletic performance (39, 54).

A consistent decrease in short-duration, high-intensity exercise performance while wearing body armor indicates that some physical training should include wearing body armor while performing similar tasks the tactical athlete may encounter. Adding body armor during training will add additional load, increasing overall training volume, and increase the tactical athlete's ability to maneuver under the load. Running under an additional load can increase the time to accelerate and decelerate, modify the athlete's center of gravity, and affect lower-body kinematics (26, 60, 68). These performance modifications may be reduced if the athlete trains under the additional loads they will wear during their duties. Becoming more accustomed to their occupational loads can improve the perception of exertion and breathlessness, even if the load is increased (40).

6.0 Conclusion

As the world shifts into more urban environments, tactical athletes find themselves performing their occupational duties in close quarters and congested streets and alleys. These environments are more suited for quick and agile movements than the long marches typically measured using torso-borne loads. Being able to sprint repeatedly from cover-to-cover or cross streets at maximal speeds requires the athlete to perform multiple bouts of high-intensity anaerobic activity in a short period of time. Our study found that using a plate-carrier style body armor leads to a decrease in repeated sprint performance by ~10%; however, the rate of fatigue from sprinting was not significant ($\eta^2 = 0.025$). Tactical athletes should wear whatever style of body armor they may need during their occupational duties to improve their experience while under the additional weight and thoracic cavity restriction.

While wearing body armor, pulmonary function was found to be similar to previous research that used a similar style and load as ours. However, this is the first-time lung capacity has been measured while wearing body armor. We found that TLC decreased by ~ 6% in the LOAD condition, along with a decrease in FRC of ~17%. These decreases to lung capacity are the same variables as those observed in obese populations compared to a non-overweight control, indicating that body armor has a similar thoracic restriction as that found in people with obesity. This similarity may prove problematic in tactical populations with growing rates of obesity among their ranks (3, 83). Improving body composition while training with torso-borne loads may improve job performance and lead to safer occupational task completion.

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Curriculum Vitae

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Education

- **Ph.D.**, 2020, Interdisciplinary Health Sciences, University of Nevada, Las Vegas
- **MS**, 2015, Kinesiology, California State University, Fullerton
  Thesis: Upper body muscle activation between bench press with stable and unstable loads.
- **BS**, 2011, Health and Exercise Science, University of Oklahoma, Norman

Certifications

- Certified Strength and Conditioning Specialist (CSCS), 2019 - present

Professional Experience

- Assistant Professor, 2020, Arkansas Tech University
- Co-Lab Director, 2019 - 2020, Exercise Physiology Laboratory, University of Nevada, Las Vegas
- Graduate Assistant, 2016 – 2017, 2019, Department of Kinesiology & Nutrition Sciences, University of Nevada, Las Vegas
- Assistant Lab Director, 2014 – 2015, Human Performance Lab, California State University, Fullerton, CA
- Personal Trainer, 2011 - 2012, The Health Club, Norman, OK

Research Experience

- Conducted and assisted in research utilizing the following laboratory equipment and software:
  - Plethysmography (Vmax Encore PFT System)
  - Metabolic Measurement System (Parvo)
  - Motion Capture (Vicon, Visual 3D)
  - Cycle Ergometer (Monark)
  - Velocity transducers (Unimeasure)
  - Electromyography amplifier (Myopac, Delsys)
  - Force plate (AMTI, Kistler)
  - MATLAB
  - LabVIEW data collection and analysis software
  - SPSS 21
- Conducted research in the area of strength & conditioning involving the use of Olympic weightlifting, powerlifting, and sprinting

Teaching Experience

- Arkansas Tech University, Assistant Professor, Department of Health and Physical Education:
  - Exercise Physiology, Fall 2020
  - Anatomy and Physiology, Fall 2020
- University of Nevada, Las Vegas, Teaching Assistant, Department of Kinesiology and Nutrition Sciences:
  - Exercise Physiology Laboratory, Spring & Fall 2019, Spring 2020
  - Biomechanics Laboratory, Spring 2017

Scholarships

- Northwest Native American Research Center for Health (NW NARCH) Fellowship, 2017 - 2019
- Gates-Millennium Scholarship (Native American), Bill and Melinda Gates Foundation, 2007

