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THE EFFECTS OF BODY ARMOR ON LOWER BACK AND KNEE
BIOMECHANICS DURING BASIC AND MILITARY INSPIRED TASKS

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
at the University of Kentucky

By
Megan Pagano Phillips

Lexington, Kentucky

Co- Directors: Dr. Robert Shapiro, Professor of Kinesiology and Health Promotion
and Dr. Babak Bazrgari, Professor of Biomedical Engineering

Lexington, Kentucky

2014

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ABSTRACT OF DISSERTATION

THE EFFECTS OF BODY ARMOR ON LOWER BACK AND KNEE BIOMECHANICS DURING BASIC AND MILITARY INSPIRED TASKS

With increased military personal protection equipment, body armor, comes the addition of carried load. Such person protection in recent history has been instrumental in combating the imminent threats (e.g., improvised explosive devices) of hostile environments, preventing otherwise lethal injuries. However, body armor has been suggested to degrade warfighters' performance and compound the risk of musculoskeletal injuries. Both performance and risk of injury are intensely related to joint biomechanics. Therefore the objective of this project was set to determine the immediate and prolonged effects of wearing body armor on biomechanics of the lower back and knee. A randomized cross-over study design, wherein 12 sex-balanced, physically fit, young participants completed a series of tests before and after 45 min of treadmill walking with and without body armor. Tests included two simple tests (i.e., toe-touch and two-legged squat), two military inspired tests (i.e., box drop and prone to standing) and four knee torque tests (i.e., maximum isometric contraction of knee flexors and extensors, and concentric and eccentric isokinetic contraction of knee flexors and extensors). During these tests, kinematic, kinetic and torque measurements were used to investigate the immediate and prolonged effects of exposure to body armor on several measures of knee and lower back mechanics related to performance and risk of injuries.

For the simple tests, the immediate effects of body armor were an increase of > 40 ms ($p \leq 0.02$) in flexion duration of the dominant joint and an ~ 1 s ($p \leq 0.02$) increase in overall test duration as well as an $\sim 18\%$ ($p = 0.03$) increase in the lumbopelvic rhythm ratio near mid-range trunk flexion. For the military inspired tests, the immediate effects of body armor were an increase of ≥ 0.02 s ($p \leq 0.001$) in temporal test durations and an increase of ~ 158 N ($p = 0.01$) box drop peak ground reaction force. Finally during the dynamometer testing, the BA condition was found to cause a greater reduction, ~ 10 N·m, in the maximum isometric strength of knee flexors ($p = 0.04$) and an increase ($p \leq 0.03$) of strength ratios compared to the no armor condition.

KEYWORD: Military Body Armor, Prolonged Walking, Performance, Risk of Injury,
Military Ergonomics

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December 2, 2014
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THE EFFECTS OF BODY ARMOR ON LOWER BACK AND KNEE
BIOMECHANICS DURING BASIC AND MILITARY INSPIRED TASKS

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List of Acronyms and Abbreviations

ALICE	All-Purpose Lightweight Individual Carrying Equipment
BA	Body Armor
BD	Box drop
ESAPI	Enhanced Small-arms Protective Inserts
FS	Foot Strike
GRF	Ground Reaction Force
IRMSCs	Injury Related Musculoskeletal Conditions
IBA	Interceptor Multi-Threat Body Armor
IMTV	Improved Modular Tactical Vest
IOTV	Improved Outer Tactical Vest
ITAR	International Traffic in Arms Regulations
LPR	Lumbopelvic Rhythm
MOLLE	Modular Lightweight Load-Carrying Equipment
MTV	Modular Tactical Vest
NM	Neuromuscular
OTV	Outer Tactical Vest
PAGST	Personnel Armor System for Ground Troops
PS	Prone-to-standing
Q:H	Quadriceps to Hamstrings
SAPI	Small-arms Protective Inserts
TLS	Two-legged Squat
TOFF	Toe Off
TT	Toe-touch
U.S.	United States
VO ₂	Maximal Oxygen Consumption; Maximum Oxygen Uptake

Chapter 1 Introduction and Specific Aims

1.1 Introduction

Military body armor's (BA) primary and crucial purpose is to provide personal protection to dismounted warfighters, against the deleterious threats of improvised explosive devices, small arms, armor piercing rounds, ballistic blasts, blunt trauma, and shrapnel. The evolution of BA since 2001 (i.e., start of Operation Enduring Freedom and Operation Iraqi Freedom) has been identified as one of the instrumental factors associated with the > 90% survivability rate of injured warfighters [1]. The lowest proportion of thorax wounds (6%), and reduction in conventional war injuries has been largely attributed to BA [2, 3]. Specifically, abdomen casualties associated with genitourinary injuries had a 2.1% rate of injury, and kidney injuries had a 0.5% rate of injury, the lowest rates documented in the past 70 years of conflict [3].

However, with greater personal protection come trade-offs. Trade-offs associated with risk of injury related musculoskeletal conditions (IRMSCs) and reduced performance. Unlike a warfighter's load carriage system (i.e., backpack type apparatus to carry equipment and supplies), BA is rarely removed when operating in-theater [4]. Non-combat IRMSCs have a ~63% prevalence among U.S. service members (Hauret *et al.* 2010). In 2006, IRMSCs accounted for ~25% of the medical evacuations from Afghanistan compared to the ~7% of evacuations associated with combat injuries (Cohen *et al.* 2010). Additionally, they impose an immense economic challenge (~ \$1.5 billion in 2006) to the federal government, medical treatment facilities and Veterans' Administration [5, 6]. IRMSCs can lead to a disability classification for military personnel, either permanent or temporary. Temporary classifications give rise to loss of active duty status (e.g., days, weeks, or years). Permanent classifications are followed by a service member's discharge from active duty. These disability classifications and subsequent discharge from service are associated with multiple entitlements, (1) full compensation for life, (2) separation with severance pay, (3) separation without benefits, (4) temporary disability and (5) fit for duty [7]. In both of these disability classifications, IRMSCs equate to dollars and reduced manpower, wherein BA has been identified as a contributing factor to such injuries [8].

Additionally, BA adversely affects a warfighters' performance individually and also as a military unit. Individually, BA-induced reduced performance has been identified as diminished marksmanship accuracy, reduced speed and decrease mobility (e.g., increasing the time to execute a task, cross a street, clear a building, and exit/enter a vehicle [9]). Such reduced performance can be just as deadly as insufficient personal protection. In conflict zones, warfighter speed, maneuverability and accuracy are tools and weapons. Warfighters train relentlessly to hone these skills and are not commodities eagerly exchanged or surrendered. As a military unit, performance can be compromised by reduced manpower, of which another cause are IRMSCs.

Heavy loads carried by dismounted warfighters can adversely impact military force presence and sustainment, due to manpower-reducing musculoskeletal injuries and impaired warfighter's performance in combat situations [10]. BA accounts for ~20-30% of a warfighter's total carried load and has been identified as a risk factor for IRMSCs [11, 12] and therefore performance. Since 2003, full torso BA has approximately doubled in weight. The increase in BA weight comes from the requirements of handling multiple ballistic round penetrations and limiting backface deformation [13].

Despite the identified adverse effects of BA's weight on performance degradation and risk of IRMSCs, there is a heightened demand for more surface coverage protection (i.e., extremity armor). This demand is driven by the steady shift in mechanism of combat injuries, wherein explosive devices (i.e., improvised explosive devices, bombs, grenades, mortars and land mines) account for 78% of all wounds [2] and afflict the extremities to the greatest percentage (54-68%) (i.e., highest percentage of wounds caused by such mechanism) [2, 14, 15]. Thus, the demand for extended coverage, has the potential to increase the load carried, risk of injury and financial burden, while further diminishing performance. Further, understanding sex differences associated with load and extended surface coverage is relevant, due to women's increased occupational combat opportunities and their reported bias toward greater risk for certain musculoskeletal injuries than their male counterparts [16-24]. To control and limit the negative impact of BA, we must first identify how such load and surface coverage impacts a warfighter's performance and risk of musculoskeletal injury.

There is minimal literature addressing BA's effect on NM behavior related to performance and IRMSCs. A key reason being BA's association with risk of IRMSCs, reduced performance, and service connected disabilities has been developing over the past decade. This association has resulted from the evolving sophistication of the enemies explosive threats (e.g., improvised explosive devices) encountered in recent conflicts (e.g., Operation Enduring Freedom and Operation Iraqi Freedom), along with the BA modifications (i.e., increased coverage and weight) to address such threats. However, new studies are emerging related to BA's effect on warfighters' performance, and risk of injury that are summarized in the next few sections. A more comprehensive review of this literature is given in Appendix A.

1.1.1 Physical exertion and body armor

Physical exertion studies found a significant increase in heart rate while treadmill walking for a moderate (i.e., 30 minutes) and prolonged intermittent (i.e., 4 hr) durations while wearing BA [25, 26]. Additionally, an increase in maximum oxygen consumption (VO_2) was reported while walking and running with three different armor conditions [27]. Finally multiple groups reported increased heart rate, increased core temperature and increased rating of perceived exertion while participants performed a circuit of military tasks with BA [28, 29]. From these studies, an overall noticeable increased demand (i.e., physiological measures of performance) of physical activity was observed while wearing BA.

1.1.2 Performance and body armor

Performance based studies observed increased times to complete runs, sprints, shuttle runs, and military inspired obstacle courses and circuits with BA [27-31]. They also reported altered walking and running biomechanics [27, 32, 33], decreased maximum number of box lifts [27], balance impairments [30, 34], decreased number of pull-ups, decreased hang time, decreased stair stepping and altered grip strength [26] while wearing armor. As a whole, these examples highlight the performance decrement induced by BA.

1.1.3 Injury and body armor

Warfighter comfort and risk of injury have been investigated as it related to BA. During a six month period in 2006, ~3500 Army soldiers were surveyed while deployed to various locations in Iraq. The results revealed two times as many soldiers attributed their increased back, neck and upper extremity pain to wearing BA than performing their occupational tasks or participating in physical training [12]. More recently, it was reported that with increase BA weight conditions, study participants reported increased neck, shoulder, and lower back pressure and strain [35]. Additionally, gait kinematics and temporal-spatial parameters association with BA and risk of IRMSCs have been reported by Park, Nolli [33].

Walking and running at a set pace on a treadmill may provide insight into the performance and risk of IRMSCs associated with a road march in varying BA conditions, but may not provide the necessary insight into performance and risk of IRMSCs associated with military tasks and combat situations. A warfighter must be able to carry loads to the battlefield but also navigate the battlefield while confronted by hostile threats. Likewise, knowing military task decrement associated with BA conditions may provide insight into military performance but is not sufficient to determine risk of IRMSCs. The fundamental mechanism(s) responsible for such diminished performance continues to be elusive. Likewise, the effects of BA on risk of injury remains to be thoroughly investigated.

1.2 Conceptual model

Loads and stability of the musculoskeletal system depend on the mechanical behavior of the system and the physical demands of the task/mission. The mechanical behavior of the system is a function of passive mechanical properties of tissues and active mechanical responses of the neuromuscular (NM) system to equilibrium and stability requirements. Active mechanical response involves both feedforward (via muscles) and feedback (via sensory mechanisms) aspects of NM behaviors. More important are the physical demands of the task/mission when assessing the effect of BA on loading and stability on musculoskeletal system. Physical demands of a task will affect loading and stability not only by altering the kinematics (posture, motion), and kinetics (force) of the musculoskeletal system, but also by their effects on the mechanical behaviors of the

system. Viscoelastic changes in tissue, alterations in muscle force generating capacity, and changes in muscle spindle sensitivity [36-38] following prolonged loading conditions (which is the case when wearing BA) will substantially affect the mechanical behaviors of the system. These changes need to be accounted for when assessing the effects of BA on biomechanics of the musculoskeletal system. On this basis, BA can potentially increase the risk of IRMSCs via its influence on the demand of a task/mission and mechanical behaviors of musculoskeletal system. Masses and volumes of BA components which are located on extremities and the trunk will alter the mechanical demands of a tasks performed by warfighters through their effects on inertial properties of body segments as well as stiffness and range of motion of joints. Persistent influences of such biomechanical effects over prolonged operations, will further affect mechanical behaviors of the system.

1.3 Objective and specific aims

The objective of this exploratory project was to understand how BA affects the NM behavior of the musculoskeletal system, specifically the knee and lower back, related to risk of IRMSCs and performance. The central hypothesis was that BA-induced changes in NM behavior of the knee and lower back would be associated with reduced performance and increased risk of injury hence enabling us to identify potential pathways linking BA with reduced performance and increased risk of injury. This work was carried out through Specific Aims 1-2.

Specific Aim 1: Determine the effects of military body armor on the lower back and knee mechanics:

a. during toe-touch and two-legged squat tests

Whole body kinematics of participants performing two simple tests (i.e., toe-touch (TT) and two-legged squats (TLS)) were analyzed at the knee and lower back for armor and no armor conditions pre- and post-exposure (i.e. 45 minutes of brisk treadmill walking).

b. during box drop and prone-to-standing tests

Whole body kinematics and force platform (i.e., kinetic) data of participants

performing two military inspired tests (i.e., box drop (BD) and prone-to-standing (PS)) were analyzed at the knee and lower back for armor and no armor conditions pre- and post-exposure (i.e. 45 minutes of brisk treadmill walking).

For Specific Aim 1, it was hypothesized that BA-induced changes in NM behavior would alter timing, kinematics and kinetics (SA 1(B) only) of the lower back and knee joints during the tests considered. Specifically, it was hypothesized that BA-induced changes in our outcome measures would be consistent with increased risk of IRMSCs (e.g., increased loading rate or joint moment) and/or impaired performance (e.g., increased time). Finally, it was hypothesized that the above mentioned changes of the lower back and knee mechanics would be amplified with duration of wearing BA.

Specific Aim 2: Determine the Effects of Military Body Armor on Isometric and Isokinetic Knee Behaviors

Isometric and isokinetic behavior of the knee flexors and extensors were analyzed for armor and no armor conditions pre- and post-exposure (i.e., the completion of all simple and military tests before and after 45 minutes of brisk treadmill walking). It was hypothesized that exposure-induced changes in NM behavior would reduce maximum force generation capacity of the knee extensor and flexor muscles during isokinetic and isometric testing. It was also hypothesized that exposure-induced changes in NM behavior would increase isokinetic quadriceps to hamstrings strength ratios. Further these changes in our outcome measures were expected to be consistent with amplified risk of IRMSCs and/or compromised performance.

Changes in kinematics (e.g., joint angles and range of motion), kinetics (e.g., net joint moments), temporal parameters, as well as, isometric and isokinetic measures were used to identify if the immediate and prolonged exposure to BA had a significant effect on the NM behavior of the musculoskeletal system. Further, if these changes were indicative of an increased risk of IRMSCs and reduced performance.

The following chapters of this dissertation are presented in a manner to address each specific aim and provide a comprehensive embodiment of this project. Chapter 2 will focus on Specific Aim 1(a), determining changes in several measures of knee and lower

back mechanics as related to performance and risk of IRMSCs during two simple tests, TT and TLS. Likewise, Chapter 3 will concentrate on the Specific Aim 1(b), investigating knee and lower back mechanics during two military inspired tests, BD and PS. Chapter 4 will speak to Specific Aim 2, exploring the NM changes of the knee flexor and extensor muscles and their relationship to immediate and prolonged exposure to BA during isometric and isokinetic testing. Overall project discussion and future work are presented in Chapter 5. Finally, the appendices contain a literature review, a complete description of tests conducted during experimental testing sessions, institutional review board documentation and International Traffic in Arms Regulations (ITAR) documentation.

Chapter 2 The Effects of Military Body Armor on the Lower Back and Knee Mechanics during Toe-touch and Two-legged Squat Tasks

This chapter reproduced from an accepted manuscript, Phillips, M., B. Bazrgari and R. Shapiro. "The effects of military body armor on the lower back and knee mechanics during toe-touch and two-legged squat tasks." *Ergonomics*. 27 October 2014 (online)."

2.1 Introduction

Military BA has been proven effective in the prevention of otherwise lethal injuries [13]. However, such success has come at the expense of a significant increase to the weight carried by dismounted warfighters. Since 2003, the weight of full torso BA has substantially increased due to the added requirements of handling multiple ballistic round penetrations and limiting BA back face deformation [13]. This new generation of BA constitutes up to ~21% of the total load carried by warfighters [13, 39]. Moreover, as a result of increased casualty survival rate, there has been a rise in number of extremity injuries [40, 41], motivating further increase in BA weight to address the need for extremity protection.

A warfighter's load, performance and risk of injury are intimately related. Heavy loads have been reported to result in reduced performance, unnecessary deaths and lost battles [42-45]. It has also been suggested to be an important risk factor for IRMSCs costing the Department of Defense >\$1.5 billion per year. Hence, control and management of such adverse effects require an understanding of the underlying mechanisms linking warfighter's load to reduced performance and increased risk of IRMSCs.

Contrary to research related to load carriage [46-51], limited research has been done on the effects of BA on performance. BA has been shown to adversely affect several physical (i.e., hand grip strength, stair step duration, timing of gait events and balance) and physiological (i.e., oxygen uptake and heart rate) measures of performance [27, 30, 34, 35, 52]. Such adverse effects have been shown to increase with the level of load [34, 35, 52] and coverage area [34, 35, 53]. Wearing BA has also been associated with impaired performance of individuals during high intensity tasks [29]. However, the underlying mechanism(s) responsible for such impaired performance remains unclear. Moreover, the effects of BA on risk of IRMSCs have not been investigated in the past.

It is well accepted that abnormal mechanics of the human joints are the proximate cause of most IRMSCs [11]. Abnormal mechanics means stress and strain distributions within a joint and its surrounding tissues that instantaneously or cumulatively exceed their injury thresholds. For any joint, such stress and strain distributions depend on the equilibrium and stability status of the joint. Equilibrium and stability of a joint are in turn directly affected by the interaction between the external physical demand of task and corresponding internal tissue responses (Figure 2.1). The added weight and inertia of BA increases the physical demands of tasks performed by dismounted warfighters. Furthermore, a prolonged period of exposure to BA can alter both the active and passive mechanical responses of tissues in response to task demands. Examples of such changes include viscoelastic changes in tissue, alterations in muscle force generating capacity and changes in muscle spindle sensitivity [36-38]. Performance is also in part dependent on the mechanical response of tissues to task demand. As such BA-induced alterations in mechanical tissue responses not only affect the mechanical environment of the joint (e.g., risk of IRMSCs) but also influence the warfighter's performance.

Based on the conceptual model, described in the previous paragraph, we have conducted a project which was designed to assess the effects of BA on an individual's performance as well as on knee and lower back (i.e., two locations with highest number of IRMSCs) [54] risk of injury. Within that larger project, the objective of this study was to quantify BA-induced kinematic and temporal changes in several aspects of the lower back and knee mechanics during two basic tasks, each involving large isolated mechanical demands on either the lower back or knee. The underlying rationale for starting with these two basic tasks rather than military-inspired tasks was that while imposing considerable large mechanical demand on the joint, the simplicity of these tasks facilitated achieving our goal of unraveling and understanding the underlying mechanism responsible for the higher prevalence of knee and lower back injuries among this cohort. It was expected that BA-induced changes in tissue responses would be reflected in our kinematics and time measures. In particular, it was hypothesized that BA-induced changes in tissue responses would alter timing and excursion of lower back and knee joints during the considered tasks. Furthermore, it was hypothesized that BA-induced changes in our outcome measures would be consistent with increased risk of IRMSCs

and/or impaired performance. Finally, it was hypothesized that the above mentioned changes of the lower back and knee mechanics would be amplified with duration of wearing BA.

2.2 Methods

2.2.1 Study design

A cross-over study design was used to test the effects of BA and wear duration on several measures of the lower back and knee tissues behavior related to performance and risk of IRMSCs. Participants attended two testing sessions, within a 7-day period, each

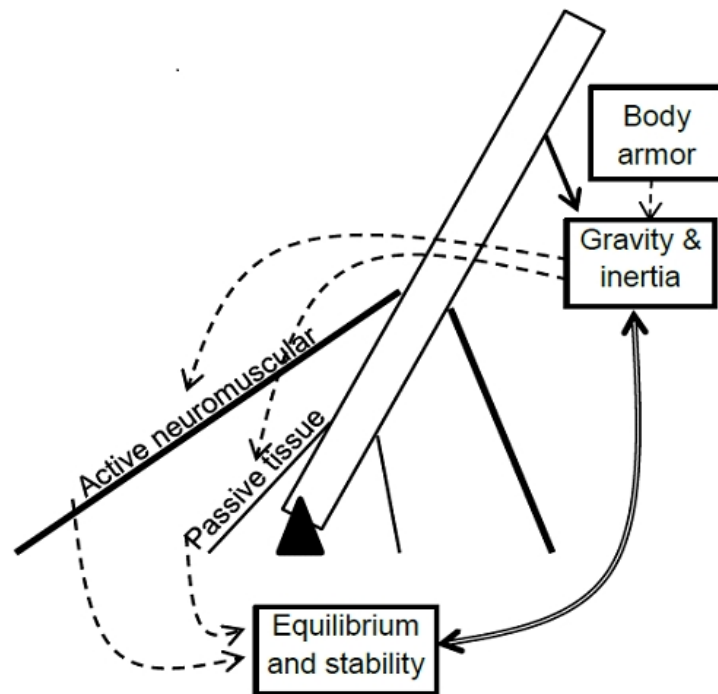


Figure 2.1: A conceptual model for the underlying mechanism(s) that links BA to increased risk of IRMSCs via BA-induced changes in tissue responses and its resultant effects on joint mechanical environment.

lasting ~2.5 h. In a randomized order (Figure 2.2), the participants wore no body armor at one session and body armor at the other session. During each testing session,

participants completed a randomized battery of tests before (pre-exposure) and after (post-exposure) 45 min of treadmill walking (i.e., hereafter called exposure) at a speed of 1.65 m/s (5.95 km/h) to simulate a military foot march [55]. Therefore, each test was performed four times by each participant (two testing sessions \times two exposure conditions). A complete list of the physical tests performed during each session along with their respective methods and order randomizations can be found in Appendix B. In this paper, we only present methods and results from two tests: (1) repetitive toe-touch (TT) and (2) repetitive two-legged squat (TLS) motions.