Funding Sought

- Research Participation Funding, UNLV Department of Kinesiology and Nutrition Sciences, $520; 2019
- Graduate Research Grant, National Strength and Conditioning Coaches Association Foundation, $5,688 (not funded); 2018
- Warrior Performance Research Grant, US Army Natick Soldier Research Development and Engineering Center, $291,404 (not funded), 2018

Memberships

- ACSM, 2012 - present, American College of Sports Medicine
- NSCA, 2011 - present, National Strength and Conditioning Association

Professional Service

- Student Managing Editor, International Journal of Exercise Science, 2019 - present
- Reviewer, Journal of Science in Sports and Exercise, 2019 - present
- Writer, Research Column, Tactical Strength & Conditioning Report, 2018 - present
- Reviewer, International Journal of Exercise Science 2017 - present
- Sports Testing, Las Vegas Golden Knights, September 2017 & June 2019
- Reviewer, Journal of Strength and Conditioning Research, 2015 - present
- Sports Testing, Anaheim Ducks, September 2015 & June 2016
- Sports Testing, Los Angeles Kings, September 2014

Peer-Reviewed Journal Articles

1. Wright K, **Dunnick DD,** Navalta JW, Schilling BK. Can A Simulated Climbing Machine Test Predict Anaerobic Work Capacity? (In Preparation)

2. Dunnick DD, Guillotte C, Bhammar DM, Schilling BK. The Effect of Body Armor on Sprint Performance. (In Preparation)

3. Dunnick DD, Guillotte C, Bhammar DM, Schilling BK. The Effect of Body Armor on Pulmonary Function and Lung Volume. (In Preparation)

4. Bair AC, Strang AJ, Young JC, Kruskall LJ, **Dunnick DD**, Schilling BK. Dietary Intake and Energy Expenditure of Pararescuemen During Routine Training. (In Preparation)

5. Harry, JR, Eggleston JD, **Dunnick DD,** Edwards H, Dufek JS. Effects of Task Difficulty on Kinematics and Task Performance During Walking Workstation Use. Translational Journal of the American College of Sports Medicine. 3(11), 74-84.

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Book Chapters

1. Malyszek KK, **Dunnick DD**, Brown LE. Strength Assessment. In: Strength Training, 2nd Edition. Brown LE (Ed.) Champaign, IL: Human Kinetics, 2016.
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4. Malyszek KK, **Dunnick DD,** Brown LE. Safety, Soreness and Injury. In: Strength Training, 2nd Edition. Brown LE (Ed.) Champaign, IL: Human Kinetics, 2016.

Abstracts and Presentations

1. **Dunnick DD,** Wright K, Navalta JW, Schilling BK. A Simulated Climbing Test Is Correlated with Total Work from The Wingate Anaerobic Test, ACSM Annual Meeting, 2020
2. **Dunnick DD,** Wright K, Navalta JW, Schilling BK. A Simulated Climbing Test Is Correlated with Total Work from The Wingate Anaerobic Test, SWACSM Annual Meeting, 2019
3. **Dunnick DD.** The Effect of Body Armor on Lung Function, UNLV Rebel Grad Slam 3-Minute Thesis Competition, 2018.
4. Bartolini, JA, Nealer, AL, **Dunnick, DD**, Malyszek, KK, Wong, MA, Costa, PB, Coburn, JW, Brown, LE. Elastic-cord assistance provides sustained supramaximal-sprint speed even after assistance has lapsed. SWACSM Annual Meeting, 2016
5. Bartolini JA, Nealer AL, **Dunnick DD**, Malyszek KK, Wong MA, Costa PB, Coburn JW, Brown LE. Elastic band assisted sprints increase acute acceleration speed in collegiate female soccer players. NSCA Annual Meeting, New Orleans, LA, July 6-9, 2016. Journal of Strength and Conditioning Research, 30(12):S, 2016
6. Thornberry JH, **Dunnick DD**, Barillas SR, Malyszek KK, Brown LE. Relationship between Margaria-Kalaman stair climb and vertical jump power in males and females. NSCA Annual Meeting, New Orleans, LA, July 6-9, 2016. Journal of Strength and Conditioning Research, 30(12):S, 2016
7. Camara K, Coburn JW, **Dunnick DD**, Brown LE, Galpin AJ, Costa PB. An examination of muscle activation and power characteristics while performing the deadlift exercise with straight and hexagonal barbells. ACSM Annual Meeting, Boston, MA, May 31-June 4, 2016. Medicine and Science in Sports and Exercise 48(5):S, 2016
8. Harmon RA, Malyszek KK, **Dunnick DD**, Costa PB, Coburn JW, Brown LE. 32 Correlation between isometric deadlift with Olympic and hexagonal barbells to a vertical jump. ACSM Annual Meeting, Boston, MA, May 31-June 4, 2016. Medicine and Science in Sports and Exercise 48(5):S, 2016.
9. Malyszek KK, Harmon RA, **Dunnick DD**, Costa PB, Coburn JW, Brown LE. Relationship between dynamic and isometric force measured at mid-thigh and deadlift positions. ACSM Annual Meeting, Boston, MA, May 31-June 4, 2016. Medicine and Science in Sports and Exercise 48(5):S, 2016.