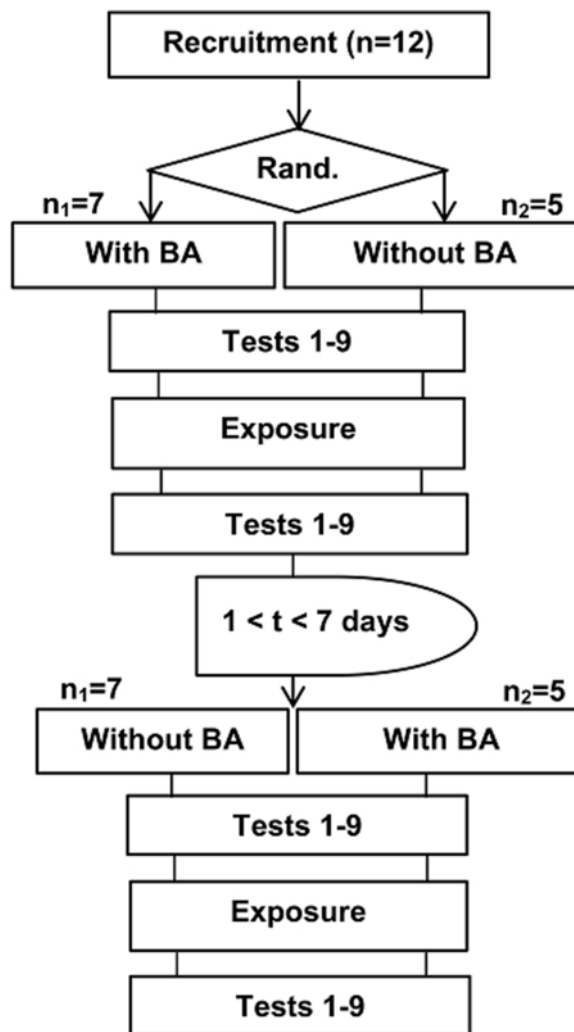


Figure 2.2: Study design. Where ‘Exposure’ refers to our walking protocol and ‘*t*’ refers to washout time.

2.2.2 Participants

Twelve asymptomatic, sex-balanced, young individuals volunteered for this study. Mean (standard deviation) age, weight, and height were 26.67 (5.47) years, 78.77 (9.41) kg and 1.79 (0.05) m for males and 24.00 (5.02) years, 61.54 (7.38) kg and 1.66 (0.10) m for females. Following a consenting process, approved by the University of Kentucky's Institutional Review Board, participants completed a Par-Q medical questionnaire [56] and Tegner scale [57] to ensure their ability to complete vigorous exercise without medical supervision. All participants were highly active and had extensive experience with load carriage. Participants consisted of current and previous active duty and reserve service members, one male collegiate cyclist/avid backpacker and one female cross-fit athlete.

2.2.3 Testing procedures

For the experiments, participants were asked to wear athletic clothing, while sport shoes were supplied by the experimenters to decrease confounding factors. In the 'A' testing sessions, participants also wore a protective vest with two ceramic thorax plates in conjunction with upper arm and thigh plates (106N in total; same size armor used for all subjects) that were carried during instrumentation, tests and exposure.

Participants were instrumented with reflective markers to capture the motion of their body segments. Initially, a static marker set consisting of 77 reflective markers, to include several rigid clusters of three and four markers, was strategically attached on each subject using double-sided toupee tape. Markers denoting anatomical landmarks (i.e., 22 markers) were then removed following quantification of their geometrical relationship with tracking marker using a standing '*t-pose*' calibration procedure. The remaining markers were then used for tracking during the TT and TLS tests, using a motion capture system involving 10 cameras (Motion Analysis, Santa Rosa, CA). Motion data were sampled at 120 Hz and then filtered using a second order, low pass, bi-directional Butterworth filter. A cutoff frequency of 10 Hz was determined using the residual method described by Winters [58]. For the TT test (i.e., test 1), participants started with their feet shoulder width apart, shoulders in 90° of forward flexion, elbows extended with palmer side of hand parallel to the floor. Participants were instructed to touch their toes with their hands, while

keeping their knees as straight as possible and return to the starting position. For TLS test (i.e., test 2), participants started with their feet shoulder width apart, their shoulders in 90° of forward flexion, elbows in 90° of flexion and hands in neutral position. Participants were instructed to lower themselves by flexing their knees and keeping their trunk as upright as possible until their thighs were parallel with the floor and then return to the starting position.

For both the TT and TLS tests, participants were instructed to repeat the motion non-stop 10 times both using a self-selected (as fast as possible) and a metronome-generated pace. The former pace was set to evaluate their performance while the latter was set to evaluate risk of injury. The metronome paces were 60 beats/min and 80 beats/min for the TT and TLS tests respectively. If the proper form was not maintained throughout the duration of the test, participants were asked to repeat the test.

2.2.4 Data analyses for TT and TLS tests

Kinematic data were collected and tracked with Cortex (v3.6, Motion Analysis Corp, Santa Rosa, CA). Three dimensional (3D) coordinate data and calculations of outcome measures were performed using Visual 3D (C-Motion Corp, Germantown, MD) and an in house Matlab (Mathworks, Natick, MA) program. Joint angles were determined using Visual 3D's default segment coordinate system (+z up and +y anterior), a standard Cardan angle rotation (x-y-z). All outcome measures in this study are reported in the sagittal plane.

For each test, trial duration was defined as the time to complete the test (i.e., 10 repetitions of each motion) and was calculated as the time difference between the times of 1st and 11th maximum z-position of a C7 marker (on a cluster) and the L5S1 marker for the TT and TLS tests respectively (Figure 2.3). The flexion time (i.e., ~half time of a repetition) of the dominant joint (i.e., lower back for TT tests and knee for TLS tests) was calculated as the mean (i.e., over the 10 repetitions of each motion) of the time differences between the times of maximum and minimum angles of the joint during each repetition (Figure 2.3). Sagittal plane excursion of the lower back and knee during the TT and TLS tests was calculated as the mean (i.e., over the 10 cycles of each test) of differences between the maximum and minimum sagittal plane angles of these joints

during each repetition. Due to difficulties in objective calculation of lower back maximum and minimum flexion, thorax angles relative to the laboratory were used to determine the flexion time and excursion of the lower back.

Lumbopelvic rhythm (LPR) was calculated over three, consecutive, equal, time intervals spanning the entire flexion phase of each TT repetition (Figure 2.3). This was done by initially calculating the mean thorax and pelvic rotations over each time interval of each repetition. These rotations were calculated with respect to the laboratory coordinate frame. Mean thorax and pelvic rotations were calculated as the arithmetic mean of the sagittal plane thorax and pelvic rotations within each time interval, for each flexion phase. These mean thorax and mean pelvic rotations were then averaged over the 10 repetitions for their respective time interval. Lumbar rotation was then calculated as the difference between the above-described averaged means of pelvic and thorax rotations. This resulted in three total lumbar rotations, each associated with a time interval, for one TT test. The LPR as the ratio of lumbar to pelvic rotation was then calculated for each time interval. Similar to lumbar rotation, resulting in three total LPRs, each associated with a time interval, for one TT test.

Statistical analyses were performed using the above-described values of outcome measures for each person and condition. Analyses were carried out in SAS software (version 9.3, SAS Institute Inc., Cary, NC, USA). An REML GEE model with unstructured covariance structure utilizing Mancl and DeRouen [59] bias-corrected standard errors was used to examine the effects of armor and sex on pre-exposure measures, and the change in measures from pre-exposure to post-exposure. Statistical significance was set at $p \leq 0.05$. The pre-exposure model allowed the investigation of the immediate effect of armor and sex alone on risk of injury and performance, where the change model (post-exposure minus pre-exposure) allowed the investigation of the prolonged effect of exposure to BA on risk of injury and performance.

2.3 Results

All 12 subjects completed both testing sessions. No injuries or pain resulted from participation in this study.

2.3.1 The effects of body armor (pre-exposure model)

The effects of BA on the pre-exposure outcome measures during the TT and TLS tests are presented in Tables 2.1 - 2.3. Trial duration during self-paced tests significantly increased ($p \leq 0.02$) while wearing BA. Furthermore, despite no significant change in excursion while wearing BA, the flexion time of the dominant joint (i.e., the lower back for TT tests and the knee for TLS tests) significantly increased ($p \leq 0.02$) during the self-paced trials. There was a significant increase ($p = 0.03$) in the LPR during the second time interval of the self-paced trials (Table 2.2). Although no significant changes in the

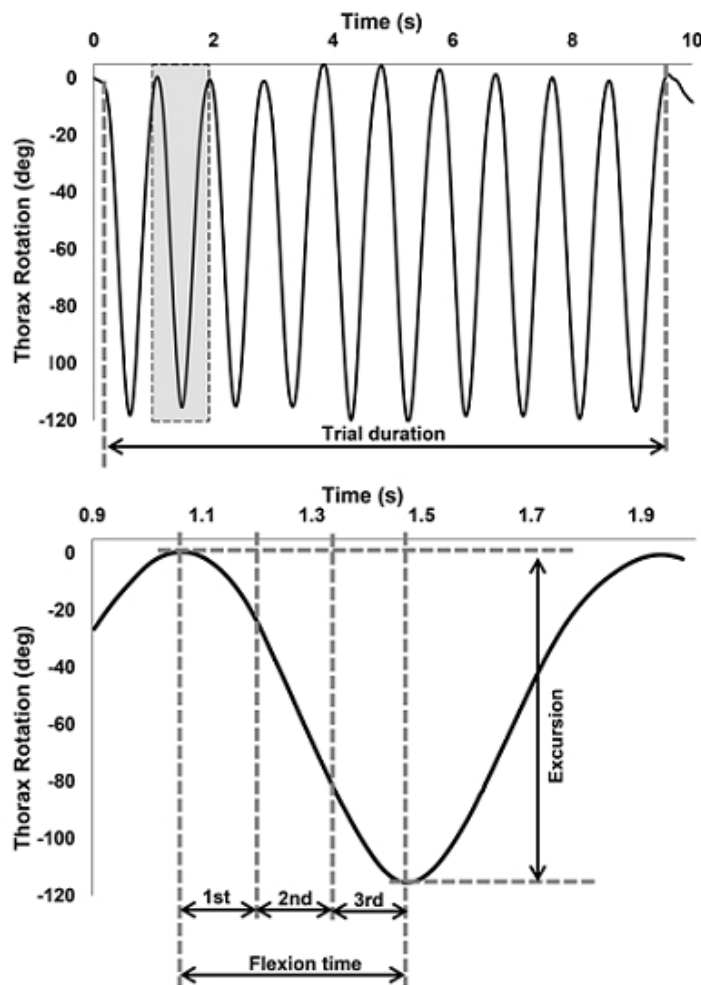


Figure 2.3: Visual descriptions of trial duration, flexion time, joint excursion as well as the three time intervals used to calculate lumbopelvic rhythm.

LPR were found during the metronome-paced tests, thorax excursion during the third time interval of these trials was significantly ($p = 0.045$) larger in no armor conditions than in armor conditions. No other outcome measures were affected by the pre-exposure BA condition ($p \geq 0.07$). In addition, no sex effects on any of the pre-exposure outcome measures were found ($p \geq 0.18$).

Table 2.1: Pre-exposure effects of body armor as well as sex differences in trial duration, flexion time and knee excursion during TT tests.

Outcome Measures	Pace	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Trial duration (s)	S-P	15.50 (0.62)	14.50 (0.54)	0.01 *	14.37 (0.60)	15.60 (0.93)	0.29
	M-P	19.84 (0.17)	20.11 (0.17)	0.17	19.77 (0.24)	20.18 (0.16)	0.20
Thorax flexion time (s)	S-P	0.76 (0.03)	0.72 (0.03)	0.02 *	0.71 (0.03)	0.77 (0.05)	0.28
	M-P	0.97 (0.01)	0.97 (0.01)	0.56	0.971(0.01)	0.97 (0.012)	0.89
Knee excursion (°)	S-P	-17.20 (3.12)	-18.70 (3.32)	0.33	-16.78 (4.04)	-19.08 (5.75)	0.77
	M-P	-18.11 (3.40)	-14.95 (2.76)	0.14	-15.94 (3.85)	-17.12 (5.16)	0.87

Notes: * $p \leq 0.05$; values are estimated means (SE). For excursion values, a negative sign indicates flexion. S-P: self-paced, M-P: metronome-paced.

Table 2.2: Pre-exposure effects of body armor as well as sex differences in LPR and thorax excursion during the three time intervals over the flexion phase of TT tests.

Outcome measures	Pace	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value	
First time interval	S-P	LPR	-3.79 (1.83)	4.04 (5.20)	0.23	0.74 (3.36)	-0.49 (2.20)	0.70
		Excursion	-23.01 (1.00)	-22.60 (0.84)	0.54	-22.05 (1.51)	-23.56 (0.84)	0.40
	M-P	LPR	-0.59 (1.48)	-5.57 (2.63)	0.14	-3.24 (1.84)	-2.92 (2.30)	0.92
		Excursion	-21.0 (1.10)	-19.93 (1.60)	0.17	-20.24 (2.21)	-20.69 (1.38)	0.87
Second time interval	S-P	LPR	0.66 (0.08)	0.54 (0.08)	0.03 *	0.66 (0.14)	0.54 (0.06)	0.45
		Excursion	-47.02 (1.20)	-47.88 (1.74)	0.47	-48.28 (1.83)	-46.62 (2.09)	0.57
	M-P	LPR	0.73 (0.14)	0.65 (0.13)	0.64	0.75 (0.19)	0.63 (0.08)	0.60
		Excursion	-51.79 (1.32)	-52.25 (0.80)	0.76	-53.73 (1.19)	-50.30 (1.15)	0.07
Third time interval	S-P	LPR	0.51 (0.10)	0.47 (0.15)	0.75	0.47 (0.16)	0.51 (0.14)	0.85
		Excursion	-29.50 (1.41)	-30.65 (1.27)	0.35	-30.92 (1.50)	-29.23 (1.89)	0.50
	M-P	LPR	0.49 (0.11)	0.53 (0.01)	0.74	0.45 (0.12)	0.57 (0.10)	0.44
		Excursion	-29.19 (1.95)	-31.97 (1.79)	0.05*	-30.45 (2.54)	-30.70 (2.42)	0.94

Notes: * $p \leq 0.05$; values are estimated means (SE). For excursion values, a negative sign indicates flexion. For LPR values, a negative sign indicates pelvic and lumbar motions are in opposite directions. S-P: self-paced, M-P: metronome-paced.

Table 2.3: Pre-exposure effects of body armor as well as sex differences in trial duration, flexion time and knee and trunk excursions during TLS tests.

Outcome measures	Pace	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Trial duration (s)	S-P	12.61 (0.40)	11.67 (0.29)	0.02 *	11.70 (0.50)	12.58 (0.33)	0.18
	M-P	14.90 (0.16)	14.93 (0.29)	0.92	14.95 (0.31)	14.88 (0.20)	0.85
Knee flexion time (s)	S-P	0.65 (0.03)	0.57 (0.02)	0.01 *	0.60 (0.03)	0.62 (0.02)	0.60
	M-P	0.78 (0.02)	0.75 (0.017)	0.07	0.79 (0.03)	0.74 (0.01)	0.20
Knee excursion (°)	S-P	-109.93 (6.94)	-111.00 (4.82)	0.74	-113.75 (7.13)	107.18 (7.67)	0.50
	M-P	-110.41 (6.15)	-109.69 (5.19)	0.79	-112.53 (7.16)	-107.58 (7.47)	0.62
Trunk excursion (°)	S-P	-32.46 (2.58)	-31.22 (2.60)	0.58	-30.79 (3.08)	-32.89 (3.83)	0.69
	M-P	-31.66 (2.43)	-31.61 (1.40)	0.97	-30.43 (2.20)	-30.43 (2.20)	0.51

Notes: * $p \leq 0.05$; values are estimated means (SE). For excursion values, a negative sign indicates flexion. S-P: self-paced, M-P: metronome-paced.

2.3.2 The effects of exposure (change model)

Exposure-induced changes in outcome measures are presented in Tables 2.4 – 2.6 for TT and TLS tests. Although very small, exposure-induced changes in trial duration of metronome-paced TT tests were significantly ($p = 0.03$) different between the armor and no armor conditions. In particular, the exposure was associated with an increase (~ 0.5 s) in the trial duration for the armor condition and a decrease (<0.1 s) for the no armor condition. The exposure-induced changes in excursion of the non-dominant joint (i.e., knee joint) during the self-paced TT tests (Table 2.4) were also significantly different ($p \leq 0.04$) between the armor and no armor conditions. For these tests, knee excursion following treadmill walking increased by 3.7° and decreased by 0.8° for the armor and no armor conditions, respectively. No significant difference in exposure-induced changes of all other outcome measures was found between armor and no armor conditions.

Exposure-induced changes in the LPR during the first and third time intervals of the metronome-paced trials were significantly ($p \leq 0.03$) different between males and females (Table 2.5). Exposure-induced changes in other outcome measures, however, were not different between males and females.

Table 2.4: Exposure-induced changes in trial duration, flexion time and knee excursion during TT tests. Body armor and sex-related differences are presented.

Outcome measures	Pace	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Trial duration (s)	S-P	-0.54 (0.44)	-0.25 (0.38)	0.69	-0.41 (0.26)	-0.35 (0.38)	0.88
	M-P	0.51 (0.28)	-0.08 (0.40)	0.03	0.45 (0.48)	-0.02 (0.37)	0.43
Thorax flexion time (s)	S-P	-0.03 (0.02)	-0.01 (0.02)	0.62	-0.01 (0.02)	-0.03 (0.02)	0.28
	M-P	0.003 (0.006)	-0.01 (0.01)	0.43	-0.001 (0.01)	-0.003 (0.004)	0.83
Knee excursion (°)	S-P	-3.69 (1.17)	0.84 (1.76)	0.04 *	0.66 (1.62)	-3.52 (1.67)	0.11
	M-P	-1.02 (0.66)	-1.03 (0.65)	0.99	-0.32 (0.90)	-1.72 (0.68)	0.26

Notes: * $p \leq 0.05$; values are estimated means (SE). For excursion values, a negative sign indicates flexion. S-P: self-paced, M-P: metronome-paced.

Table 2.5: Exposure-induced changes in LPR and thorax excursion during the three time intervals over the flexion phase of TT tests. Body armor and sex-related differences are presented.

Outcome measures	Pace		Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
First time interval	S-P	LPR	5.78 (2.19)	-3.36 (3.96)	0.06	2.08 (3.15)	0.34 (2.76)	0.64
		Excursion	-0.21 (0.63)	-0.02 (0.58)	0.81	-0.27 (0.37)	0.04 (0.79)	0.70
	M-P	LPR	0.24 (2.51)	5.43 (2.43)	0.23	7.93 (2.35)	-2.26 (1.96)	0.01*
		Excursion	0.92 (0.77)	0.25 (0.81)	0.60	1.55 (0.83)	-0.38 (0.58)	0.09
Second time interval	S-P	LPR	-0.05 (0.04)	-0.03 (0.04)	0.71	-0.05 (0.04)	-0.03 (0.05)	0.76
		Excursion	1.01 (0.65)	1.62 (1.11)	0.66	0.85 (0.93)	1.79 (0.77)	0.44
	M-P	LPR	0.09 (0.16)	-0.02 (0.05)	0.48	0.04 (0.13)	0.03 (0.08)	0.99
		Excursion	-0.30 (1.45)	-1.57 (1.10)	0.49	0.35 (1.08)	-2.22 (1.61)	0.23
Third time interval	S-P	LPR	-0.05 (0.05)	-0.05 (0.05)	0.13	0.031 (0.04)	-0.06 (0.04)	0.08
		Excursion	2.29 (1.25)	2.13 (0.87)	0.91	2.00 (1.37)	2.42 (0.89)	0.81
	M-P	LPR	0.03 (0.04)	-0.004 (0.03)	0.45	0.08 (0.05)	-0.06 (0.03)	0.03*
		Excursion	-1.68 (0.97)	0.12 (1.19)	0.17	-1.75 (1.09)	0.19 (1.21)	0.22

Notes: * $p \leq 0.05$; values are estimated means (SE). For excursion values, a negative sign indicates flexion. For LPR values, a negative sign indicates pelvic and lumbar motions are in opposite directions. S-P: self-paced, M-P: metronome-paced.

Table 2.6: Exposure-induced changes in trial duration, flexion time and knee and thorax excursion during TLS tests. Body armor and sex-related differences are presented.

Outcome measures	Pace	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Trial duration (s)	S-P	-0.37 (0.29)	-0.48 (0.19)	0.80	0.37 (0.18)	-0.49 (0.18)	0.65
	M-P	-0.07 (0.17)	0.20 (0.24)	0.42	-0.11 (0.17)	0.24 (0.15)	0.12
Knee flexion time (s)	S-P	0.05 (0.02)	-0.02 (0.01)	0.22	-0.05 (0.03)	-0.21 (0.01)	0.35
	M-P	-0.04 (0.03)	-0.01 (0.02)	0.26	-0.03 (0.03)	-0.02(0.02)	0.72
Knee excursion (°)	S-P	1.98 (2.01)	4.43 (1.39)	0.23	2.36 (1.76)	4.07 (1.97)	0.50
	M-P	-2.12 (1.77)	-2.73 (1.49)	0.76	-1.87 (2.15)	-2.98 (1.85)	0.72
Trunk excursion (°)	S-P	1.05 (1.61)	-1.69 (1.50)	0.24	-0.43 (1.24)	-0.21 (1.77)	0.92
	M-P	-3.94 (1.44)	-2.86 (1.63)	0.36	-3.46 (1.06)	-3.34 (2.40)	0.96

Notes: * $p \leq 0.05$; values are estimated means (SE). For excursion values, a negative sign indicates flexion. S-P: self-paced, M-P: metronome-paced.

2.4 Discussion

The amount of load that is carried by dismounted warfighters not only negatively affects their performance [13, 30] but also has a significant role in the development of IRMSCs [32, 42]. Reducing IRMSCs positively impacts the warfighter's quality of life, increases the successful completion of mission objectives and eases rehabilitation costs and medical discharges. Survival of dismounted warfighters highly depends on BA. As such control of such adverse effects of load carriage on performance and risk of IRMSCs should not compromise the survival of warfighters. This is not possible without a quantitative knowledge of how contributing factors into performance and risk of IRMSCs are influenced by wearing BA. Performance is in part affected by active (motor and sensory) and passive mechanical tissue responses associated with task demands. These mechanical tissue responses also directly affect mechanical environment of different joints within the body (Figure 2.1), hence influencing risk of IRMSCs. As a part of a larger study aimed at understanding how wearing BA affects different mechanical aspects of the knee and lower back musculoskeletal system, the objective of this study was to determine changes in several measures of knee and lower back mechanics during two simple tasks. Though wearing BA alone (i.e., results from the pre-exposure model) was found to affect some measures of performance and IRMSCs, in general, the effects of exposure (i.e., results from the change model), on our outcome measures were the same whether or not the participants wore BA. Therefore, BA effects were not altered by exposure.

To increase the likelihood of finding changes in our measures of performance and risk of IRMSCs, a moderate-to-fast pace was selected for tests considered in this study. Furthermore, tests were performed using a self-selected pace (i.e. as fast as the participant could perform the test while maintaining the proper form) to assess performance and metronome-controlled pace to assess risk of IRMSCs. Our rationale for the metronome-controlled pace was based on results from our earlier work [60], wherein, for similar tasks and paces but without BA, very large spinal loads (i.e., > 5000 N) were predicted in the lumbar area. Although inclusion of wearing BA was expected to increase the amount of spinal loads, we chose to use the same pace as our earlier study for the metronome-controlled test due to the high physical fitness level of participants in this study.

However, participants performed tests at self-selected paces significantly faster than tests at the metronome-controlled pace. Faster completion of the self-selected paced test while wearing BA, although an indication of the very high physical fitness of our study participants, raises a concern as to whether injury threshold is equally elevated among these individuals? The compression strength of lumbar motion segments has been reported to be in the range of 2-10 kN [61-64]; Jager and Luttmann [62] reported values of 5.81 ± 2.58 kN for males and 3.97 ± 1.5 kN for females based on relatively large sample populations. On the other hand, Tsuzuku, Ikegami [65] found $\sim 20\%$ higher bone mineral density of lumbar vertebrae among power lifters than controls [65]. It remains to be investigated whether the actual amount of spinal load experienced by our study participants may exceed such elevated injury thresholds.

Diminished warfighter performance is defined as decreased accuracy, decreased maneuverability and changes in time to perform a task [26, 30, 52, 53]. Wearing BA has been shown to increase the time to complete walking or running tasks [52, 53], to reduce the number of pull-ups [26], to increase balance impairment [30] and to reduce the number of repetitive box lifts [53]. The longer trial durations while wearing BA during the TT and TLS self-selected paced tests, observed in our pre-exposure model, concur with these earlier findings on the effects of BA on performance. Trial durations increased an average of ~ 1 second while wearing BA. Although the flexion time of the TT repetitions significantly increased while wearing BA, it only contributed $\sim 40\%$ to the increase in the trial duration. This suggests that BA affected the extension phase of the dominant joint (i.e., lower back) more than its flexion phase during TT repetitions. In contrast, 80% of the increase in trial duration of the TLS tests was due to the significant increase in flexion time of the knee. Weight (gravitational) and inertia of BA add to the physical demands of a task, hence requiring larger tissue responses to assure equilibrium and balance (Figure 2.1). Since none of our posture related measures (i.e., joint angles) that affect gravitational demands of the tasks were changed while wearing BA, the increase in trial durations may suggest an attempt to decrease the inertial demand of the task. Whether such increase in time is an indication of reduced capability (performance) or an attempt by the central nervous system to avoid injury remains unclear. The muscles controlling the movement of the dominant joints are under eccentric activation during the

decelerating phase of flexion. Providing one is at a higher risk of injury during eccentric muscle activity and considering that gravity also assists these motions during the flexion phase, such increased flexion times seem to be an attempt to reduce the risk of injury via reducing the inertial demand of the task. On the other hand, the extension phase of these tasks involved motions that were in the opposite direction of gravity. Therefore an increased extension time may be an indication of reduced capability while wearing BA. It is of note that such reduced capability was more evident during the TT test than during the TLS tests, which could be due to a higher increase in BA-induced gravity demand.

LPR is an indicator of the synergy between the hip and lower back tissues during sagittal plane forward bending. Due to the influence of such synergy on lower back mechanics and risk of injuries, LPR has been studied extensively in the past [66-72] but never applied to the military population. Consistent with earlier results from healthy individuals, our findings indicated a larger contribution of lower back (i.e., lumbar rotation) during the early phase of flexion of the TT tests. This was then reversed during the latter two-thirds of the flexion period. The large degree of variance in calculated LPR for the first time interval of both self-paced and metronome-paced tests was due to relatively small value of pelvic rotation which vacillated around zero. There is conflicting literature associated with LPR and reduced spinal loads. LPR has been shown to increase with the addition of external loads [67]. Such an increase of LPR has recently been suggested as an attempt of reducing spinal loads via exploitation of larger contribution from passive lower back tissues into spine equilibrium [72]. Therefore, a decrease in LPR would be associated with higher spinal loads and risk of injury. Others [66] have suggested a reduced risk of injury associated with lower LPRs due to reduced tension in lumbar tissues. When calculating spinal loads, assumed lumbar rotation to be distributed but remain fixed among all lumbar vertebrae despite changes in LPRs. Using an alternative assumption (i.e., distribution of lumbar rotation across all vertebrae, to minimize predicted stress across all trunk muscles), we found spinal loads to decrease with a decrease in LPRs [73]. The only significant change in LPR while wearing BA, found in our pre-exposure model, was an increase in LPR during the second time interval of the self-selected paced trials. Though it remains unclear how lumbar segment rotations change with LPR, it seems more likely for individuals to adjust their LPR

during self-selected paced test in an effort to reduce rather than to increase risk of IRMSCs.

We expected to see more exposure-induced changes in our outcome measures while wearing BA (Tables 2.4 – 2.6). However, except for knee excursion during the self-paced TT tests, no other outcome measures demonstrated changes between the armor and no armor conditions. Neuromuscular function has been shown to be altered following prolonged walking or running with or without carrying a load [74, 75]. These alterations have been suggested to require a much longer recovery time (i.e., > 24 h) than the initial prolonged walking or running time [74]. We are not aware of any study on BA-induced changes in active and passive mechanical tissue responses to task demand. However, an earlier work on prolonged walking with and without backpack load carriage reported significant decrease in maximum voluntary contraction only after walking with a backpack load [74]. A number of reasons for discrepancy between our findings and those of Blacker, Fallowfield [74] could be (1) difference in magnitude and distribution of the load (i.e., 25 kg inside a backpack vs. 10.8 kg distributed on thorax, upper arms and thighs), (2) difference in exposure duration and pace (i.e., 120 min at 6.5 km/h vs. 45 min at 5.98 km/h), (3) difference in study participants (i.e., 10 healthy males with experience in backpack carrying vs. 12 healthy, sex-balanced, physically fit individuals) and (4) differences in task demands (i.e., knee maximum voluntary contraction vs. TT and TLS).

In general, we did not find any difference between males and females. Significant sex differences were only found in the LPR change model, of the metronome-controlled TT tests, wherein on average females demonstrated a smaller change (absolute value) in LPR during the first and third time intervals of flexion than males. In particular from pre- to post-exposure, LPR increased during both first and third time intervals among males while it increased during the first time interval and decreased during the third time interval among females. Individuals with a history of back pain have been shown to demonstrate on average a smaller (not statistically significant) LPR than individuals with no history of back pain [66]. Since it is unclear whether such difference in LPR among individuals with and without a history of back pain has a causal role or is a consequence of back pain, it is difficult to interpret our finding as to whether such different sex-related changes in LPR are indicators of risk of injury or impaired performance. However, with

recent changes to military policy, specifically the 2013 inclusion of females into combat roles and considering the reported higher risk of musculoskeletal injuries among females, there is a need for enhanced understanding of sex-related differences in impact of wearing BA on performance and the risk of IRMSCs

There were a number of limitations associated with our study that should be considered when interpreting our findings. First, due to the small sample size of this exploratory study, our statistical model was unstable for study of any potential interaction between the independent variables. With a larger cohort in a future study, we would be able to tease out these effects. Second, this study was conducted within the confines of a climate-controlled laboratory. Real world military operating conditions differ greatly from laboratory conditions (e.g., terrain and climate). Third, our tests and associated kinematics measures presented here represent alterations in the musculoskeletal system's behavior only in the sagittal plane. Fourth, we used one size BA (i.e., size small) for all participants which was due to our lack of access to all BA sizes. Such a small BA size might have caused less than actual BA-induced changes among our larger framed participants. Finally, our results represent the acute effects of wearing BA. Whether there was a delayed change/response remains unclear. A minimum of 24 h was provided between the two testing sessions of each participant to allow adequate washout period. Furthermore, unlike other components of loads carried by warfighters, BA is rarely removed when operating in-theater [4], and depending on mission durations, a warfighter may wear BA between 48 and 72 h. Such prolonged periods of carrying BA not only may affect performance differently but can also increase the risk of IRMSCs. Further testing should be considered with enhanced exposure, more authentic conditions and further evaluation of sex differences.

In conclusion, although wearing BA altered our measures of performance and risk of IRMSCs, exposure with BA was not found to cause more changes in our measures than exposure without BA. Performance-related casualties and IRMSCs have a significant impact on military force generation and sustainment [10]. Availability of quantitative data related to the effects of BA on different aspects of human musculoskeletal behavior can provide an enhanced decision-making platform than merely the weight of BA alone. These data could potentially be used for the planning of

warfighter's duties, such as to reduce risk of IRMSCs without compromising performance during various missions.

Chapter 3 The Effects of Military Body Armor on the Lower Back and Knee Mechanics during Box Drop and Prone to Standing Tasks

This chapter reproduced from a submitted manuscript, “Phillips, M., B. Bazrgari and R. Shapiro. The effects of military body armor on the lower back and knee mechanics during box drop and prone to standing tasks. *Ergonomics*, 2014, in review.”

3.1 Introduction

Diminished performance and escalated injuries of warfighters can influence mission success and personal safety, ultimately resulting in reduced military manpower, readiness, presence and sustainment. The annual prevalence of non-combat IRMSCs among U.S. service members is ~63 % [54]. Compared to combat injuries that accounted for ~7% of all medical evacuations from Afghanistan in 2006, IRMSCs were responsible for ~25% of the medical evacuations [76]. IRMSCs adversely affect warfighters’ performance [9], hence could also increase the risk of performance-related casualties. In addition to personal suffering and compromised safety, IRMSCs impose a substantial economic burden on the military with a reported total cost of ~ \$1.5 billion in 2006 [5].

An important risk factor for IRMSCs is the amount of load carried by warfighters [11]. A considerable portion (i.e., ~21%) of such load comes from BA [13, 39]; an amount which has nearly doubled since 2003 [13]. BA has been shown to reduce warfighter’s maneuverability, performance and perceived physiological response [13, 26, 30, 52, 77]. It has also been suggested to increase the risk of IRMSCs [12, 32, 42]. Despite the considerable weight of current BA, there is a growing demand for the addition of extremity armor to address the significant rise in number of extremity injuries [40, 41]. Therefore, managing the unfavorable effects of BA requires knowledge and comprehension of the effects of such added weight of BA and its distribution (i.e., coverage area) on performance and risk of IRMSCs. Additionally with the expansion of occupational specialties now open to women, who have historically been reported to be at a higher risk for musculoskeletal injuries than their male counterparts [20-24], there is a

need to understand how the weight and increased surface coverage of BA effects female warfighters.

We have conducted a project to evaluate the effects of BA on an individual's performance as well as on knee and lower back (i.e., two locations with highest number of IRMSCs) [54] risk of injury. The project was designed based on a conceptual model [78] which relates BA induced changes in NM behavior with impaired performance and increased risk of IRMSCs via abnormal mechanical changes in body joints. Within this project, the objective of the present study was to quantify BA-induced changes in several aspects of the lower back and knee mechanics during two military inspired tasks: (1) box drop (BD) and (2) prone-to-standing (PS). These tasks were included due to their similarities to tasks experienced in military. Dismounted warfighters must often navigate uneven terrain, jump from a vehicle or transverse a wall/obstacle. Additionally, warfighters are trained in marksmanship from the standing and prone positions. It was hypothesized that BA-induced changes in NM behavior would alter timing, kinematics and kinetics of the lower back and knee joints during the BD and PS tasks. Specifically, it was hypothesized that BA-induced changes in our outcome measures would be consistent with increased risk of IRMSCs (e.g., increased loading rate or joint moment) and/or impaired performance (e.g., increased time). The unique difference of BA in comparison to other components of load carriage is that BA is often worn for longer durations of time while deployed due to emanate threats. U.S. service members currently function at an increased operational tempo and it is not uncommon for them to be deployed to an active combat theater for more than twelve months at a time. Hence, it was also hypothesized that the above mentioned changes of the lower back and knee mechanics would be amplified with duration of wearing BA. Decreasing IRMSCs has the potential to lessen rehabilitation costs and reduce medical discharges, thus easing the government's cost burden related to training new warfighters and paying service-connected disability pay (a possible life time entitlement) [5, 7].

3.2 Methods

3.2.1 Study design

A randomized cross-over study design, wherein participants wore BA in one of two sessions, was used to test the effects of BA and wear duration on several measures of the lower back and knee mechanics. Each session lasted ~2.5 hours during which participants completed a battery of nine tests before (pre-exposure) and after (post-exposure) 45-minutes of treadmill walking (i.e., hereafter called exposure) at a speed of 1.65 m/s (5.95 km/h). Duration and pace of exposure were set to be consistent with a military foot march [55]. Methods and results from two tests: (1) BD and (2) PS motions will be presented in this paper. However, a comprehensive list of all tests performed as well as their associated methods, measured variables and randomization order can be found in Appendix B.

3.2.2 Participants

Six males with mean (standard deviation) age, weight, and height of 26.67 (5.47) yrs., 78.77 (9.41) kg, and 1.79 (0.05) m, along with six females with mean (standard deviation) age, weight, and height of 24.00 (5.02) yrs., 61.54 (7.38) kg, and 1.66 (0.10) m participated in this study after completing a consenting process, approved by the University of Kentucky's Institutional Review Board. Inclusion criteria consisted of (1) lack of any musculoskeletal disorder, (2) negative answer to all questions of a physical activity readiness questionnaire [56] and (3) scoring ≥ 5 on the Tegner scale [57]. Participants consisted of current and previous active duty and reserve service members, one male collegiate cyclist/avid backpacker and one female Cross-fit athlete.

3.2.3 Body armor

BA included a protective vest with two ceramic thorax plates in conjunction with upper arm and thigh plates (106N in total; same size armor used for all subjects) that were carried during instrumentation, testing and exposure of the armor sessions. Front and back thorax plates were military issued ceramic plates. Plates used for the upper

arms and thighs were manufactured in-house to simulate the added weight of extremity armor.

3.2.4 Data collection

Participants were asked to wear athletic clothing for experiments while sport shoes were supplied to decrease confounding factors. During each session, kinematic data were obtained using a motion capture system with ten cameras (Motion Analysis, Santa Rosa, CA) within a calibrated volume on a runway with two in-ground Bertec (Columbus, Ohio) force platforms. Initially, a static marker set consisting of 77 reflective markers were attached to each subject while completing a standing '*t-pose*' calibration procedure. Markers denoting anatomical landmarks (i.e., 22 markers) were then removed following quantification of their geometrical relation with tracking markers (i.e., 55 markers) during the standing '*t-pose*' calibration procedure.

For the BD test, participants stood on a box (height: 37.5 cm) located next to an in-ground force platform. The participants initiated the test by stepping down onto the force platform following the investigators signal to start. They were instructed to step down on the force platform with their dominant foot (i.e., right foot for all subjects in this study) and continue walking in the forward direction off of the force platform (Figure 3.1). For the PS test, participants started lying prone on the floor. Their feet were plantar flexed with the foot dorsum in contact with the ground. Their shoulders were in 180° of forward flexion, elbows extended with the palmer side of their hand in contact with the ground. When signaled by the investigators to begin the test, in one dynamic movement the participants brought their hands underneath their shoulders, pushed up, jumped their feet in towards their hands and stood upright (Figure 3.1). Each of the BD and PS tests took less than ~10 sec to complete and were repeated three times for each condition. If the proper form was not maintained during an individual test (visually judged by the examiner and through inspection of the captured trial), participants were asked to repeat the test until three successful tests were captured.

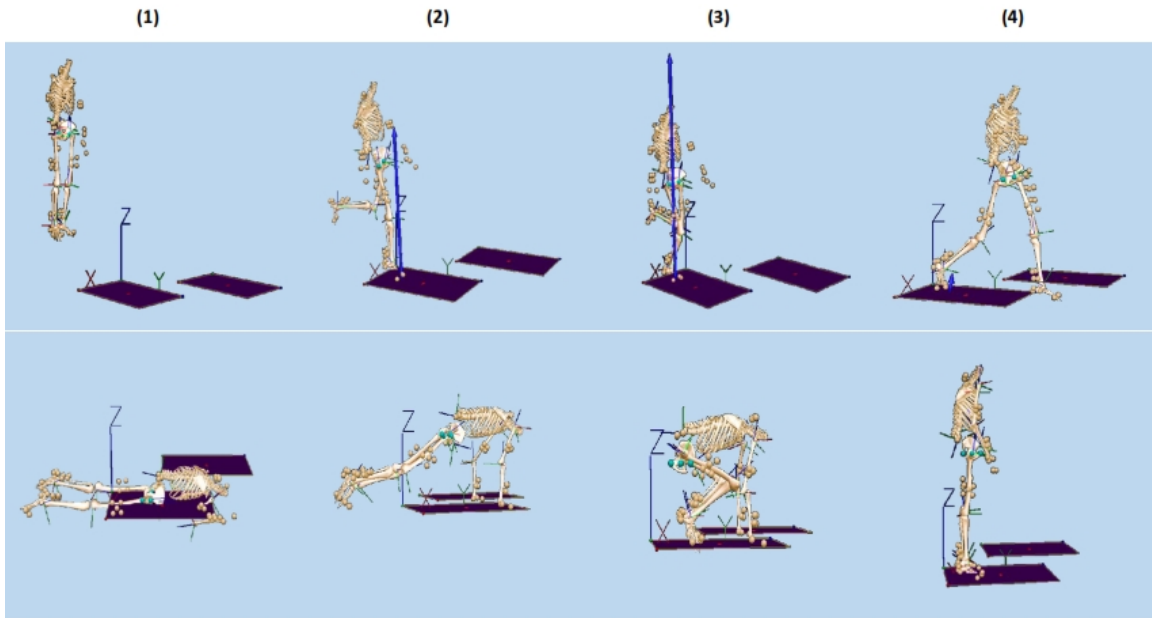


Figure 3.1: Screenshots of tests from Visual 3D. Top (box drop): from left to right representing participant's posture at approximate times of (1) start of test, (2) foot impact, (3) maximum knee flexion and (4) toe off; Bottom (prone to standing): from left to right representing participant's posture at approximate times of (1) start of test, (2) start of forward jump, (3) foot strike and (4) test completion.

3.2.5 Data analyses for BD and PS tests

Kinematic data were collected and tracked with Cortex (v3.6, Motion Analysis Corp, Santa Rosa, CA). Data from the standing t-pose calibration procedure was then used to build subject-specific, whole body link-segment models in Visual 3D (C-Motion Corp, Germantown, MD). Subsequent data processing was performed using these subject specific models in Visual 3D and an in-house Matlab (Mathworks, Natick, MA) program. Motion data were sampled at 120 Hz and force data were synchronously sampled at eight times motion data (960 Hz). Motion data were then filtered using a second order, low pass, bi-directional Butterworth filter. A cutoff frequency of 10 Hz was determined using the residual method described by Winters [58]. Joint angles were determined using Visual 3D's default segment coordinate system (+z up and +y anterior), a standard

Cardan angle rotation (x-y-z). For kinetic data analyses, inertial properties of each body segment were defined as functions of mass and height of each subject in the Visual 3D. However, to account for the added inertia of armor during session with BA, a second subject specific model was developed for each participant (i.e., 24 unique models total) wherein trunk, upper arms and thighs were modified accordingly. For both tests, all outcome measures in this study were reported in the sagittal plane and the average of the three trials per condition were used for subsequent statistical analyses.

For each of the BD and PS tests, multiple temporal measures were investigated. For the BD test, an overall duration was defined as the time difference between foot impact (impact) and toe off (TOFF) of the same foot from the force platform. This duration represented the stance phase on the foot used to step down from the box. Impact and TOFF (Figure 3.2) were defined from the force vector (z-component) crossing the threshold of 0.01 N, while ascending and descending respectively. Two subcomponents of the BD overall duration were also calculated: (1) the time difference between impact to maximum knee flexion, representing the weight acceptance phase of the test and (2) the time difference between maximum knee flexion and TOFF, representing the propulsion phase of the test. For the PS test, the overall duration was defined as the time difference between participant's initiation of movement (start) and completion of the test (completion). The start of the PS test was defined as the first motion of the third metacarpal marker (i.e., the absolute velocity became greater than zero) while completion was defined as minimum velocity of the L5/S1 marker in the z-direction. Similarly, two subcomponents were calculated from the overall PS duration: (1) time difference between start and foot strike (FS) and (2) the time difference between FS and completion. FS was defined as the first time instance after the start when the fifth metatarsal marker velocity became zero (stationary) in the z-direction. For the BD test, the magnitude and timing (as percent of stance phase) of the peak ground reaction force (GRF) in z-direction and maximum knee extension moment (Figure 3.2), along with knee angle and thorax rotation (i.e., normalized thorax angle) at these two time events were calculated. The displacements of fifth metatarsal marker (jump distance), as well as knee angle and thorax rotation at the event of FS were calculated for the PS test. Finally, during the BD test, peak instantaneous loading rate was also obtained.

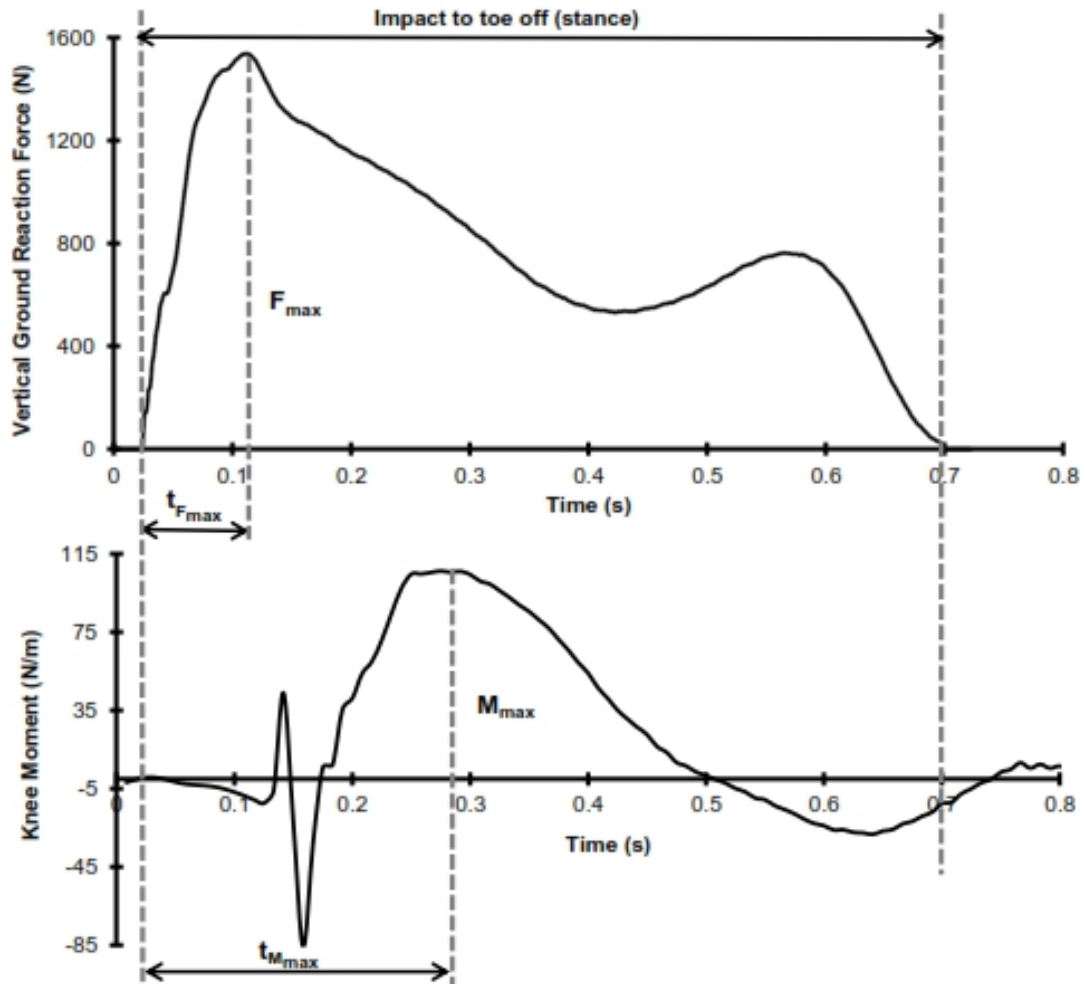


Figure 3.2: Vertical ground reaction force and knee moment during the stance phase of a typical box drop test. Peak vertical ground reaction force (F_{max}), maximum knee extension moment (M_{max}), and trial duration are indicated by dashed lines. $t_{F_{max}}$: Time to peak vertical ground reaction force; $t_{M_{max}}$: Time to maximum knee extensor moment.