10. Camara K, Coburn JW, **Dunnick DD**, Brown LE, Galpin AJ, Costa PB. An examination of muscle activation and power characteristics while performing 33 the deadlift exercise with straight and hexagonal barbells. SWACSM Annual Meeting, Costa Mesa, CA, October 16-17, 2015.
11. Eckel TL, Munger CN, Malyszek KK, **Dunnick DD**, Harmon RA, Tran TT, Costa PB, Coburn JW, Brown LE. Differences between dynamic strength index and delta dynamic strength index of a hex bar mid-thigh pull. SWACSM Annual Meeting, Costa Mesa, CA, October 16-17, 2015.
12. Munger CN, Eckel TL, Malyszek KK, **Dunnick DD**, Harmon RA, Tran TT, Costa PB, Coburn JW, Brown LE. Differences in dynamic strength index between an isometric mid-thigh pull and isometric deadlift. SWACSM Annual Meeting, Costa Mesa, CA, October 16-17, 2015.
13. Barillas SR, **Dunnick DD**, Malyszek KK, Brown LE. Wingate power correlates with high intensity sprinting as distance increases. SWACSM Annual Meeting, Costa Mesa, CA, October 16-17, 2015.
14. **Dunnick DD**, Barillas SR, Malyszek KK, Brown LE. Effect of different Margaria Kalaman stair climb test analysis techniques on correlation with Wingate power. SWACSM Annual Meeting, Costa Mesa, CA, October 16-17, 2015.
15. Vahradian D, Brown LE, Coburn JW, Galpin AJ, **Dunnick DD**. An analysis of ascent and descent velocity of the lifter and barbell during a clean. SWACSM Annual Meeting, Costa Mesa, CA, October 16-17, 2015.
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20. Barillas SR, **Dunnick DD**, Brown LE, Coburn JW, Lynn SK. Upper body muscle activation between stable and unstable load during concentric bench press. ACSM Annual Meeting, San Diego, CA, May 26-30, 2015.
21. **Dunnick DD**, Barillas SR, Brown LE, Coburn JW, Lynn SK. Upper body muscle activation between stable and unstable load during eccentric bench press. ACSM Annual Meeting, San Diego, CA, May 26-30, 2015.
22. Beaudette TL, Brown LE, Coburn JW, Lynn SK, **Dunnick DD**. Acute effects of assisted jumping on relative peak power and peak velocity of a vertical jump. ACSM Annual Meeting, San Diego, CA, May 26-30, 2015.
23. Barillas SR, **Dunnick DD**, Brown LE, Coburn JW, Lynn SK. Upper body muscle activation between stable and unstable load during concentric bench press. SWACSM Annual Meeting, Costa Mesa, CA, October 17-18, 2014.
24. **Dunnick DD**, Barillas SR, Brown LE, Coburn JW, Lynn SK. Upper body muscle activation between stable and unstable load during eccentric bench press. SWACSM Annual Meeting, Costa Mesa, CA, October 17-18, 2014.
25. Beaudette TL, Brown LE, Coburn JW, Lynn SK, **Dunnick DD**. Acute effects of assisted jumping on relative peak power and peak velocity of a vertical jump. SWACSM Annual Meeting, Costa Mesa, CA, October 17-18, 2014.

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27. Beaudette TL, **Dunnick DD**, Brown LE, Coburn JW, Lynn SK. Acute effects of assisted jumping on muscle activation. NSCA Annual Meeting, Las Vegas, NV, July 9-12, 2014. Journal of Strength and Conditioning Research, 2014.