Statistical analyses were performed using the above described values of outcome measures for each participant and condition. Analyses were carried out in SAS software (version 9.3, SAS Institute Inc., Cary, NC, USA). A REML GEE model with unstructured

covariance structure utilizing Mancl and DeRouen [59] bias-corrected standard errors was used to examine the effects of armor and sex on pre-exposure measures, and the change in measures from pre-exposure to post-exposure. Statistical significance was set at $p \leq 0.05$. To study the immediate effect of armor and sex alone on risk of injury and performance, the pre-exposure model was utilized. Additionally, the change model (post-exposure minus pre-exposure) was used to study the prolonged effect of exposure to BA and risk of injury and performance.

3.3 Results

All twelve subjects completed both testing sessions. No injuries or pain was reported from participation in this study.

3.3.1 The effects of body armor (pre-exposure model)

The effects of BA on the pre-exposure outcome measures during the BD and PS tests are presented in Tables 3.1- 3.3. All temporal measures (Table 3.1) for both test demonstrated an increase while wearing body armor. Statistically significant increases ($p \leq 0.02$) included the overall trial duration (~ 30 ms) and the weight acceptance phase (~ 20 ms) of the BD test as well as the FS to completion (~ 110 ms) phase of the PS test. While wearing BA during the BD test (Table 3.2), there was a significant increase (~ 159 N) in peak GRF, however peak instantaneous loading rate ($p = 0.64$) and maximum knee extension moment ($p = 0.09$) were not found to be affected by BA. Additionally, timing of peak GRF and maximum knee extension moment, along with corresponding knee angle and thorax rotation at these two specific time instances during BD tests were not affected by BA ($p \geq 0.22$). Wearing BA was associated with significantly increased knee flexion (~ 7 degrees) and decreased, but not significantly, thorax rotation (~ 5 degrees) at the instance of FS for the PS test (Table 3.3). However, jump distances were not affected by BA. No other outcome measures were affected by the pre-exposure BA condition ($p \geq 0.08$).

During the BD tests (Table 3.2), the peak GRF was greater (~ 380 N) and occurred significantly earlier ($p = 0.02$) among males than females. Peak instantaneous loading rate and the maximum knee extension moment were ~ 23100 N/s and ~ 29 N·m

greater ($p \leq 0.03$) among males than females respectively. Additionally, at the instant of the peak GRF, males showed $\sim 7^\circ$ more ($p = 0.04$) knee flexion than females. Finally, male jump distance (Table 3.3) was ~ 20 cm greater ($p = 0.002$) than females' in the PS test. No additional sex-effect on any other pre-exposure outcome measures was found ($p \geq 0.10$).

Table 3.1: Pre-exposure effects of body armor as well as sex differences in timing data (sec), during box drop and prone to standing tests.

Outcome measures	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Box drop						
Impact to toe off	0.65 (0.035)	0.62 (0.37)	0.01*	0.67 (0.06)	0.59 (0.037)	0.29
Impact to max. knee flexion	0.16 (0.009)	0.14 (0.006)	0.001*	0.15 (0.01)	0.14 (0.005)	0.84
Max. knee flexion to toe off	0.49 (0.04)	0.48 (0.04)	0.34	0.52 (0.07)	0.45 (0.03)	0.36
Prone to standing						
Start to completion	2.24 (0.11)	2.10 (0.99)	0.08	2.04 (0.13)	2.30 (0.14)	0.20
Start to foot strike	1.20 (0.66)	1.17 (0.07)	0.58	1.14 (0.07)	1.23 (0.093)	0.39
Foot strike to completion	1.04 (0.07)	0.93 (0.05)	0.02*	0.90 (0.08)	1.07 (0.07)	0.15

Notes: * $p \leq 0.05$; values are estimated means (SE).

Table 3.2: Pre-exposure effects of body armor as well as sex differences in, kinetic and kinematic data during box drop tests. GRF: Ground reaction force.

Outcome measures	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Peak GRF (N)	2002.18 (116.61)	1843.86 (105.43)	0.01*	2112.94 (181.88)	1733.10 (106.87)	0.10
Peak inst. loading rate (N/s)	87064 (7121.36)	83268 (5474.30)	0.64	96743 (7235.07)	73590 (6082.96)	0.03*
Time of peak GRF (% of stance)	10.00 (1.00)	10.00 (1.00)	0.91	9.00 (2.00)	12.00 (1.00)	0.02*
Thorax rotation at peak GRF ($^\circ$)	3.03 (1.41)	2.46 (1.48)	0.31	0.79 (2.06)	4.70 (2.32)	0.27
Knee angle at peak GRF ($^\circ$)	-15.10 (1.62)	-14.91 (1.78)	0.89	-11.68 (2.31)	-18.34 (1.82)	0.04*
Max. knee extension moment (Nm)	114.33 (5.55)	98.29 (9.87)	0.09	120.90 (7.12)	91.72 (9.50)	0.02*
Time of max. knee extension moment (% of stance)	21.00 (2.00)	20.00 (2.00)	0.22	20.00 (4.00)	21.00 (2.00)	0.87
Thorax rotation at the time of max. knee extension moment ($^\circ$)	-1.24 (1.87)	-1.23 (1.76)	0.99	-3.94 (2.81)	1.47 (2.54)	0.21
Knee angle at the time of max. knee extension moment ($^\circ$)	-33.70 (1.59)	-31.43 (2.06)	0.34	-33.61 (2.40)	-31.52 (1.59)	0.49

Notes: * $p \leq 0.05$; values are estimated means (SE). For joint angles, a negative sign indicates flexion.

Table 3.3: Pre-exposure effects of body armor as well as sex differences in kinematic data during prone to standing tests.

Outcome measures	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Time of foot strike (% of trial duration)	0.54 (0.02)	0.56 (0.01)	0.16	0.56 (0.02)	0.54 (0.15)	0.30
Jump distance (m)	0.95 (0.03)	0.95 (0.03)	1.00	1.05 (0.03)	0.85 (0.04)	0.002*
Thorax rotation at foot strike (°)	-5.30 (3.30)	-10.05 (3.96)	0.13	-5.82 (4.75)	-9.53 (4.52)	0.58
Knee angle at foot strike (°)	-89.44 (5.32)	-82.70 (5.44)	0.01*	-81.64 (8.36)	-90.50 (6.21)	0.41

Notes: * $p \leq 0.05$; values are estimated means (SE). For joint angles, a negative sign indicates flexion.

3.3.2 The effects of exposure (change model)

Exposure-induced changes in outcome measures are presented in Tables 3.4 – 3.6 for the BD and PS tests. No significant difference in exposure-induced changes in outcome measures was found between the armor and no-armor sessions. In general there was no exposure-induced change in outcome measures between males and females, with the exception of thorax rotation at FS (Table 3.6). Men experience a significant decrease in flexion ($p = 0.05$) after exposure when compared to their pre-exposure thorax rotation.

Table 3.4: Exposure-induced effects of body armor as well as sex differences in timing data (sec) during box drop and prone to standing tests.

Outcome measures	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Box drop						
Impact to toe off	-0.03 (0.02)	-0.02 (0.01)	0.75	-0.012 (0.01)	-0.03 (0.02)	0.64
Impact to max. knee flexion	0.006 (0.008)	0.006 (0.006)	0.99	0.008 (0.006)	0.004 (0.008)	0.62
Max. knee flexion to toe off	-0.03 (0.02)	-0.03 (0.01)	0.74	-0.023 (0.01)	-0.031 (0.02)	0.88
Prone to standing						
Start to completion	-0.14 (0.05)	-0.08 (0.06)	0.50	-0.07 (0.06)	-0.15 (0.05)	0.35
Start to foot strike	-0.04 (0.03)	-0.02 (0.05)	0.74	-0.003 (0.03)	-0.05 (0.04)	0.23
Foot strike to completion	-0.10 (0.04)	-0.07 (0.21)	0.44	-0.09 (0.03)	-0.74 (0.03)	0.63

Notes: * $p \leq 0.05$; values are estimated means (SE).

Table 3.5: Exposure-induced effects of body armor as well as sex differences in kinetic and kinematic data during box drop tests. GRF: Ground reaction force.

Outcome measures	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Peak GRF (N)	64.05 (38.48)	64.55 (60.56)	0.99	75.38 (49.40)	53.23 (57.69)	0.74
Peak inst. loading rate (N/s)	761.58 (3612.72)	9869.77 (9476.40)	0.42	8924.02 (5500.57)	1707.33 (5431.12)	0.23
Time of peak GRF (% of stance)	1.00 (0.70)	0.50 (0.70)	0.45	0.80 (0.50)	0.80 (0.90)	0.94
Thorax rotation at peak GRF (°)	-1.66 (0.62)	-8.33 (9.40)	0.49	-5.00 (4.58)	-5.00 (5.02)	1.00
Knee angle at peak GRF (°)	-0.42 (0.98)	-0.31 (1.11)	0.92	-1.77 (1.18)	1.03 (1.29)	0.13
Max. knee extension moment (Nm)	1.83 (4.65)	6.50 (3.01)	0.46	6.27 (4.10)	2.07 (2.31)	0.38
Time of max. knee extension moment (% of stance)	3.00 (1.40)	2.00 (1.00)	0.52	2.00 (1.00)	3.00 (2.00)	0.53
Thorax rotation at the time of max. knee extension moment (°)	-1.93 (0.89)	-0.75 (0.53)	0.20	-0.92 (0.89)	-1.76 (0.73)	0.47
Knee angle at the time of max. knee extension moment (°)	-1.71 (1.55)	-1.67 (1.71)	0.99	-1.22 (1.11)	-2.17 (1.96)	0.66

Notes: **p* < 0.05; values are estimated means (SE). For joint angles, a negative sign indicates flexion.

Table 3.6: Exposure-induced effects of body armor as well as sex differences in kinematic data during prone to standing tests.

Outcome measures	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Time of foot strike (% of trial duration)	0.02 (0.01)	0.01 (0.01)	0.96	0.02 (0.00)	0.01 (0.01)	0.81
Jump Distance (m)	-0.01 (0.01)	0.02 (0.02)	0.26	0.02 (0.02)	-0.003 (0.02)	0.44
Thorax rotation at foot strike (°)	0.59 (0.86)	0.43 (1.28)	0.92	2.14 (1.12)	-1.12 (0.95)	0.05*
Knee Angle at foot strike (°)	2.55 (2.25)	2.93 (2.04)	0.89	3.32 (2.23)	2.15 (3.05)	0.78

Notes: **p* ≤ 0.05; values are estimated means (SE). For joint angles, a negative sign indicates flexion.

3.4 Discussion

As a part of a larger study aimed at understanding how wearing BA affects a warfighter's performance and risk of IRMSCs, the objective of this study was to determine changes in performance and risk of IRMSCs via investigation of several measures of knee and lower back mechanics during two military inspired tasks. Though wearing BA alone (i.e., results from the pre-exposure model) was found to affect some performance and IRMSCs related measures, in general, the effects of exposure (i.e., results from the change model) on our outcome measures were the same between the with and without BA conditions.

Consistent with an earlier study [79], wearing BA in the pre-exposure condition was found to be associated with a significant increase in the duration of the weight acceptance phase of the BD test. Such increased duration, though an indication of

reduced performance, is more likely due to an effort from the individual to control their motion and reduce risk of injury rather than a change in the balance between the demand of task and individual capability. This is further supported by finding no change in the propulsion phase of the BD test where individuals had to move in opposition to gravity and overcome the added inertia and gravitational demands of BA. In contrast, the longer FS-completion duration of the PS test with BA is more likely due to a change in the balance between the task demand and individual capability.

The temporal variation of the vertical GRF during the BD test (Figure 3.2) was consistent with the reported pattern for stair descending [80] wherein the first peak of the double-wave vertical GRF was greater than the second peak. Despite a significant increase in the peak vertical GRF while wearing BA during the pre-exposure BD test, peak instantaneous loading rate which occurred on the ascending part of first vertical GRF did not change significantly. An increase in loading rate has been suggested to be associated with an increase in risk of injury [81-83]. No significant change in loading rate, as found here, may be an indication of participants' success in overcoming the BA-induced increase in task demand without a significant increase in risk of injury. Although all of our kinetic measures during the BD test increased while wearing BA, no kinematic measures (i.e., thorax and knee angles) were affected by BA, suggesting no BA effect on postural performance of the BD task. This finding concurs with results from Kulas, Zalewski [84]. They reported the addition of 10% of body weight did not change knee kinematics during drop landings (i.e., a similar test to our BD). Nonetheless, in another study (Sell et al 2010) which involved a more demanding drop task (i.e., participants jumped from a height of 50 cm with the addition of a helmet and rifle) both kinematic and time measures were found to significantly change in BA condition. Diminished warfighter performance has been defined as decreased accuracy, decreased maneuverability and changes in time to perform a task [26, 30, 52, 53]. As such, our pre-exposure findings suggest that not all aspects of performance (i.e., timing vs. postural) for the BD test considered here are immediately affected by BA.

In contrast to the weight acceptance phase of the BD test wherein no changes in knee and thorax kinematics were seen with BA, a significant change in knee kinematics was found during the first subcomponent of the overall PS test duration (Table 3.2 - 3.3).

In particular, a posture with more knee and less thorax flexion was adopted at the time of FS with BA. Such change in knee and thorax kinematics indicated an increase in demand on the knee and a decrease on the lower back (i.e., shifting the demand of the task from the lower back to the knee) just prior to the participant's effort to stand up. In an earlier study [78], we found that while the capability of individuals for extending their trunk from a flexed posture (i.e., a posture with maximum trunk flexion during a toe-touching task) was affected by BA, their capability of extending their knee from a flexed posture (i.e., a posture with maximum knee flexion during a two-legged squat task) was not affected. Although at the time of FS with BA, participants' postures were not the same as these earlier tests, participants did however change their posture towards a posture closer to the latter (i.e., two-legged squatting task). Such change in posture enabled individuals to benefit from knee extensor muscles that we found not to be affected by BA.

Due to the nature of the PS test, there was limited comparative literature. Previous studies have reported timing differences associated with multiple load carriage systems at different loads [85, 86]. While the overall duration of the PS test was not affected by BA, the second phase of the PS test was longer in duration (Table 3.1). Such an increase in duration while wearing BA could be due to the amplified effect of BA on lower back muscles at the time of FS when there is a large thorax flexion angle (i.e., ~ -100° with respect to the laboratory coordinate frame). This is also consistent with our earlier findings wherein the duration of extension phase of a toe touching task was significantly greater while wearing BA. As a whole it appears that participants were able to deal with the added demand of BA (i.e., via change in posture) without compromising their temporal performance.

NM function has been shown to be altered following prolonged walking or running with or without carrying a load [74, 75]. These alterations have been suggested to require a longer recovery time (i.e., > 24 hours) than the initial prolonged walking or running time [74]. There was no significant difference in exposure-induced changes in the outcome measures of our study between conditions with and without BA. This suggests that the exposure considered in this study with BA does not cause more changes in performance and risk of injury while performing the BD and PS tests as compared to exposure without BA. Nonetheless, the overall duration of both tests reduced following

the exposure protocol. There was also an increase in peak vertical GRF of the BD test after exposure for both the armor and no armor conditions. Though it is not clear why participants performed both tests faster (i.e., decreased duration) after exposure, the increase in peak vertical GRF of the BD test could be due to either faster landing (higher impact) or landing with a stiffer knee condition (e.g., extended knee or higher co-activations). Since there was negligible change in knee posture following exposure (i.e., < 0.4 degrees), the increase in peak vertical GRF is likely due to both higher impact and increased co-activation of the knee flexor and extensor muscles. Higher impact could be due to a reduced control of motion prior to impact while increased co-activity could be a NM effort to reduce risk of knee instability.

Despite higher values of peak vertical GRF in males compared to females, their normalized values with respect to subject mass was greater for females than males. Peak vertical GRF occurred at a later instant of overall trial duration and in a more flexed knee posture among females; both of these differences have contributed to a significantly smaller peak instantaneous loading rate among females than males. Furthermore, females experienced a significantly lower maximum knee extension moment than males during the BD test. These results suggest that males accepted a greater mechanical demand on their knee joint than females during the BD test considered in this study. Unfortunately, we were not able to investigate the interaction between BA exposure and sex due to small sample size of our study (see study limitation in the next paragraph). However, earlier studies have suggested a higher risk for musculoskeletal related injuries in females than men [22, 23].

This study being part of a larger study was an initial investigation into the effects of BA and exposure as they relate to risk of injury and performance. There were multiple limitations that should be addressed in future studies. Currently the small sample size rendered the statistical model unstable to study interactions between independent variables. Additionally, this study was performed in a laboratory setting, differing greatly for the environment of real world military operations. Although the exposure and tests presented were military inspired, they were not as physically demanding as traversing difficult terrain or jumping out of a military vehicle. Other limitations

included only the study of sagittal plane kinematic and vertical kinetic data as well as using one size of BA for all study participants.

In summary BA was found to impair the timing aspect of performance during the tests considered in this study. However, it was not found to be associated with higher risk of IRMSCs. Furthermore, walking with BA for 45 minute was not found to cause any additional changes in our outcome measures than walking the same duration without BA. Heavy loads carried by dismounted warfighters, including BA, can adversely impact force generation and sustainment, due to manpower-reducing injuries and impaired warfighter's performance in combat situations [10]. The findings of this exploratory study can guide design of future studies aimed at understanding the underlying mechanisms responsible for the adverse effects of BA on warfighters' performance and risk of IRMSCs.

Chapter 4 The Effects of Military Body Armor on Isometric and Isokinetic Knee Behaviors

This chapter reproduced from a submitted manuscript, “Phillips, M.P., C.P. Starnes, B. Bazrgari and R. Shapiro. The effects of military body armor on isometric and isokinetic knee behaviors. *Journal of Electromyography and Kinesiology*, 2014, in review.”

4.1 Introduction

Dismounted warfighters are often required to negotiate diverse terrain and obstacles while performing daily tasks and missions. Navigating these conditions is often analogous to athletic activities that have been identified as high risk for knee injuries, involving dynamic movements such as landing, pivoting, sudden decelerating and changing of direction [87-89]. However, there are two unique aspects of the dismounted warfighter’s working environment that may substantially increase the risk of knee injury under the above mentioned high risk movements as compared to athletes. These include (1) the warfighter’s carried load (e.g., supplies, ammunition and body armor) and (2) extreme duration of tasks/missions. It is, therefore, important to determine how such differences in a warfighter’s working environment as compared to an athlete’s training/performance environment affect the risk of knee injury.

Body armor (BA) constitutes a substantial percentage (i.e., ~21%) of carried load by warfighter [13, 39]. Unlike other components of carried load, BA is often worn for longer, continuous durations due to impending threats (e.g., improvised explosive devices). The mitigation of such threats, has been achieved at the expense of significant increase in BA weight over the past decade [13]; a factor which is expected to further increase due to the recent need for extremity armor [2]. However, with increases in BA weight comes its adverse effects on performance and risk of developing musculoskeletal related injuries [12, 13]. BA has been associated with heat stress, altered physiological responses, and diminished warfighter agility, responsiveness, and functionality, [26, 28, 30, 35, 53]. It has also been associated with increased risk of IRMSCs [12, 42]. Yet, the underlying mechanism linking the added weight of BA to such reduced performance and increased risk of IRMSCs, in particular knee injuries, remains unclear.

Founded on a conceptual model [78, 90] which relates BA induced changes in NM behavior to increased risk of IRMSCs via abnormal mechanical changes, we have

carried-out a study to assess the effects of BA on an individual's performance as well as on knee and lower back (i.e., two locations with highest number of IRMSCs) [54] risk of injury. Within this broader project, the objective of present study was to determine BA-induced impairments in NM behavior of the knee extensor and flexor muscles by means of isometric and isokinetic contraction tests. In this context, performance decrement due to NM impairment was defined as a reduction of force generating capacity (e.g., maximum strength, power) of each of the two muscle groups [91], while increase risk of injury was defined as an increase in ratio of maximum isokinetic extensor over flexor strengths [92].

It was hypothesized that prolonged duration of wearing BA would reduce maximum force generation capacity of the knee extensor and flexor muscles during isokinetic and isometric tests. It was also hypothesized that BA-induced changes in NM behavior would be associated with an increased risk of knee injury, which was expected to be seen as an increase of isokinetic extensor to flexor strength ratios. A reduction in IRMSCs improves a warfighter's quality of life and decreases their suffering. It also cuts rehabilitation costs and curtails medical discharges, thus alleviating the government's cost burden associated with underwriting service-connected disability pay (a possible life time entitlement) [5, 7] and training new warfighters.

4.2 Methods

4.2.1 Study design

A cross-over study design was used to assess the effects of carrying BA on multiple measures of knee NM behavior. In a randomized order, participants completed two data collection sessions with and without BA. Each session lasted ~2.5 hours wherein knee flexor and extensor NM behavior was assessed at the beginning and the end of each session. Between these two sets of measurement, participants completed a series of tests and a walking protocol; the sum of which, hereafter, is called exposure. These tests included a series of basic (i.e., repetitive toe-touching and two-legged-squatting, along with quiet standing) and military inspired (i.e., box drop and prone to standing) movements that were completed in a randomized order before and after the walking

protocol (i.e., 45-minutes of a treadmill walking). A detailed description of these tests can be found in [78, 90]. Assessments of knee NM behavior included 1) maximum isometric contraction of knee flexors, 2) maximum isometric contraction of knee extensors, 3) concentric (CON) and eccentric (ECC) isokinetic contractions of knee flexors, and 4) CON and ECC isokinetic contractions of knee extensors. All isometric and isokinetic tests were randomized for each testing session (i.e., with and without BA) and condition (i.e., pre- and post-exposure).

4.2.2 Participants

Six females with mean (standard deviation) age, weight, and height of 24 (5) yrs., 61.54 (7.38) kg, and 1.66 (0.10) m together with six males with mean (standard deviation) age, weight, and height of 26 (5) yrs., 78.77 (9.41) kg, and 1.79 (0.05) m, volunteered and participated in this study after completing the University of Kentucky's Institutional Review Board approved consenting process. Inclusion criteria consisted of (1) no musculoskeletal disorders, (2) no history of lower back or lower extremity surgeries, (3) no positive answers on a physical activity readiness questionnaire [56] and (4) a self-selecting score of ≥ 5 on the Tegner scale [57]. Participants were comprised of previous and current reserve and active duty service members, one female cross-fit athlete and one male collegiate cyclist/avid backpacker.

4.2.3 Body armor

BA included a military issued tactical vest with two ceramic thorax plates as well as in-house manufactured thigh and upper arm plates to simulate extremity armor (106N in total; one size used for all subjects). During the BA testing session, participants wore the complete set of BA for the entire duration of instrumentation, testing and exposure.

4.2.4 Testing procedures

Participants were asked to wear athletic clothing during the testing sessions while athletic shoes were supplied to decrease confounding factors. All tests and data collections were performed using a BIODEX System 3 dynamometer (BIODEX Medical, Shirley, NY) (Figure 1). For these tests, participants were seated in the BIODEX test

chair with their back fully supported and the thigh of their dominant leg (i.e., the right leg for all participants) secured with a seat belt like strap. Additional seat-belt like straps crossed the chest and hips to stabilize the participant. A tibial pad was also placed around the distally third of the shank and held in position with a hook-and-loop fastener (e.g., Velcro© like strap). The axis of rotation of the dynamometer knee attachment was aligned with the right lateral femoral epicondyle. Limb gravity correction was accounted for in accordance with the manufacturer's recommendations. All participants underwent familiarization training during session one. During this time, participants performed a series of submaximal familiarization contractions until they felt comfortable with the equipment and all testing procedures. An approximate 10 minute rest period followed before testing commenced. To limit bias, verbal encouragement was not given during the isometric and isokinetic testing [93]. If a particular test was not completed properly, participants were asked to repeat the test.



Figure 4.1. Dynamometer testing setup. Included are the BIODEX test chair, right knee attachment, as well as, chest, waist, thigh and tibia stabilization straps.

Isometric tests of knee flexors and extensors were conducted at 60° (from full extension) of knee flexion. For these tests, participants were instructed to hold a maximal

knee flexor/extensor isometric contraction for five seconds. Each tests was performed twice with fifteen seconds of rest between maximum isometric contractions to avoid fatigue. Isokinetic tests were performed at an angular velocity of $180^{\circ}\cdot\text{s}^{-1}$ through a range of 80° during the ECC and CON contractions of both the knee flexors and extensors. This velocity was chosen to reflect the approximate timing of conservative muscle contractions during physical activity [94]. For isokinetic tests, the BIODEX's actuator, via knee attachment, was set for each participant to generate/limit knee range of motion between 15° and 95° of knee flexion. This range was determined using a goniometer and enforced by the set BIODEX mechanical stops to prevent injury during the isokinetic testing. For the isokinetic testing of the knee flexors, participants started the ECC contraction phase at 95° of knee flexion. They were instructed to maximally resist as their knee was extended by the BIODEX's actuator to 15° of knee flexion (i.e., try to flex their knee). They were further instructed to start the CON contraction phase immediately following the ECC contraction phase (i.e. from 15° of knee flexion) by exerting a maximal downward force, against the BIODEX's resistance, bringing their knee back to 95° of flexion. For the isokinetic testing of the knee extensor, participants started the CON contraction phase at 95° of knee flexion. They were instructed to maximally extend their knee against the BIODEX's resistance to 15° of knee flexion. They were further instructed to start the ECC contraction phase immediately following the CON contraction phase (i.e. from 15° of knee flexion) by maximally resisting with an upward force, as the BIODEX's actuator flexed the knee to 95° of flexion. For both the isokinetic knee flexor and extensor tests, the isokinetic cycles described above were repeated three times within each test, followed by a one minute rest period.

4.2.5 Data analyses for isometric and isokinetic dynamometer tests

Body armor–induced alterations in knee NM behavior were investigated by analyses of BIODEX recorded knee torques using an in-house Matlab (Mathworks, Natick, MA) program. Maximum isometric knee flexor/extensor strength was calculated as the average peak torque of the two isometric repetitions per condition. As described in the testing procedures, for a given muscle group the ECC and CON contractions were conducted in succession with one contraction type immediately followed by the other

contraction type. In shifting from ECC to CON (or vice versa) contractions, a transient period occurred during which knee angular velocity dropped from $180^{\circ}\cdot\text{s}^{-1}$ to $0^{\circ}\cdot\text{s}^{-1}$ and then increased back to $180^{\circ}\cdot\text{s}^{-1}$ but in the opposite direction. Therefore, to avoid obtaining a maximum isokinetic torque within the transition period between contraction types, ECC and CON maximum torques were obtained within the tenth to ninetieth percentile of the range of motion (i.e., where knee angular velocity was $180^{\circ}\cdot\text{s}^{-1}$), Figure 2. These ECC and CON maximum torques were averaged across repetitions for each muscle group and condition. They were then used to calculate a number of extensor to flexor strength ratios (i.e., quadriceps to hamstrings; (Q:H)). These ratios included (1) conventional Q:H ratios that were calculated by dividing the maximum knee extensor (Q: quadriceps) torque by the maximum knee flexor (H: hamstrings) torque obtained under the same contraction type (i.e., conventional: $Q_{\text{CON}}:H_{\text{CON}}$, $Q_{\text{ECC}}:H_{\text{ECC}}$) [17, 95], and (2) functional Q:H ratios that were the maximum knee extensor (Q) torque divided by the maximum knee flexor (H) torque obtained under opposing contraction types (i.e., functional $Q_{\text{ECC}}:H_{\text{CON}}$, $Q_{\text{CON}}:H_{\text{ECC}}$) [92, 96]. The mean maximum isometric and isokinetic strengths, along with Q:H ratios per condition were used for subsequent statistical analyses. Strength outcome measures in this study are reported in the Newton-meters (N.m), while Q:H ratios are unitless.

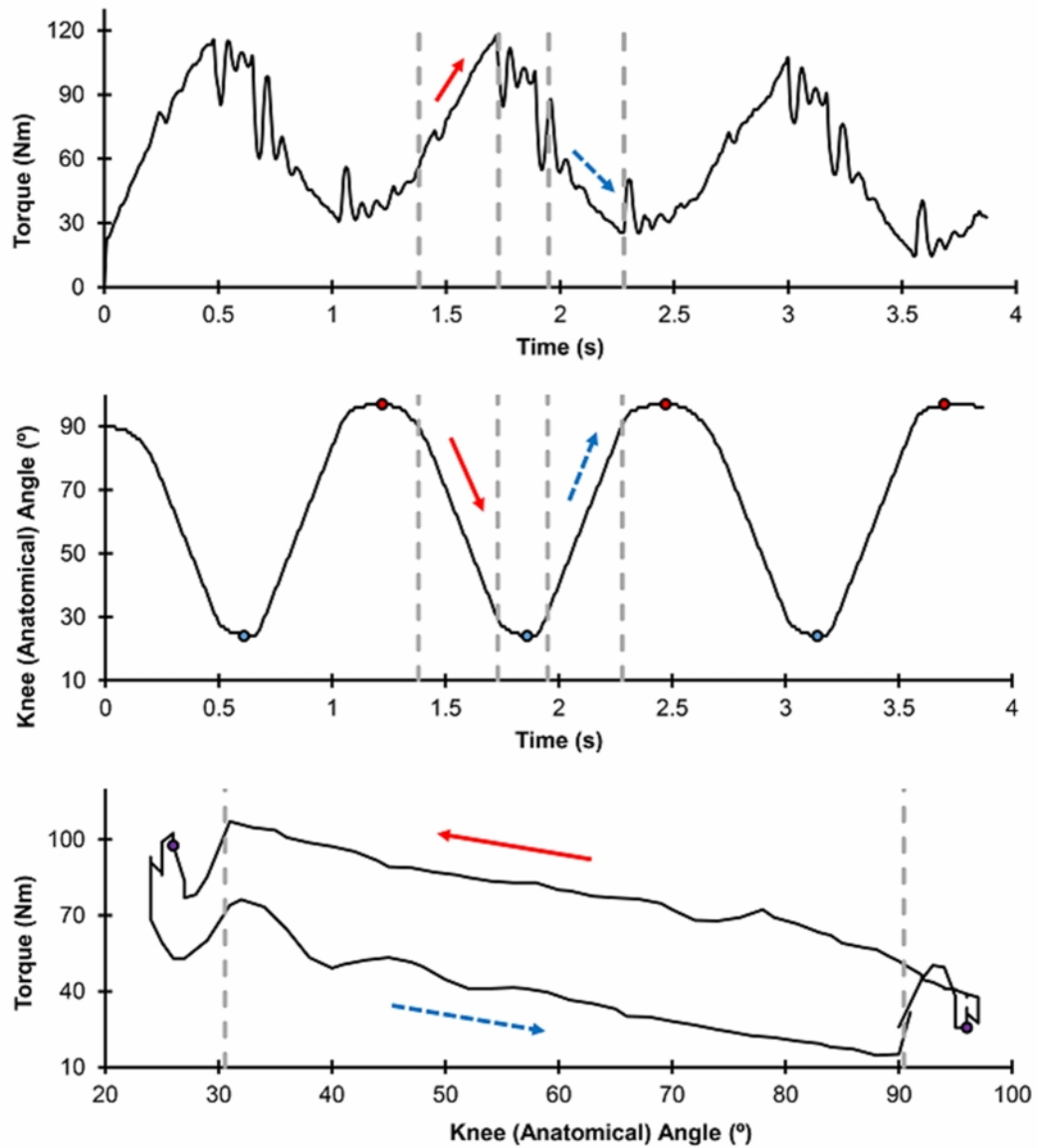


Figure 4.2. Sample torque and kinematic data obtained during concentric and eccentric isokinetic testing of knee flexors. Top (torque vs. time): three repetitions of the eccentric and concentric contraction phases. Middle (knee angle vs. time): three repetitions of the eccentric and concentric contraction phases; Bottom (torque vs. knee angle): one repetition of the eccentric (i.e., upper portion of the curve) and concentric contraction phase. Vertical dotted lines represent the 10th and 90th percentile for range of motion. Red solid arrows indicate eccentric contractions; blue dashed arrows indicate concentric contractions.

Statistical analyses were carried out in SAS software (version 9.3, SAS Institute Inc., Cary, NC, USA). A REML GEE model with unstructured covariance structure utilizing Mancl and DeRouen [59] bias-corrected standard errors was used to examine the effects of armor and sex on pre-exposure measures, and the change in measures from pre-exposure to post-exposure. Statistical significance was set at $p \leq 0.05$. We used the pre-exposure model to investigate of the immediate effect of armor and sex alone on risk of injury and performance; where the change model (post-exposure minus pre-exposure) permitted the investigation of the prolonged effect of exposure to BA on risk of injury and performance.

4.3 Results

No pain or injury was reported from participation in this study. All participants successfully finished both testing sessions.

4.3.1 The effects of body armor (pre-exposure model)

The effects of BA and sex on the isokinetic and isometric measures of knee strength are presented in Tables 4.1-4.2. Although not significant ($p \geq 0.11$), there was a general trend of increased peak torque production during the armor conditions when compared with the no armor conditions (Table 4.1). All Q:H strength ratios for the no armor condition were greater than the armor conditions with only changes in the $Q_{CON}:H_{CON}$ strength ratios being significant ($p = 0.05$) (Table 4.2). In general, males had greater maximum isokinetic and isometric knee strengths, along with lower Q:H ratios than females. However, only maximum isometric strength of knee flexors were significantly ($p = 0.02$) greater among males when compared to females (Table 4.1).

Table 4.1: Pre-exposure effects of body armor on isometric and isokinetic knee behavior along with corresponding sex differences during dynamometer tests. All units are in N·m.

Outcome measures	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Flexors						
Isokinetic Flexors ECC	99.60 (10.69)	88.61(6.420)	0.32	95.10 (10.46)	93.10 (9.07)	0.89
Isokinetic Flexors CON	87.36 (9.21)	69.47 (9.84)	0.11	82.38 (13.86)	74.46 (7.41)	0.62
Isometric Flexors	84.56 (6.52)	78.89 (4.39)	0.30	95.07 (8.6310)	68.38 (4.63)	0.02*
Extensors						
Isokinetic Extensors ECC	133.05 (28.55)	135.44 (16.69)	0.95	135.48 (22.07)	133.01 (21.41)	0.94
Isokinetic Extensors CON	103.29 (21.71)	93.65 (12.61)	0.66	94.71 (21.04)	102.23 (17.55)	0.78
Isometric Extensors	148.51 (11.83)	141.71 (11.82)	0.45	166.88 (15.60)	123.34 (15.28)	0.08

Notes: * $p \leq 0.05$; values are estimated means (SE).

Table 4.2: Pre-exposure effects of body armor on the ratio of knee extensor to flexor strengths (Q:H ratios) along with corresponding sex differences during dynamometer tests. Q: quadriceps; H: hamstrings

Outcome measures	Armor	No Armor	<i>p</i> value	Male	Female	<i>p</i> value
Conventional						
Q _{ECC} :H _{ECC}	1.28 (0.19)	1.60 (0.21)	0.27	1.42 (0.27)	1.45 (0.11)	0.92
Q _{CON} :H _{CON}	1.15 (0.17)	1.45 (0.17)	0.05*	1.28 (0.25)	1.32 (0.21)	0.92
Functional						
Q _{ECC} :H _{CON}	1.58 (0.27)	2.58 (0.86)	0.24	2.03 (0.70)	2.13 (0.43)	0.87
Q _{CON} :H _{ECC}	1.01 (0.15)	1.21 (0.17)	0.33	1.11 (0.20)	1.12 (0.18)	0.97

Notes: * $p \leq 0.05$; values are estimated means (SE).

4.3.2 The effects of exposure (change model)

Exposure-induced changes in outcome measures are presented in Tables 4.3-4.4 for the isokinetic and isometric tests. Among our measures of knee strength, the maximum isometric strength of knee flexors experienced a significantly ($p = 0.04$) greater reduction during the armor condition than the no armor condition (Table 4.3). All Q:H ratios increased/decreased after exposure with/without body armor (Table 4.4). Particularly, the exposure-induced change in Q_{CON}:H_{CON} and Q_{CON}:H_{ECC} strength ratios were significantly different ($p \leq 0.03$) between the armor and no armor conditions. Specifically, both the post-exposure Q_{CON}:H_{CON} and Q_{CON}:H_{ECC} strength ratios increased during armor condition and decreased during the no armor condition. Finally, following exposure, females experienced a significantly greater reduction ($p = 0.03$) in maximum

isometric knee extensor strength as compared to males (Table 4.3). All other exposure-induced changes in outcome measures were not different between males and females ($p \geq 0.15$).

Table 4.3: Exposure-induced changes of body armor on isometric and isokinetic knee behavior along with corresponding sex differences. All units are in N·m.

Outcome measures	Armor	No Armor	p value	Male	Female	p value
Flexors						
Isokinetic Flexors ECC	-11.50 (6.98)	6.11 (7.53)	0.14	-0.14 (8.27)	-5.26 (4.88)	0.61
Isokinetic Flexors CON	-10.13 (9.93)	4.88 (4.16)	0.15	3.97 (9.55)	-9.21 (3.60)	0.15
Isometric Flexors	-20.83 (6.50)	-10.65 (2.87)	0.04*	-16.10 (7.51)	-15.38 (2.82)	0.92
Extensors						
Isokinetic Extensors ECC	1.16 (11.41)	-17.47 (23.89)	0.53	-12.09 (18.49)	-4.22 (11.21)	0.69
Isokinetic Extensors CON	1.26 (7.13)	-3.56 (14.95)	0.81	-5.33 (6.30)	3.03 (10.39)	0.48
Isometric Extensors	-11.10 (7.65)	-10.20 (3.81)	0.91	-2.48 (6.64)	-18.82 (4.14)	0.03*

Notes: * $p \leq 0.05$; values are estimated means (SE).

Table 4.4: Exposure-induced changes of body armor on the ratio of knee extensor to flexor strengths (Q:H ratios) along with corresponding sex differences during dynamometer tests. Q: quadriceps; H: hamstrings.

Outcome measures	Armor	No Armor	p value	Male	Female	p value
Conventional						
Q _{ECC} :H _{ECC}	0.17 (0.14)	-0.30 (0.29)	0.09	-0.09 (0.32)	-0.04 (0.14)	0.87
Q _{CON} :H _{CON}	0.23 (0.05)	-0.15 (0.14)	0.02*	0.05 (0.13)	0.03 (0.07)	0.82
Functional						
Q _{ECC} :H _{CON}	0.18 (0.29)	-0.92 (0.95)	0.18	-0.46 (0.90)	-0.29 (0.38)	0.81
Q _{CON} :H _{ECC}	0.24 (0.12)	-0.15 (0.11)	0.03*	0.12 (0.11)	-0.03 (0.13)	0.4

Notes: * $p \leq 0.05$; values are estimated means (SE).

4.4 Discussion

As part of a larger pilot project designed to investigate BA's effect on warfighters' performance and risk of IRMSCs, the purpose of this study was to determine any impairment in the NM behavior of knee extensors and flexors. We hypothesized that prolonged duration of wearing BA would reduce maximum force generation capacity of the knee extensor and flexor muscles during isokinetic and isometric tests, which was partially confirmed by finding a significant force reduction between the armor and no

armor conditions of maximum isometric knee flexor strength. We also hypothesized that BA-induced changes in NM behavior of the knee would be associated with an increase of Q:H strength ratios but found only significant increases in the conventional strength ratios when comparing the armor to no armor condition.

While wearing BA, post-exposure maximum isometric contractions showed a 25% and a 7% reduction in knee flexor and extensor strengths respectively, compared to the corresponding 13% and 7% respective reductions for conditions without BA. Additionally, in the post-exposure BA condition, there was an approximate 12% reduction in both maximum CON/ECC isokinetic strength of knee flexors, while there was a <1% increase in maximum CON/ECC isokinetic strength of knee extensors. Although no significant difference in exposure-induced changes in isokinetic strength of knee flexors and extensors was found between the with and without BA conditions, the significantly larger decrease in the isometric strength of knee flexors suggests a higher exposure-induced degradation of performance with BA as compared to without BA. An earlier study by Blacker, Fallowfield [74] investigated alterations in NM function of the knee following a two-hour load carriage (i.e., 25 kg) on both a level and a downhill ground surface at a constant speed of 6.5 km·h⁻¹. Our findings are relatively consistent with their reported results for the level ground walking, wherein they reported a 15% decrease in isometric strength of knee extensors and 11% and 5% reductions in CON isokinetic strength of knee flexors and extensors respectively. Another study by Grenier, Millet [97], evaluated alterations in NM function of the knee extensors and plantar flexors, pre- and post a 21 h simulated military mission while carrying ~27 kg during battles and ~43 kg during marches. A similar, but significant, decline in the maximum isometric knee extensor strength (i.e., 10.2 ± 3.6%) was reported.

Dismounted warfighters routinely perform tasks that involve repetitive ECC contractions of the knee flexor and extensor muscles for prolonged periods (e.g., during extended road marches or while conducting patrols). Muscle activation following such periods of repetitive ECC contraction have been associated with an intensified loss of strength and muscle damage [75, 98]. Further, knee flexor injuries are extremely prevalent among athletes and associated with repeated ECC contractions and dynamics movements [95]. Warfighters often perform landing and jumping tasks (e.g., while traversing uneven

terrain or jumping off a vehicle) with a fully (or nearly fully) extended knee. In such a knee posture, ECC contraction of the knee extensors cause an anterior tibial shear force that is thought to be a contributing risk factor for anterior cruciate ligament (ACL) injuries [19, 99, 100]. The CON co-contraction of the knee flexors under such conditions can reduce loading on the ACL by producing a posterior tibial shear force. Therefore, any deterioration of knee flexor strength as a result of repetitive ECC contractions may impose a higher risk for ACL injury if it compromises its protecting role via co-contraction. It has been suggested that such a compromised protecting role of knee flexors may be reflected in an increase in the ratio of maximum isokinetic knee extensor torque to maximum isokinetic knee flexor torque (i.e., Q:H strength ratio) [17, 92, 101]. Our exposure-induced Q:H ratios (both conventional and functional) showed a general trend of a ratio increase > 0.17 for the BA condition and a > 0.15 ratio reduction for the no armor condition. Whether protecting against ACL injury or contributing to the overall stability of the knee joint, the general trend of exposure-induced increases in Q:H ratios while wearing BA (i.e., a possible indicator of impaired protecting ability via co-activation) suggests an increased level of risk for knee injuries.

With Q:H strength ratios often used as one of the screening/predicting tools for knee injury, there was a general trend observed where females had greater Q:H strength ratios than males in both the pre-exposure and exposure-induces models. These results are consistent with literature, where for numerous reasons (e.g., anatomical, biomechanical, hormonal, neuromuscular), it has been established that females are at a heightened risk of musculoskeletal injuries than males, specifically ACL injuries [17, 87, 102].

In our study, BA was added to the thorax, upper arms and thighs. Due to BA placement locations and the participant posture during the tests (i.e., sitting posture), we did not expect to find any differences in the pre-exposure outcome measures when comparing the armor and no armor conditions (i.e. results from the pre-exposure model). However, there was a general trend in Q:H strength ratios, where all pre-exposure ratios were lower for BA conditions than their respective no armor conditions. Particularly, such differences were statistically significant for the $Q_{CON}:H_{CON}$ ratio. Although, due to the testing setup, the presence of BA should not have affected the actual demand of any of the pre-exposure tests, it might have had an impact on our participants' perceived level of test

demand. However, we did not have our participants complete a ‘rating of perceived exertion’ to verify if the observed trend could possibly be explained as anticipated physiological exertion [103, 104].

There were multiple limitations related to our study. As an initial exploratory study we had a small sample, therefore, we couldn’t investigate any armor-gender interactions without creating numerical instabilities within our statistical models. Although the overall testing sessions contained military inspired tasks and walking protocol, all tests were performed in a laboratory setting. As such, terrain and temperature were not consistent with real world military operations. Finally, all participants wore the same size BA due to limited availability.

In conclusion, although not all of our measures of knee NM behavior were effected by BA, those that were affected suggest BA-induced NM impairment associates with reduced performance and increased risk of injury. If strength deficiencies are known to occur after prolonged exposure to BA, such observed NM changes may be used as an injury risk assessment tool, to develop physical training programs that decrease or correct a particular imbalance and to establish return to service (i.e., post injury) standards for dismounted warfighters. This may lead to an improved functional outcome (i.e., performance) and also prevent future injuries.

Chapter 5 Conclusions and Future Work

5.1 Conclusions

This is the first study at the University of Kentucky to examine the immediate and prolonged effects of exposure to BA on performance and risk of IRMSCs.

For our target population of military service members, the two locations that have the highest reported prevalence for a musculoskeletal injury are the lower back and knee. While acute effects of added load (BA or other components of a load carriage system) on performance and risk of injury has been investigated in the past, there has been limited information (none for BA alone) related to prolonged impact of added load on performance and risk of injury among warfighters. In our search for NM mechanisms responsible for the role of BA in such elevated prevalence of injury among military personnel, we first chose two simple tests each involving an isolated large mechanical demand on either the lower back or knee (i.e., TT and TLS respectively). The simplicity of these tests (i.e., involving one joint at a time) was expected to facilitate the understanding of the underlying mechanisms. The underlying conceptual model used for the study design guided us to choose outcome measures (e.g., LPR) that not only allowed identification of any change in active and passive NM contribution to joint mechanics (e.g., change in the synergy between pelvis and lower back muscles for the case of LPR) but also have been novel to this field of research. Alterations in our measures of joint mechanics, when immediately exposed to armor, reflect changes in NM behavior in response to immediate changes in task demand with BA. Such alterations were increased flexion time of the dominant joint in both simple TT and TLS tests and also a decreased contribution of pelvis rotation during the TT test near the mid-range of trunk flexion. Next, we chose to study military inspired tests that involved multiple coupled joints in the body (i.e., BD and PS). Changes in NM behavior of the lower back and knee were indicated by increased temporal test durations and an increased BD peak ground reaction force. Lastly, we used the knee flexors and extensors maximum isometric and isokinetic torques as well as Q:H strength ratios to identify BA-induced changes in NM behavior associates with performance and lower extremity risk of injury. While, not all outcome measures of knee NM behavior were effected by BA, those that were changed suggest BA-induced NM impairment associates with reduced

performance and increased risk of injury. Specifically, exposure-induced changes with BA caused a greater reduction in maximum isometric strength of the knee flexors and an increase in $Q_{CON}:H_{CON}$ and $Q_{CON}:H_{ECC}$ strength ratios when compared to the no armor condition.

Providing the small sample size of our study, to increase the likelihood of finding any potential BA-induced changes in the lower back and knee mechanics, we designed our simple and military inspired tests to be demanding on either lower back or knee hence increasing the likelihood of finding any potential BA-induced effects. The simple tests were performed fast and repetitive rather than quasi-static and consisting of a single excursion. Likewise three trials of military inspired tests were performed during each armor and exposure condition. Nonetheless, we found limited change in simple and military inspired outcome measures after walking with BA as compared to walking without BA. However, the immediate NM changes observed warrant future research to determine the impact of such changes in NM behavior on joint mechanics (i.e., stress and strain distributions).

The nature of this project was exploratory and the results of the study are important for design of our future studies involving a larger sample size, diverse military inspired tasks, and more realistic exposure conditions. In an effort to build a foundation for future studies associated with this cohort, it was necessary to establish evidence regarding the conceptual model and outcome measures that are novel to this area of research. Although the presented materials may not have substantially transformed our knowledge of the injury-causing mechanism(s) of BA, we believe it has generated important insight that is essential for our future efforts in this area. Without such knowledge, it would be hard if not impossible to design studies with longer exposure durations that might have unnecessarily exposed our study participants to increased risk of musculoskeletal injury.

5.2 Future work

The ability to non-invasively identify biomechanical and NM changes permits the identification of risk factors for injury and degraded performance, and assessing the

effectiveness of treatments/interventions. This project opens up a new line of research for future collaborations and studies.

Future work should focus on the sensitivity associated with NM changes. First, our targeted population was very physically fit. The authenticity of the exposure period needs to be intensified. To overcome Institutional Review Board restrictions, two possible solutions involve using a warfighter's mission/training as the exposure. For example, 1) run study participants through a laboratory testing protocol before and immediately following their training or missions (e.g., schedule testing session to coincide with campus Reserves Officer's Training Corps (ROTC) road marches), 2) bring the testing equipment to the field and test study participants before and after multiple day field training (e.g., conduct testing at Fort Campbell or Fort Knox). Second, acquire multiple sets and sizes of armor. Third, expand outcome measure and tests beyond sagittal plan motion to include the frontal and transvers planes. Fourth, although study participants are already heavily instrumented, the incorporation of electromyography and electric stimulation would provide amplifying information when discerning contribution of muscle involvement to net joint moments (e.g., with inverse dynamics alone, net joint moments suffer from indeterminacy) and origin of functional impairment (e.g., central or peripheral). Fifth, an increased sample size is needed to power the statistical model appropriately to investigate armor and gender interaction.

Beyond experimental testing, the next step is computational analysis. Finite element models are widely used to study numerous aspects of human biomechanics ranging from intervertebral discs, mitral valves, the collagen pattern of articular cartilage and femoral head fracture risk factors [105-108]. Additionally, there have been numerous lumbar spine loading studies [109-117] but to our knowledge, there are no studies employing the technique of finite element modeling to study joint load and stability related to the wearing of military body armor. In the past, the lab has developed a dynamic kinematics-driven approach to computationally solve the kinetics and kinematics redundancies resulting from multiple muscles spanning a deformable spine with large degrees of freedom [118]. In this approach, measured trunk kinetic and kinematic data are prescribed into a nonlinear finite element model of the spine. Muscle forces, spinal loads, and stability are estimated through an iterative procedure by solving nonlinear differential

equations of motion using a direct implicit integration method [119]. This finite element model of the human trunk has been applied to study the effects of manual material handling, whole body vibration, sudden loading and impact on trunk neuromuscular behavior and spine biomechanics (muscle forces, compression and shear forces) at different lumbar and spinal levels [60, 120, 121]. In continuation of this earlier works, application of such model should be used to quantify the association between BA changes in NM behavior and joint load and joint stability of the trunk. Additionally, this model will be expanded to include the knee joint.

Appendix A Literature Review

A.1 Body armor

The use of ballistic personal protective equipment is not a new concept to the U.S. military. In World War II ‘flak-vests’ (i.e., steel plates sown into cloth) were issued to air bomber crews. Cumbersome, they were impractical for dismounted warfighters. The Korean War was possibly the first employment of ballistic vests, M-1951, to dismounted warfighters. Still awkward but lighter, these vest were updated with nylon material and able to stop shrapnel but not riddle or small arms fire. Further adaptations to the M-1951 were made during the Vietnam War but it was not until the late 1970s and early 1980s, with the development of Kevlar © and ceramic materials [122], that the next noteworthy innovation in body armor was seen. The Personnel Armor System for Ground Troops (PAGST) vest and helmet were introduced in the 1980s. This vest was not only superior to the Vietnam nylon era vest in ballistic ability [123], but also in terms of comfort and coloring (i.e., camouflage) [123, 124]. The PAGST armor had an additional over-vest. The combination of the two systems (i.e., PAGST and over-vest) were capable of stopping 7.62-mm rounds when worn together, however, the combined weight of the two systems (i.e., 25.1 lb) were regarded as too heavy by most warfighters [124]. In the late 1990s, the Interceptor Multi-Threat Body Armor System (IBA) provided enhanced protection while weighing ~10 lb less than its predecessor, and became the primary BA system for both the U.S. Army and U.S. Marine Corps. The IBA is comprised of two key modular components (1) Outer Tactical Vest (OTV), 8.4 lb and (2) small-arms protective inserts (SAPI), 4 lb each [125]. The OTV is unisex, made of Kevlar weave and provides protection against 9-mm rounds (from pistols) and fragmentation. It is also outfitted with a removable collar and detachable groin and throat protectors. When the SAPI, front and back, ceramic (silicon carbide/boron carbide) plates are inserted, the vest is able to stop 7.62-mm rounds (from rifles and machine gun fire). The SAPI were extremely successful and have continued to be utilized in subsequent generations of BA vests.

In 2006, the U.S. Marine Corps adapted a new armor system, the Modular Tactical Vest (MTV) while using the same SAPI from the IBA. Although the MTV weighs ~30 lb (3 more than the fully loaded IBA), it provides greater coverage, superior

weight distribution and a quick release system. This quick release system, new cummerbund style closure and shoulder release design, allows medics to treat casualties without having to move the warfighter or cut away their outer vest. However, the MTV is considered very heavy for the mountainous terrain of Afghanistan. A lighter alternative, the Scalable Plate Carrier, is often used by Marines while operating in Afghanistan. In 2013 some improvements were made to include and Improved Modular Tactical Vests (IMTV) and Improved Scalable Plate Carrier. Specifically, the IMTV is made for smaller stature Marines who cannot wear the full-sized MTV comfortably.

Similarly in 2007, the U.S. Army started issuing the Improved Outer Tactical Vest (IOTV) with enhanced SAPI (ESAPI) plates to all ground troops. In 2005, the ESAPI started replacing the SAPI. The main improvement of the ESAPI was their ability to stop armor-piercing rounds with a steel or tungsten penetrator. With such improvements came an increase in weight. A medium insert increased from 4 lb to 5.5 lb [126]. Additionally, a size medium IOTV when fully equipped with all components (i.e., four ceramic plates (front, back and side plates), collar and groin protector and soft armor insert) weighs ~ 30 lb [127]. A key feature of the IOTV is a quick release lanyard. When pulled the armor falls apart into its individual components allowing the warfighter a quick means of egress if in water or trapped in some other hazardous environment. This lanyard also allows medical personnel easier access to casualties [127].

Each of the follow-on vests since the initial introduction of the IBA have taken into account the ergonomic needs of the warfighter [122, 125, 127]. Due to their effectiveness in combat and design these vests are now worn by dismounted warfighters on all missions and have played a significant role in the 90% survivability of battle field wounds when compared to previous wartime casualties, 69.7% and 76.4% from World War II and the Vietnam War respectively [41]. Advances in medicine and battle field medical treatment have played a role in such survivability statistics but the use of Kevlar vests and ceramic plates have been associated with the greatest contribution of such statistics [41, 128, 129]. Additionally, the reduction in thorax injuries first observed during Operation Desert Storm have been attributed to the wearing of individual BA, when such injuries were reduced to 5% from the previous 13% experience during the

Vietnam War [128] and a continued pattern has been reported for Operations Enduring Freedom and Operations Iraqi Freedom [2, 128].

Such data underscores the scientific progress in materials, improved ergonomic design and effectiveness of individual BA over the past 60 years.

A.2 Load carriage

Dismounted warfighters often must carry what they need to the battle field. This load is called a warfighter's combat load (e.g. supplies, equipment, water, food, ammunition, weapon, BA). There are two main types of combat load, fighting march load and approach march load, where 48 lb and 72 lb should not be exceeded respectively [55]. However, there are situations when the topography is not accessible to vehicles or air support and warfighters are required to carry loads in excess of 72 lb (i.e., emergency approach march loads). In these situations warfighters can expect to carry loads between 120 lb – 150 lb, covering 20 km/day for numerous days [55]. Although the above-mentioned combat loads are 'not to exceed' parameters, Knapik, Reynolds [11] studied the loads carried in combat by a light infantry brigade for 29 duty positions. The brigade was engaged in intense conflict in the deserts and mountains of Afghanistan. They found the average fighting and approach march loads to be ~64 lb and ~101 lb respectively.

A warfighter's combat load is typically carried between a load bearing vest and backpack system. There are two main load-carrying systems used today 1) the All-Purpose Lightweight Individual-Carrying Equipment (ALICE) pack and 2) the Modular Lightweight Load-Carrying equipment (MOLLE) pack. The ALICE pack was first introduced in 1974. It was the first load carriage system that allowed the separation of the fighting load and the existing load (e.g., food, supplies and equipment to complete a mission [130]). It consisted of an external frame, and cargo shelf holding the rucksack away from the body, while secured with shoulder, lower back and waist straps. The system had a quick release function to facilitate dropping the existing load while retaining the fighting load. A study by Sampson, Leitch [131] conducted a front end analysis of the overall load bearing requirements for the U.S. Army and U.S. Marine Corps. Results revealed the necessity for an improved load carriage system, to include improved equipment compatibility of fitting the system to a variety of users, the main

system should be modular in nature to accommodate many purposes and the second system should have the storage capability to carry cold weather gear. This resulted in the development of the MOLLE pack, adapted by the Marine Corps in 1999 and the Army in 2001. The MOLLE pack consists of a taller, narrower profile than the ALICE pack. This design was to address concerns around load distribution, allowing dismounted warfighters to shift the load center of mass to a more optimal body position [11, 132]. Additionally, it had padded shoulder straps, waist belt and straps for obtaining an improved load distribution. The main pack has a load bearing vest to accommodate many modular pouches and accessories, a butt pack and a sleeping bag. Moreover, a patrol pack can be detached for separate use.

Technological advances in communication equipment, weaponry, ammunition and BA have increased the combat load carried by a dismounted warfighter. Pack design is an essential aspect of load carriage. It offers the end user load carriage flexibility depending on the mission, terrain and equipment carried.

A.2.1 Performance and load carriage

Throughout history, military load carriage has been linked to lost conflicts and battles, needless deaths, and individual reduced performance, ultimately all contributing to a unit's diminished performance. This has been documented from the Omaha Beach invasion in 1944 [133], Grenada in 1986 [134], Saudi Arabia and Iraq in 1990 [135], and Iraq and Afghanistan (2001 - present day) [42, 44]. A warfighter's agility and reaction time degrade with load. Factors contributing to such performance degradation are load mass, load volume and load distribution [8]. The Army [55] reported a soldier requires a 10%-15% increase in time to complete an obstacle course for every 10 lb of equipment carried. Additionally they reported, for every 10 lb carried in excess of 40 lb the distance traveled in six hours is reduced by 2 km. Holewun and Lotens [136] studied loss of physical performance related to backpack weight and volume during a battery of test (i.e., obstacle course, jumping, sprinting, running, hand-grenade throwing, and a mobility test). An average loss of performance of 1% per kg mass and 0-2% per liter backpack volume were found. Additionally, they found the distribution of weight in the backpack influenced the performance of individual tests. The metabolic cost of carrying a load,

while walking or standing, increases as the mass, walking speed, and grade increase, as well as with distribution of loads and load placement [136-141]. For instance, significant increases in oxygen consumption, ventilation and heart rate with increased weight of load carriage (i.e., 30%, 50% and 70% of the participants' lean body mass) during marching trials (30 minutes at 6 km/h) were reported by Beekley, Alt [141]. Results suggested, increased load carriage may negatively affect a dismounted warfighters road march performance [141].

These results indicate placement and volume, in addition to mass, have been shown to degrade a warfighter's performance. Speed, agility and quickness are often a warfighter's greatest tool on the battlefield. A reduction in those abilities can be lethal to an individual and extremely detrimental to overall unit's mission.

A.2.2 Injuries and load carriage

There are some injuries that are extremely common to load carriage and military marches that occur during or directly following a load carriage activity. Although, these injuries may seem superficially minor, their unfavorable effect on a warfighter's movements can detrimentally effect the military unit as a whole. Some of these injuries include, foot blisters, metatarsalgia (i.e., pain and swelling on the sole of the foot), stress fractures of the lower extremities, rucksack palsy (i.e., upper extremity numbness, paralysis and cramping; scapular winging), meralgia paresthetica (i.e., pain, paresthesia and weakness of the anterolateral thigh), knee pain, and lower back pain [8]. Furthermore, the prolonged, repeated exposure of load carriage to a dismounted warfighter over the duration of a deployment or training period has been suggested to be a risk factor for overuse, and chronic musculoskeletal injuries. Specifically, it has been shown that load added in 8 kg increments invoked a proportional response in the vertical ground reaction force, which has been associated with the overuse injury of lower extremity stress fractures [47]. Load carriage has been associated with altered gait kinematic and spatiotemporal parameters, such as reduced range of flexion/extension motion of the knee, reduced pelvic rotation, increased pelvic tilt, increased rotation of the hip, as well as, increased double support and decreased stride length [46, 49]. Where these kinematic changes have been associated with increased risk of injury and the

spatiotemporal gait parameters have been identified as potential compensating mechanisms to control for the stress added to the body through load carriage [46, 49]. Load carriage has also been found to increase trunk flexion, decrease the craniovertebral angle, placing the head in a more forward position to function in unison with the trunk to counterbalance the carried load. The higher muscular tensions required to maintain these biomechanical changes have also been associated with joint issues, and injury [142]. Finally, loads have been found to effect balance and cognitive thinking [143, 144]. The addition of 18.1 kg, has been shown to increase center of pressure path length by 64%, medial-lateral excursion by 131%, anterior-posterior excursion by 54% and center of pressure area by 229%. These changes in postural sway have been associated with increased likelihood of falls and increased injuries [143]. Additionally, May, Tomporowski [144] found load carriage negatively alters both balance control and situational awareness. They conducted a study where participants completed two dual-task testing sessions (i.e., with no load and while carrying 30% of their body weight using and ALICE pack) requiring balance and rapid decision making. Their within subject results reveal load carriage disrupted stability and reduced cognitive processes in trials that required executive, higher-level, mental processing.

Injuries themselves reduce moral and warfighter quality of life. In a war zone, an injury associated with load carriage will degrade a warfighter's ability. Thereby, potentially resulting in consequences similar to those mentioned in the above-mentioned §A.2.1.

A.2.3 Performance, injury and body armor

Depending on the combat load, BA can accounts for 20%-30% of the total load carried by a dismounted warfighter [11, 12]. Similar to load carriage as a whole, BA has been identified as a risk factor IRMSCs and reduced performance, but unlike load carriage there is minimal literature addressing BA. A primary reason for this is the evolving type of threats (e.g., explosive) experienced in recent conflicts (e.g., Operation Enduring Freedom and Operation Iraqi Freedom), along with the transition/development of BA to address such threats. Therefore, the association of BA with risk of IRMSCs,

degraded performance, and service connected disabilities has been unfolding. BA has been shown to affect a warfighter's performance, and injury.

A.2.3.1 Performance and body armor

Physical exertion-based and task-based performance studies have found a significant increase in heart rate while treadmill walking with for a moderate duration (i.e., 30 min) and prolonged intermittent duration (i.e., 4 h) with BA [25, 26]. In addition, while participants performed a circuit of military tasks increased heart rate, increased core temperature and increased rating of perceived exertion were reported [28, 29]. Ricciardi, Deuster [26] examined the physical work performance, energy cost and physiological fatigue of military personnel with and without BA (i.e., vest, 10 kg) during 30 min (5 min warm-up, 10 min at 5% grade ~ 2.4 mph (slow), 10 min at 10% grade ~ 3.7 mph (moderate), 5 min cool down) of treadmill walking, followed by the completion of series of tests (i.e., hang grip strength, stair stepping and pulls-ups (males) or hang time (females)). During each testing session, while walking, self-reported rating of perceived exertion, heart rate, minute ventilation, oxygen uptake (VO_2), carbon dioxide and respiratory exchange ratio were continuously monitored. Further, blood was drawn three times, pre- and post- treadmill walking, as well as, post physical testing for blood lactate levels. While wearing BA, subjects had significantly greater increase in: VO_2 , slow (~ $2\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) and moderate paces (~ $6\text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$); blood lactate at a moderate pace (~ 3.7 mmol/L); heart rate at slow (~11 bpm) and moderate paces (~16 bpm); and ratings of perceived physical exertion at slow (~2 units) and moderate paces (~2.5). Physical tasks were also significantly affected while wearing BA: males performed 61% fewer pull-ups and female's hang time was reduced by 63% and stair stepping was reduced by 16%. In a study conducted by Chevront, Goodman [25], the impact of a protective vest on physiological strain and the potential of a spacer garment to reduce physiological strain was examined. Participants performed three trials of intermittent treadmill walking (4 hrs), in three conditions (1) military uniform, (2) uniform plus armor vest (7.5 kg) and (3) uniform, armor vest and spacer garment (0.2 kg). Condition 1 was performed at 2.5 m/s and a 3% grade, while Conditions 2 and 3 were performed at 1.56 m/s and a 2% grade. Measurements included core temperature,

mean skin temperature, chest temperature, heart rate and sweat rate. In Condition 2, heart rate significantly increased by 7 bpm after 1 hr and 19 bpm after 4 hours when compared to condition 1. Although, condition 3 did decrease the physiological measure of temperature and sweat rate, the magnitude was small and not significant when compared with Condition 2.

A study by DeMaio, Onate [30] assess the effect of BA (vest and helmet, ~ 9.8 kg) on physical performance by cardiovascular (V_{O_2} max), balance (center of pressure), strength (upper extremity climbing strength) and function field tests (300 yd shuttle run, box agility, rope pull and dummy drag). V_{O_2} max measurements were taken during fast treadmill walking up steep grades (4 mph, 0% grade to 20 % grade in increments of 5 % grade every 3 min). While participants were verbally encouraged to walk as long as possible, no participant completed the full treadmill test. All participants completed the physical performance tests with and without BA. During the BA testing session, there was a significant reduction (~2 min) in maximum treadmill duration, as well as, aerobic capacity (~7 ml·min⁻¹·kg⁻¹). Center of pressure motion was shown to significantly increase in both the anterior-posterior and medial-lateral directions while wearing BA. However only the shuttle run was significantly affected by BA. Other studies investigating the effects of BA will be discussed in section *A.3 Extremity Armor*, as these studies [27-29, 32] compare the no armor, armor and extremity armor condition.

The above summary highlights the significant decrement in the physical work capacity of militarily relevant tasks associated with the personal protective equipment of BA.

A.2.3.2 Injury and body armor

Warfighter comfort and risk of injury have been investigated as it related to BA. During a six month period in 2006, ~3500 Army soldiers deployed to various locations in Iraq were surveyed by Konitzer, Fargo [12]. The survey was conducted to investigate the relationship between back, neck and upper extremity musculoskeletal pain and the wearing of BA. The results revealed two times as many soldiers ascribed their increased back, neck and upper extremity pain to wearing BA than performing their occupational tasks or physical training [12]. In addition, there was a significant positive correlation

between self-reported musculoskeletal conditions and those soldiers who wore BA for more than four hours a day. More recently, a study by Park, Branson [35], studied the impact of weight magnitude and distribution of BA on walking patterns and perceived comfort. Spatial-temporal walking parameters, plantar pressure and contact area were measured during multiple balanced and unbalanced BA conditions. Conditions included (1) no armor, (2) armor vest (9 kg), while conditions (3)–(7) explored the effect of low weight magnitude of small carried loads attached to armor. Conditions (3) and (4) had one additional 9 kg load to either the front, right or left pocket respectively. Condition (5) had a total of 9 kg distributed evenly between the two front pockets (4.5 kg per front pocket). Conditions (6) added a total of 9 kg distributed evenly between the two back pockets pocket in addition to the 9 kg of condition 5. Finally, condition (7) had 18 kg total, evenly distributed between the back two pockets (9 kg per back pocket).

Participants performed two bare-foot walking tests, one on a pressure sensor mat (repeated four times) in each garment condition and one using motion capture repeated five times in each garment condition. An increased plantar pressure and contact area was observed during heavier load conditions causing increase impact forces. Such forces have been linked with overuse injuries. In addition, mass placement on the non-dominant side of the front torso resulted in the greatest stance and double support spatial-temporal gate parameters. Also, participants reported increased neck, shoulder, and lower back pressure and strain [35]. In a follow-on study using the same armor conditions, Park, Branson [34], investigated BA distribution on static body balance and leg muscle function. Static body balance was performed on a foot pressure sensor for a duration of 30 sec, repeated three times in each condition. Electromyography was conducted on selected lower extremity muscles (i.e., rectus femoris, biceps femoris, tibialis anterior and medial gastrocnemius) of both legs. Participants performed maximum voluntary isometric contractions before a barefoot walking protocol (5 m, self-selected pace, repeated 5 times per condition). Results showed, uneven weight distribution of loads above 9 kg (vest alone) significantly impaired static body balance as seen by increased trajectory of center of pressure and medial-lateral excursion. Furthermore, these results were see to a larger extend when a load was worn on the non-dominant side. Increased weight also elevated peak electromyography amplitude, in a significant linear trend, of

the rectus femoris and medial gastrocnemius. Under load bearing conditions and increased inertia, the results of the rectus femoris were suggested to maintain body balance and decelerate the lower limb. Whereas, the behavior of the medial gastrocnemius was suggested to increase the propulsive force. Furthermore, these results were suggested to lead to early muscle fatigue and potential injury. Although limited, the previously mentioned studies stress BA connection with increased risk of injury. As mentioned earlier, dismounted warfighter injuries, may ultimately lead to individual and an overall military unit's reduced performance.

A.3 Extremity armor

The extremely high case of survivability mentioned earlier, does not however reflect the severity of the injuries experienced. U.S. forces during Operations Enduring Freedom and Operations Iraqi Freedom, no longer encountered a uniformed enemy or clear front line. They now fight an enemy that uses strategies based on insurgency, terrorism and guerilla warfare [129]. This wartime environment has shifted the mechanism of injury, from gunshot wound to explosive injury. Therefore altering the wounds sustained by dismounted warfighters, from a localized injury (e.g., involving one body location) to instantaneously suffering multiple injuries (e.g., involving multiple body locations). During Operation Iraqi Freedom and Operation Enduring Freedom approximately 70.5% of all dismounted warfighters sustained musculoskeletal injuries to an extremity [145]. Additionally, major extremity amputations were performed in 7.4% of extremity injuries on individuals who are not able to return to duty within 72 h of the sustained injury. Furthermore, 88% of these amputations were the direct result of an explosive mechanism and 18% of these amputees sustained more than one major extremity amputation [129, 145].

The need for extremity armor has been highlighted by the combination of the extreme success (i.e., survivability and reduced torso casualties) of the modern day BA vest, along with the evolving mechanism of injury (i.e., explosion) and increased wartime extremity injuries sustained. Additionally, the added mass of extremity armor should not hinder the warfighter's movement or performance. In 2006, the Department of Defense began investigating new ways to protect the extremities of our warfighters [146], since

that time there have been limited studies investigating the effects of extremity armor [27-29, 32, 53].

Hasselquist, Benseal [27] investigated three different extremity armor conditions, each covering some portion of the extremity and each integrating the IBA vest. All extremity armor conditions alone were similar in weight (5.6 kg – 6.4 kg, sans vest). Participant's treadmill walked (10 min at 1.39 m/s) and ran (10 min at 2.34 m/s) while kinematics, kinetic and oxygen uptake data were collected, then completed a battery of maximum effort tests (i.e., repetitive box lift and carry, 5- 30 m rushes, and an obstacle course). Kinematic and kinetic results reveal significant changes during the extremity armor conditions compared to wearing no armor. While wearing extremity armor, participants ran and walked with a wider stride, displayed decreased swing time, increased stance time, greater ground reaction forces at heel strike and pushed off with increased forces at toe off. Mean VO_2 , normalized to body mass, was significantly higher while walking with extremity armor when compared to walking with no armor or torso armor alone. Finally, performance during the maximum effort tests were inferior during the extremity armor trials when compared to the no armor and torso armor trials.

Larsen, Netto [29] had participants complete a circuit in two conditions, no armor and full armor to include extremities (~ 17 kg depending on size). The circuit was completed 11 times with a two minute rest between rounds. Heart rate, intestinal temperature and ratings of perceived exertion data were collected at the completion of each circuit. Additionally, time to complete each individual task within a circuit and each complete circuit time were collected. During the extremity armor condition a 7.3 sec increase in circuit time, and a 0.8 sec, 0.4 sec, and 1.0 sec increase were observed for the shooting, vaulting, and crawling individual tasks respectively. Additionally, the rating of perceived exertion increased by one point and a higher core temperature (circuits 7 to 11) were found while wearing extremity armor. As an extension to the fore mentioned study, Larsen, Netto [28], compared a torso armor condition to the full extremity armor condition. Heart rate (1 beat/min) and core temperature (1° C) were found to be higher during the full extremity armor condition, as was rating of perceived exertion (1 point higher). Participants' time to complete the total circuit was not found to be different between armor conditions, however specific tasks were hindered differently by the two

armor conditions. The authors suggesting the need to investigate task-specific armor configurations. Finally, Adams III [32] investigated walking (1.34 m/s) and running (2.46 m/s) on a level treadmill with three different levels of extremity armor configurations, no armor, partial extremity (vest and extremity armor on the upper arms and thighs, 27.2 lb), and full extremity armor (to include the forearm and shank, 29.2 lb). No differences were found in any outcome variables between the two extremity armor conditions, only changes between the no armor condition and the extremity conditions as a whole, suggesting the low mass added to the distal extremities during this study did not alter metabolic cost or gait characteristics. Metabolic cost normalized to body mass was found to increase significantly during the armor conditions when compared to the no armor condition. Double support time during walking was the only temporal variable found to increase during the armor condition, while no difference was observed between extremity armor conditions. Additionally while walking, sagittal plane kinematics revealed a decrease in ankle range of motion and an increase in both knee and hip range of motion during the two extremity armor conditions. During running, only hip range of motion and trunk flexion increased during the armor conditions when compared to the no armor conditions.

Evident from the changing mechanism of injury and rise in extremity casualties, increased extremity protection is needed. However, as the above studies have indicated the added mass to extremities can affect risk of injury, metabolic cost and performance.

A.4 Extremity loading

Although limited research has been conducted directly related to performance and extremity armor, other studies have been conducted investigating the effect of loads placed on the upper and lower extremities. Loads carried by the upper extremities during walking and running have been shown to result in a higher metabolic cost than when the equivalent load has been placed at the torso, additionally the mass of the load, placement of the load and speed of walking or running play a role [147-149]. It has been reported that walking with as little as 3 lb hand weights can increase metabolic cost when compared to walking with no weights [147]. Depending on the speed and mass carried, Soule and Goldman [149] found the energy cost of walking with a mass on the hands to

produce a 1.4-1.9 greater cost per kilogram than the no load condition. For instance, walking at 5.6 km/h. while carrying 4- and 7 kg loads at the hands produced the same, 1.9 time increase, however at slower speeds the 7 kg and 4 kg loads produced a 1.9 and 1.4 time increase respectively. Comparably, a 13% increase in energy expenditure per 1 kg was reported by Miller and Stamford [148], when 2.25 kg hand weights were added to their walking and running study. They also noted the position of the added mass in relation to the subjects' center of gravity played a role in the energy expended.

As with upper extremity loading, loading the lower extremity has an effect on metabolic cost. When carried on the feet, loads cost 5-7 times more energy than when carried on the torso [140, 150, 151]. Footwear alone has been shown to increase the energy cost of walking. Findings showed there was a 5-10% increase for every 1 kg added to the foot [27, 149, 150, 152-154], suggesting a warfighter's footwear should be as light as possible. In contrast, loading the thigh imposes a much smaller metabolic cost than loading the foot but greater than loading the waist [154-156]. Browning, Modica [155] showed a 14% and 48% increase when loading the thigh and foot respectively in comparison to loading the waist with the same load (8 kg) while walking. Additionally, it has been shown for every 1 kg added to the thigh there is an approximate 4% increase in energy expenditure [8, 154]. In general, net metabolic cost increases with more distal mass locations and increased mass [155, 156].

Areas other than the torso can be loaded but at an increased metabolic cost. Understanding and managing such costs has the potential to facilitate the design of extremity body armor, where a dismounted warfighter's performance is not compromised by increased extremity protection.

A.5 Women and load carriage

Women are holding increasingly more physically demanding positions within the U.S. military, with that comes the responsibility/requirement of fulfilling the vocational tasks associated with such positions. One such potential requirement is increased load carriage (e.g., mass, duration of carriage). After accounting for body composition and size differences many difference remain between males and females, such as females walk with a greater stride frequency and a shorter stride. As load increases, a female's

stride length has been shown to significantly decrease, whereas male stride length was not significantly changed [157]. Additionally, swing time and double support time were both shown to increase to a greater extent in females while conducting a loaded march at 6.4 km/h [158]. Females have been found to walk with a greater forward lean from the trunk and hyperextend their necks as a possible compensation strategy for less upper body strength than males [8, 157, 158].

Often when dismounted ground units move as a unit, they march in formation. There are guidelines for marching in formation outlined by the Army [55], to keep a marching unit evenly spaced both abreast and front-to-back while keeping a specific speed. This can create issues for shorter stature individuals (e.g., females). Stride frequency and stride length are the two main parameters that influence speed, when stride frequency can not be used to maintain a given speed (due to unit requirements to keep in step), stride length must be utilized (i.e., increased). This increase in stride length, may be greater than an individual's comfortable level and safe stride length. This repetitive overstriding has been shown to lead to pelvic stress fractures in army recruits, 11.6% females compared to 0.1% in males [159]. When the marching speed was decreased from 7.5 km/hr to 5 km/hr and individual stride length was encouraged instead of keeping in step, there was a reduction in pelvic stress fractures to 0.01% in the next class of female recruits [159]. Moreover, during the six weeks of Marine Corps Officer Basic Training Course, female candidates experienced an injury incidence of 80% [160]. During the 11 week Marine Corps Basic Training Course, female recruits displayed amplified levels of bone resorption markers, signifying bone stress [161]. These examples emphasize the need for gender-specific differences to be considered as females increasingly enter the wartime environment. Such considerations should include those factors already identified as impacting the female athlete, for example, the female athlete triad [162], poor nutrition and hydration practices, urinary incontinence [163], pelvic floor muscle function [164] and poor uniform and equipment fit [8, 85, 165].

A.6 Other factors

For completeness, in addition to load carriage (i.e., BA) and sex, there are multiple other factors that contribute to a warfighter's performance and risk of injury.

Some of those contributing factors are physiological (e.g., body composition, muscular strength, anaerobic capacity and aerobic capacity), stress, sleep, rest, terrain, and climate.

Appendix B Description of Tests Completed during Experimental Testing Sessions

All tests listed in Table B(1) were completed during each testing session both before and after exposure. Therefore, each test was performed four times by each participant (two testing sessions \times two exposure conditions). During each testing session, tests 6 to 9 were completed in a randomized order using a dynamometer before or after the other tests for the pre-exposure or post exposure conditions respectively. This was due to differences in preparation and instrumentation of participants between tests 6 to 9 and tests 1 to 5. In addition the orders of tests 1 to 5 were also randomized for each testing session and exposure condition.

For the TT test (i.e., test 1), participants started with their feet shoulder width apart, shoulders in 90° of forward flexion, elbows extended with palmer side of hand parallel to the floor. Participants were instructed to touch their toes with their hands, while keeping their knees as straight as possible and return to the starting position. For the TLS test (i.e., test 2), participants started with their feet shoulder width apart, their shoulders in 90° of forward flexion, elbows in 90° of flexion and hands in neutral position.

Table B1: List of test and collected variables.

Tests	Measured variables
1. Toe-touch	kinematic
2. Toe-legged squat	kinematic
3. Box drop	kinematic, kinetic
4. Prone to standing	kinematic
5. Quiet standing	kinetic
6. Isometric knee flexion	torque
7. Isometric knee extension	torque
8. Isokinetic knee flexors (concentric/eccentric)	torque
9. Isokinetic knee extensors (concentric/eccentric)	torque

Notes: Results for all data collected are not presented in this manuscript.

Participants were instructed to lower themselves by flexing their knees and keeping their trunk as upright as possible until their thighs were parallel with the floor and then return to the starting position. For both tests, participants were instructed to repeat the motion non-

stop 10 times both using a self-selected (as fast as possible) and a metronome generated pace. The former pace was set to evaluate their performance while the latter was set to evaluate risk of injury. The metronome paces were 60 beats/min and 80 beats/min for the TT and TLS tests respectively. If the proper form was not maintained throughout the duration of the test, participants were asked to repeat the test.

For the box drop test (i.e., test 3), participants stood on a box (height: 37.5 cm) located next to an in ground force platform. The participants initiated the test by stepping down onto the force platform following the investigators signal to start. They were instructed to step down on the force platform with one foot and continue walking in the forward direction off of the force platform. For the prone to standing test (i.e., test 4), participants started lying prone on the floor. Their feet were plantar flexed with the foot dorsum in contact with the ground. Their shoulders were in 180° of forward flexion, elbows extended with the palmar side of their hand in contact with the ground. When signaled by the investigators to begin the test, in one dynamic movement the participants brought their hands underneath their shoulders, pushed up, jumped their feet in towards their hands and stood upright. Each of the box drop and prone to standing tests took less than ~10 s to complete and was repeated three times for each condition. If the proper form was not maintained during an individual test, participants were asked to repeat the test until three successful tests were captured.

The quiet standing test (i.e., test 5), was conducted in a manner similar to the baseline protocol of Strang, Haworth, Hieronymus et al. (2011), where subjects stood on an in-ground force platform with their feet placed approximately shoulder width apart, eyes open, hands near their sides and asked to stand 'as still as possible' for 1 min. Finally, for tests 6 to 9 all torque testing and data collection were achieved using a BIODEX System 3 dynamometer (BIODEX Medical, Shirley, NY). For the isometric and isokinetic tests, participants were seated in the test chair of the BIODEX with their back fully supported. The right thigh was secured with a seat belt like strap. Additional straps crossing the chest and hips were used to stabilize the participant. The tibial pad was placed around the distally third of the shank and held in place with a hook-and-loop fastener (e.g., Velcro©-like strap). The point of rotation of the dynamometer knee attachment was aligned with the right lateral femoral epicondyle. Limb gravity

correction was accounted for in accordance with the manufacturer's recommendations. All participants underwent familiarization training prior to start of session 1. During this time, participants performed a series of submaximal familiarization contractions until they felt comfortable with the equipment and all testing procedures. An approximate, 10-min rest period followed before testing commenced. To limit bias, verbal encouragement was not given during the isometric and isokinetic testing [93]. If the proper form was not maintained during an individual test, participants were asked to repeat the test. All participants were tested using the following knee extensor and flexor procedure.

Isometric testing was conducted at 60° of knee flexion. Testing procedures were the same for both the knee flexors and extensors. Participants were asked to exert their maximal isometric contraction for 5 sec followed by 30 sec of rest. Participants were then asked to repeat the maximal contraction effort. Participants completed two sets (one knee flexor set and one knee extensor set) of two maximal isometric contractions for each BA and exposure condition.

Isokinetic testing was performed at a velocity of $180^{\circ}\cdot\text{s}^{-1}$ through a range of 80° during the eccentric and concentric contractions of both the knee flexors and extensors. Participant knee range of motion was goniometrically established and limited by mechanical stops at 95° (flexion) and 15° (from full extension) flexion to prevent injury during the isokinetic testing. For the knee flexor testing, participants were instructed to resist the upward force during the eccentric phase, and then without a pause, immediately follow with a maximal concentric contraction. For knee extensor testing, participants were instructed to maximally contract concentrically, and then without a pause, immediately resist the downward force during the eccentric phase. For both the knee flexor and extensor tests, the isokinetic cycles described above were repeated three times within each test, followed by a 1-min rest period. Completion of these four tests took ~15 min per BA and exposure condition.

Appendix C Institutional Review Board Forms

Supplemental C.1 Subject consent

Consent to Participate in a Research Study

Military Load Carriage and Protective Equipment, Risk of Hindered Performance and Musculoskeletal Injury

WHY ARE YOU BEING INVITED TO TAKE PART IN THIS RESEARCH?

You are being invited to take part in a research study about the effects of military load carriage systems and protective equipment on trunk and lower extremity mechanical behavior. If you volunteer to take part in this study, you will be one of about 20 people to do so.

WHO IS DOING THE STUDY?

The person in charge of this study is Megan Phillips M.S. of University of Kentucky Department of Biomedical Engineering. The supervising advisor on this project is Robert Shapiro, PhD of the University of Kentucky, Department of Kinesiology and Health Promotion and Babak Bazrgari, PhD of University of Kentucky Department of Biomedical Engineering. There may be other people on the research team assisting at different times during the study.

WHAT IS THE PURPOSE OF THIS STUDY?

By doing this study, we hope to learn if there is any relationship between wearing a military load carriage system and protective equipment (LCSPE) and changes in the mechanical behavior of the human trunk and lower extremities, risk of musculoskeletal injuries. Additionally, how the additional mass affects the ability to perform tasks and ultimately performance. This study is a part of our ultimate goal for understanding the causes of military, load carriage musculoskeletal injury, improving prevention, and performance.

ARE THERE REASONS WHY YOU SHOULD NOT TAKE PART IN THIS STUDY?

- a. Once you have read and signed this form, but before starting the actual experiments, you will be required to answer a number of questions. Your answers will be then evaluated to assure your eligibility based on some additional criteria. If you do not meet these additional criteria, you'll be excluded from the study and will be given the reason why you should not take part in this study. For example, if you have had a joint replacement, the

mechanical properties of your body are also influenced by the artificial joint. This can hinder us from reaching our goal, as we cannot separate such influence from the addition of mass influences at present. As another example, if you have a pacemaker, you'll be excluded from the study as we do not yet know the level of risk involved for participants with such cases.

- b. This study utilizes military load carriage and protective equipment. Therefore, to target the age group that most frequently wears such equipment, the participation age for this study is between the ages of 18 and 35 years. Additionally, if you are not familiar with wearing a loaded backpack, you should not participate in this study.

WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST?

The research procedures will be conducted at the University of Kentucky, Biodynamics and Human Musculoskeletal Biomechanics Laboratories. Both laboratories are located in the same building. You will need to come to the Biodynamics Laboratory in the Wenner Gren Research Laboratory at **600 Rose Street 40536-0070 two (2) times** during the study. Each visit will take approximately **three hours**.

WHAT WILL YOU BE ASKED TO DO?

Prior to testing, you will fill out a Tegner scale to assess your level of physical activity. For the testing session, you will be asked to wear athletic clothes (e.g. shorts, and t-shirt). Athletic shoes will be provided by the lab. Athletic shoes are sanitized with a medical grade disinfectant (Germ Blitz) after every use. We will provide the additional equipment (i.e. load carriage system and protective equipment (LCSPE)) that will be worn for part of the testing. All tests described in this section, during both days of testing will occur twice, once before walking 45 minutes on a treadmill and once after walking on the treadmill. Day one of testing will be performed in sport clothing. The second day of testing will take place wearing military protective equipment. Military protective equipment will be provided for you to wear during the second day of testing. The protective equipment consists of a military issued vest (~15- 23 lb depending on the size of the vest), upper arm (~3 lb/each arm) and thigh (~4 lb/each leg) weights to simulate extremity body armor.

1. Trunk Testing

After some preliminary warm up stretches, we will ask you to push and/or pull as hard as you can against a resistance. We will ask you to stay relaxed while we raise your legs and measure your body resistance against such movement. We will also apply quick but small pushes or pulls to your trunk to record reflexes.

2. Knee Testing

You will be assessed for the maximum amount of force that your leg (thigh) muscles can generate during a simple knee bending or straightening motion. Muscle strength will then be determined in your dominant leg in a seated position on the BIODEX. To minimize the use of muscles other than your leg muscles, you will be stabilized with two shoulder straps, a waist strap, an upper leg strap and an ankle strap.

- a. Your muscle strength will be the highest force generated during 2 trials of isometric (no motion) knee contractions (2 maximum pushing your ankle away and 2 maximum pulling it in toward you) held for 5 seconds each at a knee angle of 60°. A 15 sec rest period will be given between each knee contraction.
- b. Your muscle strength will also be determined by pushing and pulling your ankle in the same way at one controlled movement speeds. A one-minute rest period will be given between each contraction.

3. Full Body Motion Capture and Force Plate

Small reflective markers will be attached to your skin with tape to identify landmarks at your shoulders, back, hips, knees and ankles. We will also place small wraps around your legs and arms to hold markers that will be used to measure your measure your body posture and movements while you perform certain tasks. The cameras only pick up/identify the small reflective markers' X and Y-coordinate/position information. There is no videotaping and there are no actual video tapes. No identifiable video images are collected during motion capture.

We will then ask you to perform two simple tasks and two military related tasks:

A. Tasks

- a. Simple Tasks
 - Two legged squat - The movement begins from a standing position and is initiated by moving the hips back and bending the knees and hips to lower the torso then returning to the upright position. You will be asked to perform 10 repetitions in the shortest duration of time possible while maintaining proper form. You will also be asked to perform 10 repetitions to the cadence of a metronome, and you will be given a practice trial with the metronome and a 30 second rest between trials.
 - Touch toes - From standing position with feet shoulder width apart, the subject will be asked to bend at their waist, while

their legs remain straight and touch their toes. You will be asked to perform 10 repetitions in the shortest duration of time possible while maintaining proper form. You will also be asked to perform 10 repetitions to the cadence of a metronome. You will be given a practice trial with the metronome and a 30 second rest between trials.

b. Military Related Tasks

- Box drop – You will start by standing on a box 37.5 cm high and drop onto an in-ground force plate then proceed to run forward five steps. This motion simulates traversing difficult terrain or exiting a military vehicle (tank or High Mobility Multipurpose Wheeled Vehicle (HMMWV)). You will be asked to repeat this task three times.
- Prone position to standing upright. This motion simulates a soldier moving from a shooting position lying face down on the ground to an upright mobile position. You will be asked to perform this task as quickly as possible and you will repeat this task three times.

B. Quiet Stance

Center of pressure (COP) force data will be collected by having you stand, with feet shoulder width apart on an in-ground force plate. You will perform two trials. Each trial will be 60 seconds followed by 30 seconds of rest. The foot placement will be marked in order to eliminate variance. The force plate will be zeroed between each trial. You will be instructed to focus on a ‘target’ at a distance approximately 10’ in front of them.

The coordinate of the markers will be used to calculate trunk, pelvis and knee joint angles. The force data will be used as force proper, to calculate joint moments, sway patterns.

4. Full Body Motion Capture and Force Plate

Once you have completed the above described tests and tasks, you will be asked to walk on a treadmill briskly for 45 minutes to introduce fatigue.

At the completion of the walk, you will be asked to perform the tests and tasks for a second time.

Schedule

1st Visit (Athletic Clothing)	Informed Consent	Warm- up	Trunk testing	Familiarization & Knee Testing	Four Tasks	Quiet Stance	Treadmill Walk	Repeat Tests (Trunk, Knee, Tasks Quiet Stance)
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2nd Visit (Military Equip.)	Warm -up	Trunk testing	Knee Testing	Four Tasks	Quiet Stance	Treadmill Walk	Repeat Tests (Trunk, Knee, Tasks Quiet Stance)
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WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

To the best of our knowledge, the risks of this study are minor due to your physical fitness level. However, they include a potential for skin irritation due to the adhesives used in the adhesive of the reflective markers. If you are allergic to tape, please let a researcher know immediately. You may also feel some temporary muscle soreness such as might occur after exercising. Subjects participating in physical conditioning may experience muscle soreness and/or musculoskeletal injury associated with inherent risks of cardiovascular, strength training and therapeutic exercise. To minimize these risks you will be asked to warm-up before the tasks and tell us if you are aware of any history of skin-reaction to tape, history of musculoskeletal injury, or cardiovascular limitation.

As with any type of physical activity, the risk of a cardiac event has the possibility of occurring. In the unlikely event of a cardiac problem, there is an AED in the laboratory and the PI is First Aid/CPR/AED certified. As part of this studies research team is a certified athletic trainer. For unforeseen incidents such as a knee injury that do not warrant a 911, she will provide the necessary quick response, stabilizing treatment.

There is always a chance that any medical treatment can harm you, and the investigational treatment in this study is no different. In addition to the risks listed above, you may experience a previously unknown risk or side effect.

WILL YOU BENEFIT FROM TAKING PART IN THIS STUDY?

You will not get any personal benefit from taking part in this study. However, by participating in this study, you will help to increase our understanding of the mechanics of the spine and lower extremities, musculoskeletal injury mechanisms and performance associated with load carriage. We hope to make this research experience interesting and enjoyable for you where you may learn experimental procedures in biomechanical sciences.

DO YOU HAVE TO TAKE PART IN THE STUDY?

If you decide to take part in the study, it should be because you really want to volunteer. You will not lose any benefits or rights you would normally have if you choose not to volunteer. You can stop at any time during the study and still keep the benefits and rights you had before volunteering.

IF YOU DON'T WANT TO TAKE PART IN THE STUDY, ARE THERE OTHER CHOICES?

If you do not want to be in the study, there are no other choices except not to take part in the study.

WHAT WILL IT COST YOU TO PARTICIPATE?

We will do our best to minimize any cost to you. Potential cost may include traveling and parking cost. Center for Biomedical Engineering has a designated parking spot for its visitors which can be reserved for study participants during their visit.

WHO WILL SEE THE INFORMATION THAT YOU GIVE?

We will make every effort to keep private all research records that identify you to the extent allowed by law.

Your information will be combined with information from other people taking part in the study. When we write about the study to share it with other researchers, we will write about the combined information we have gathered. You will not be personally identified in these written materials. We may publish the results of this study; however, we will keep your name and other identifying information private.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. You will be assigned an identification number to protect your confidentiality. Hard copies of data will be stored in a locked filing cabinet. Electronic data will be stored on a password-protected computer. Access to your information will be limited to the principal investigator and other team members. Collected data will be aggregated and presented without identifying information for individual subjects. Hard copies of the data and video tapes will be stored for six years following conclusion of the study at which time they will be shredded and disposed of properly.

You should know, however, that there are some circumstances in which we may have to show your information to other people. Officials from the University of Kentucky may look at or copy pertinent portions of records that may identify you.

Please note that there may be other activities going on in the laboratory while we are collecting your data. While the people taking part in the other activities will not have access to any of your data, if you are uncomfortable participating while other activities are occurring please let us know and we will schedule you for a private data collection session.

CAN YOUR TAKING PART IN THE STUDY END EARLY?

If you decide to take part in the study you still have the right to decide at any time that you no longer want to continue. You will not be treated differently if you decide to stop taking part in the study. The individuals conducting the study may need to withdraw you from the study. This may occur if you are not able to follow the directions they give you or if they find that you being in the study is more risk than benefit to you, or if you are unable to complete the tasks.

If for any reason, you want to withdraw from the study or if we need to withdraw you from the study, any data collected up to that point will not be used and will be deleted from the computers and shredded appropriately.

ARE YOU PARTICIPATING OR CAN YOU PARTICIPATE IN ANOTHER RESEARCH STUDY AT THE SAME TIME AS PARTICIPATING IN THIS ONE?

You may take part in this study if you are currently involved in another research study. It is important to let the investigator know if you are in another research study. You should also discuss with the investigator before you agree to participate in another research study while you are enrolled in this study.

WHAT HAPPENS IF YOU GET HURT OR SICK DURING THE STUDY?

If you believe you are hurt or if you get sick because of something that is due to the study, you should call:

Megan Phillips at (619-339-3753) or Robert Shapiro (859-257-9852) immediately. Always call 911 in the event immediate medical care is needed.

It is important for you to understand that the University of Kentucky does not have funds set aside to pay for the cost of any care or treatment that might be necessary because you get hurt or sick while taking part in this study. Also, the University of Kentucky will not pay for any wages you may lose if you are harmed by this study. You do not give up your legal rights by signing this form.

WILL YOU RECEIVE ANY REWARDS FOR TAKING PART IN THIS STUDY?

You will be paid \$50 for completion of this study. If you only complete the first testing session but fail to complete the second session within the 7 day time frame they will be paid \$10 for your participation in the first part of the study.

WHAT IF YOU HAVE QUESTIONS, SUGGESTIONS, CONCERNS, OR COMPLAINTS?

Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions, suggestions, concerns, or complaints about the study, you can contact the investigator, Megan Phillips, MS at 619-339-3753. If you have any questions about your rights as a volunteer in this research, contact the staff in the Office of Research Integrity at the University of Kentucky at 859-257-9428 or toll free at 1-866-400-9428. We will give you a signed copy of this consent form to take with you.

WHAT IF NEW INFORMATION IS LEARNED DURING THE STUDY THAT MIGHT AFFECT YOUR DECISION TO PARTICIPATE?

If the researcher learns of new information in regards to this study, and it might change your willingness to stay in this study, the information will be provided to you. You may be asked to sign a new informed consent form if the information is provided to you after you have joined the study.

Signature of person agreeing to take part in the study

Date

Printed name of person agreeing to take part in the study

Name of [authorized] person obtaining informed consent

Date

Signature of Investigator

Supplemental C.2 Tegner scale

TEGNER ACTIVITY LEVEL SCALE

CURRENT: Level _____

Level 10	Competitive sports- soccer, football, rugby (national elite)
Level 9	Competitive sports- soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball
Level 8	Competitive sports- racquetball or bandy, squash or badminton, track and field athletics (jumping, etc.), down-hill skiing
Level 7	Competitive sports- tennis, running, motorcars speedway, handball Recreational sports- soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running
Level 6	Recreational sports- tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week
Level 5	Work- heavy labor (construction, etc.) Competitive sports- cycling, cross-country skiing, Recreational sports- jogging on uneven ground at least twice weekly
Level 4	Work- moderately heavy labor (e.g. truck driving, etc.)
Level 3	Work- light labor (nursing, etc.)
Level 2	Work- light labor Walking on uneven ground possible, but impossible to back pack or hike
Level 1	Work- sedentary (secretarial, etc.)
Level 0	Sick leave or disability pension because of knee problems

SURGICAL HISTORY

What procedure(s) were performed? _____

When was the surgery performed? _____

Supplemental C.3 PAR-Q and You form

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

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

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

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

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

If
you
answered

YES to one or more questions

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

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

NO to all questions

- If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:
- start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.
 - take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or
- if you are or may be pregnant — talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

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

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

NAME _____

SIGNATURE _____

DATE _____

SIGNATURE OF PARENT
or GUARDIAN (for participants under the age of majority) _____

WITNESS _____

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.



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Appendix D International Traffic in Arms Regulations (ITAR)

Supplemental D.1 Technology control plan

Technology Control Plan

Project Title: Military Load Carriage and Protective Equipment, and Risk of Hindered Performance and Musculoskeletal Injury

Project Sponsor: N/A

Prepared by: Megan Phillips, Robert Shapiro

Material: Body armor ([REDACTED])

Export Restrictions

The material (body armor) on loan from [REDACTED] is ITAR controlled. This research does not involve the testing or reverse engineering of the material. The data resulting from this research relates strictly to human factors, e.g. x-, y-, z-coordinates of anatomical landmarks used to calculate joint angles and force data.

Due to this restriction, the PI (Megan Phillips) has adopted a foreign person technology control plan (TCP) to ensure the handling of the material is adequately protected from disclosure to foreign persons who do not have an approved U.S. Green card. The plan addresses physical security, information security, and personnel screening procedures. These plans are described in detail below.

Personnel

All personnel involved in this project are US citizens or authorized U.S. Green card holders. The personnel include Prof. Robert Shapiro (FA), Megan Phillips (PI), Jaclyn Norberg (GRA), Brian Wallace (GRA), and Corey Lockridge (HSS). (FA indicates a faculty advisor; GRA indicates a graduate research assistant and HSS indicates a high school student.)

Physical Security Measures

This project involves the use of body armor on loan from [REDACTED]. Both the company's proprietary information and material are ITAR controlled. [REDACTED] body armor manufacturing division is located in Lexington KY. The PI (Megan Phillips) or FA (Prof. Robert Shapiro) will take possession and return the material directly from the manufacturing facility located at [REDACTED]. This body armor will be kept in a locked room (RM #5A) in the Wenner-Gren Research Building. Room 5A is located inside Room 5 and has no external exit and has a concrete ceiling with all walls going to the ceiling. Room 5A has a solid door that will be rekeyed and two keys will be ordered from the key shop, one for the PI and one for the Biomedical Engineering Department's Senior Administrative Assistant (Sue Mills). Ms. Mills will keep the department emergency key in locked safe. Additionally, the external doors to

Wenner-Gren Laboratory are locked from 4:40 pm – 7:30 am and the entrance to Room 5 is always locked as well. A written log will be kept showing all person accessing Room 5A.

All of the work done at the University of Kentucky for this project will be performed in the Biodynamics Laboratory located in the Wenner-Gren Research Building. The laboratory is enclosed by a 10' wall and has a locked door. The laboratory is electronically scheduled for use. The laboratory will be scheduled and access controlled while conducting research involving the use of the body armor.

The PI will contact Ms. Mills on a weekly basis to determine the status of her key. If at any time it is determined that a key is missing, Room 5A will be rekeyed.

Information Security Measures

The data generated by this project is not related to the controlled material but rather human factors, therefore the data generated is not controlled. However, all data generated by this project will be stored on a password protected server in password protected folders at the University of Kentucky. The PI (Megan Phillips), FA (Prof. Robert Shapiro) and GRAs and HSS (listed above) are the only individuals that will have access to the password protected folders. All personnel are US citizens or authorized U.S. Green card holders, and are aware of the restrictions on the data.

All computers used in this effort are housed in the locked Biodynamics Lab. All computers run Microsoft Windows XP with the latest security service pack and patches. Firewalls are installed on each of the machines to secure and monitor network access from/to the machines used in this effort.

Hardcopies (i.e., print outs) associated with this effort are maintained in a locked cabinet in Room 5A.

Tracking and secure disposal procedures will be used for all hardcopies. Hardcopies that are no longer needed will be shredded prior to disposal.

Personnel Screening Procedures

The project does not make use of any additional staff, temporaries, or third party contractors.

All project personnel working on the project will be attend a mandatory training session on export control requirements and obligations by the appropriate University office. A signed record of the training will be kept with the written project materials in Room 5A. Project personnel will be required to pass a written quiz demonstrating understanding of the ITAR rules and regulations pertaining to this investigation. Project personnel are aware of their responsibilities to prevent either active or inadvertent disclosure of ITAR-restricted information or material, and of the criminal and civil penalties (including prison sentences of up to 10 years and fines of up to \$1M) for failure to comply with US export control rules.

Non-project personnel will also be informed of their obligations, and the consequences for possessing or disseminating ITAR-restricted information. They will be required to verify their

citizenship status by producing appropriate documentation (passport, official birth certificate, green card) or if a student, citizenship status will be verified by the university registrar.

Submitted by:

Faculty Advisor (printed): Robert Shapiro

Signature: _____

Date: _____

Department Head (printed): David A. Puleo

Signature: _____

Date: _____

PI Name (printed): Megan P. Phillips

Signature: _____

Date: _____

Approved for UK by:

Vice President for Research (printed): James W. Tracy

Supplemental D.2 ITAR training slides

EXPORT CONTROL

International Traffic in Arms Regulations (ITAR)

Overview and Implications for Research Universities

1

What is Export Control?

- ❑ Federal laws to protect items, technical data and information important to the U.S.
- ❑ Laws have been in place for > 20 years
- ❑ More prominent since 9/11 resulting in heightened scrutiny

2

Government's Concern

- ❑ Open access/publication of scientific and technological results may provide unwitting assistance to nations or terrorist groups in developing weapons
- ❑ Protecting economic interests of U.S. companies
- ❑ Foreign policy

3

Regulating Agency

- International Traffic in Arms Regulations (ITAR) are administered by Department of State
 - Controls Defense related items
 - Section 22 of the Code of Federal Regulations (C.F.R.), Parts 120-130.
 - **“U.S. Munitions List” (USML)**

4

U.S. Munitions List (Part 121)

Category

- I- Firearms, Close Assault Weapons, & Combat Shotguns
- II- Guns & Armament
- III- Ammunition/Ordnance
- IV- Launch Vehicles, Guided Missiles, Ballistic Missiles, Rockets, Torpedoes, Bombs and Mines
- V- Explosives and Energetic Materials, Propellants, Incendiary Agents and Their Constituents
- VI- Vessels of War and Special Naval Equipment
- VII- Tanks and Military Vehicles
- VIII- Aircraft and Associated Equipment
- IX- Military Training Equipment

5

U.S. Munitions List (Part 121) cont'

X- Protective Personnel Equipment – Body Armor

- XI- Military Electronics
- XII- Fire Control, Range Finder, Optical and Guidance and Control Equipment
- XIII- Auxiliary Military Equipment
- XIV- Toxicological Agents, Including Chemical Agents, Biological Agents, and Associated Equipment
- XV- Spacecraft Systems and Associated Equipment
- XVI- Nuclear Weapons, Design and Testing Related Items
- XVII- Classified Articles, Technical Data and Defense Services Not Otherwise Enumerated
- XVIII- Directed Energy Weapons
- XIX- Not Used

6

U.S. Munitions List (Part 121) cont'

XX- Submersible Vessels, Oceanographic and Associated Equipment
XXI- Miscellaneous Articles

7

Purposes

- Control access of certain technology to foreign nationals whether in US or abroad.
- “Deemed export” will be the primary focus for research @ UK. Defined as: The release of technology or software to a foreign national within the U.S. is considered an export to the home country of that foreign national.
- Currently doesn't apply to U.S. citizens, individuals granted permanent residence status and certain protected individuals.
- Failure to comply can result in criminal as well as civil penalties.

8

What is Affected

- All items/technology in the U.S. except:
 - Publicly available technology & software
 - Publications that are artistic or non-technical in nature
- Items/technology located outside of the U.S.:
 - Items of U.S. origin wherever located
 - Foreign made items if it exceeds certain % U.S. content or direct product of U.S. technology

9

Questions to Consider

- **What is the technology?**
 - Must know the specifics

- **Who is going to be working on project?**
 - What nationality and status
 - Certain countries are embargoed by both agencies: Cuba, Libya, Sudan, Iran, Iraq

- **Where is the work going to be accomplished?**
 - On/off UK property?
 - If in UK offices/labs-who has access?

10

Fundamental Research/ Public Domain

- Information in the Public Domain is not controlled.

- Fundamental research in science and engineering at accredited institutions where resulting information is ordinarily published and shared broadly is considered Public Domain.

- However, university research will not be considered Fundamental Research if:
 - The university or its researchers accept other restrictions on publication, or
 - The research is funded by the U.S. Government and specific access & dissemination controls are applicable

11

Challenges

ITAR considers all foreign nationals equally as “dangerous”, however, specific technology is still a major consideration.

12

Thoughts to Consider

- Export control laws apply whether or not there is a specific reference in the award document.

- Applies not only to the PI and assigned researchers - need to consider where information is accessible (labs/computers) & control of information from other foreign persons.

13

Additional Considerations

- Technology Control Plans
 - Outlines how the controlled technology will be handled/secured to prevent access by unapproved foreign persons. Will be required even if there are no foreign persons assigned to the project.

 - Addresses physical security of labs & other work areas as well as security of data on computer networks.

14

Discussion Items

- Publication restrictions and impact on Grad students/PIs working on project

- Administrative process/burden
 - Technology Control Plans are time consuming to prepare. Requires additional interaction between PI and sponsor to determine what technology is controlled.
 - Approval process by Federal Gov't can take 8-10 weeks.

- Security of labs/work areas/computers & network

15

Body Armor Project

- The **physical Body Armor** and the **intellectual property** (i.e. engineering specifications) associated with the Body Armor are considered **ITAR controlled**.
- The **kinetic and kinematic data collected** while wearing the body armor is **not** ITAR controlled.
- However, all data will be stored on the biodynamics network drive in the access controlled folder **'phillips_study'**

16

Body Armor Project

- Successfully completing ITAR training allows you to enter the biodynamic lab while the Body Armor Project is being conducted.
- Successfully completing ITAR training **DOES NOT** allow you to escort other individuals through the biodynamics lab.
- All subjects **MUST** be U.S Citizens or granted permanent residence status (i.e. green card holder)
- Subjects do not go through ITAR training, therefore they may **NEVER** be left unattended with the body armor.

17

Penalties for Violations

- **Civil penalties:**
 - Up to **\$500,000** per violation
 - Up to **five years** in jail.
- **Criminal Penalties:**
 - Up to **\$1 million** per violation
 - Up to **ten years** in jail.
- In addition, the violator can be debarred for a period of time from obtaining export licenses and possible debarment from receiving any U.S. Government contracts.

NOTE: A single case may involve more than 100 alleged violations.

18

Questions?

19

Supplemental D.3 ITAR training quiz

Name

Date

Directions: Circle the correct response. You must correctly answer 6 questions to pass the test.

ITAR Body Armor Quiz

1. (True or False) The body armor being used in this project is on the “U.S. Munitions List” (USML), therefore it is ITAR controlled.
2. (True or False) For this project, using body armor, all faculty members and students in departments of Biomedical Engineering and Kinesiology and Health Promotion are allowed to have free and open access to all aspects of the project.
3. (True or False) For this project, using body armor, only U.S citizen and individuals granted permanent residence status (i.e. green card holders) may have access to the body armor.
4. What are the penalties for violating the ITAR rules?
 - a) Civilian - up to \$500,000 per violation and up to five years in jail.
 - b) Criminal - up to \$500,000 per violation and up to five years in jail.
 - c) Criminal - up to \$1 million per violation and up to ten years in jail.
 - d) Both a and c
5. (True or False) Although, the data collected during this project is not ITAR controlled, the only place the data will be stored is on the biodynamics network drive in the access controlled folder ‘phillips_study’.
6. (True or False) If a subject is a citizen or green card holder they may have the body armor, without supervision, while dressing in the subject prep room.
7. (True or False) As long as the project personnel have been ITAR trained, anyone can be a subject in this study.

Grade _____ Pass Fail

Grader’s Signature

Supplemental D.4 ITAR training completion form

International Traffic in Arms Regulations (ITAR) Training Completion

I, _____ have attended the ITAR training session and have successfully completes the associated quiz. I am aware of the ITAR restrictions related to this project and the actions that are being taken to protect and secure the materials.

Signature

Date

Signature of PI

Date

Supplemental D.5 Citizenship verification form

Subject Citizenship Verification

I _____ verify that I am a
(print your name)

citizen of the United States of America or

permanent resident (Green Card holder) of the United States of America

Signature

Date

Citizenship/Green Card Status Verification:

Citizenship status verified by:

Examination of official documentation (copy attached)

Confirmation from the university registrar (copy attached)

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Vita

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EDUCATION

MS Biomedical Engineering (with highest honors),
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PROFESSIONAL EXPERIENCE

United States Naval Officer 1999-2007

- Facilities Engineering and Acquisition Division Director,
Naval Facilities Engineering Command Southeast, 11/2005-07/2007
- Facilities Service Contract Manager,
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- Fire Control Officer,
USS Bonhomme Richard LHD 6, 08/2002-09/2003
- Strike Officer,
USS Higgins DDG 76, 07/2000-07/2002

RESEARCH EXPERIENCE

Awards/Honors:

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- Awarded 'Outstanding Poster' at the Bluegrass Society for Neuroscience,
University of Kentucky, April, 2011.

Publications:

- Phillips, M., B. Bazrgari and R. Shapiro. *The effects of military body armor on the lower back and knee mechanics during toe-touch and two-legged squat tasks.* Ergonomics. 2014
- Phillips, M.P., B. Bazrgari and R. Shapiro. *The effects of military body armor on the lower back and knee mechanics during box drop and prone to standing tasks.* Ergonomics, in review 2014.
- Phillips, M.P., B. Bazrgari and R. Shapiro. *The effects of military body armor on isometric and isokinetic knee behaviors.* Journal of Electromyography and Kinesiology, in review 2014.

Professional Conference Presentations (Poster):

- Megan Phillips, Babak Bazrgari, Robert Shapiro, *Body Armor-Induced Changes in Control of Sagittal Plane Trunk Motion*, Poster, World Congress of Biomechanics, Boston, MA. July 2014
- R. Shapiro, T. Cunningham, B. Wallace, J. Norberg, M. Phillips, M. Miller, *Differences in Running and Walking Gait Kinematics during Earth and Simulated Mars and Lunar Gravitational Environments: A Preliminary Investigation*, Poster, American Society of Biomechanics, Gainesville, Fl. August 2012.
- M.P. Phillips, D.K. Powell, R. Grondin, G. Gerhardt, Z. Zhang and P.A. Hardy (2011). *Correlation of Fractional Anisotropy in Rhesus Monkeys with Parkinson's Disease*, Poster, Bluegrass Society for Neuroscience, University of Kentucky, April 2011.
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