THE EFFECT OF LOADED FATIGUE ON LOADED POSTURAL STABILITY

by

Jordan Shaw Lane

Bachelor of Science in Exercise Physiology, State University of New York-The College at Brockport, 2012

Submitted to the Graduate Faculty of

The School of Health and Rehabilitation Sciences in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2017

UNIVERSITY OF PITTSBURGH
SCHOOL OF HEALTH AND REHABILITATION SCIENCES

This thesis was presented

by

Jordan Shaw Lane

It was defended on

November 17, 2017

and approved by

Heather Bansbach, PhD, Graduate Student Researcher

Chris Connaboy, PhD, Assistant Professor

Matthew Darnell, PhD, RD, CSSD, SCCC, Assistant Professor

Karen Keenan, PhD, ATC, Assistant Professor

Mita Lovalekar, MBBS, PhD, MPH, Assistant Professor

Takashi Nagai, PhD, LAT, ATC, CSCS, Assistant Professor

Thesis Director: Katelyn Fleishman Allison, PhD, ACSM EP-C, Assistant Professor

THE EFFECT OF LOADED FATIGUE ON LOADED POSTURAL STABILITY

Jordan Lane, M.S.

University of Pittsburgh, 2017

Military personnel are often required to carry heavy loads for long distances over unpredictable terrain. Additional load carriage, in conjunction with fatigue, has the potential to influence postural control mechanisms which may in turn increase injury risk. The purpose of this study was to determine if a loaded incremental march to fatigue negatively influences loaded postural stability. Loaded postural stability was measured using the NeuroCom Sensory Organization Test (SOT) and kinetic force plate variables (vertical ground reaction forces: SDvGRF, and TotSway) before and after a loaded incremental march to fatigue in 23 physically active men and women (age: 24.1 ± 4.0 years, height: 172.3 ± 11.1 cm, weight: 162.2 ± 38.2 lbs) while subjects were adorned with a weighted vest equating to 30% of their body weight. The SOT consisted of six conditions (C1-C6) aimed to perturb the sensorimotor system, which were performed before and after a loaded fatigue protocol. C1, C2 and C3 challenged the somatosensory system, C4 challenged the visual system, while C5 and C6 challenged the vestibular system. Fatigue was induced with a treadmill march at 4mph with increasing grades of 2% every three minutes until volitional fatigue. After testing for normality, paired sample t-tests or Wilcoxon signed rank tests were conducted to assess pre- to post-fatigue differences. Significant reductions in SOT scores were found in overall composite scores (pre: 82.8 ± 4.7, post: 81.6 ± 5.2, $p = 0.010$), SDvGRF of C1 (pre: 1.3 ± 0.5, post: 2.0 ± 0.9, $p < 0.001$), C2 (pre: 1.4 ± 0.6, post: 1.9 ± 1.2, $p < 0.001$), C3 (pre: 1.4 ± 0.5, post: 2.1 ± 1.8, $p = 0.026$), and C6 (pre: 2.5 ± 2.2, post: 3.5 ± 3.2, $p < 0.001$) and TotSway of all conditions. Results suggest that significant changes in loaded postural stability were caused by loaded fatigue. Findings could aid in future postural stability screenings, load carriage training and strategies for injury prevention in the military.

TABLE OF CONTENTS

List of Tables

List of Figures

PREFACE

I would like to recognize and thank several wonderful people who have helped me through this journey. First I would like to thank Dr. Katelyn Allison for providing guidance as my advisor and committee chair throughout this project. Your knowledge, advice, and support throughout this entire process has been incredibly helpful, and deeply appreciated. I cannot thank you enough for supporting and motivating me when I needed it most. I would also like to thank Dr. Matt Darnell for serving as my co-chair when I needed extra guidance. Your willingness and eagerness to help whenever needed has not gone unnoticed. Also, thank you to Dr. Heather Bansbach for acting as my mentor, and for being a Matlab wiz. You were so patient and kind throughout the entire process, and I sincerely thank you for everything you've helped with along the way.

To the rest of my committee - Dr. Chris Connaboy, Dr. Karen Keenan, Dr. Mita Lovalekar and Dr. Takashi Nagai – thank you for your willingness to serve on my committee as well as your help in the development of this project.

I would like to extend a special thank you to the NMRL graduate student researchers, interns and the rest of the NMRL staff. I could not have completed this process without your assistance and dependable kindness.

This project would not have been possible for without my study participants. I owe a great amount of thanks to each and every one of you for your effort and willingness to participate!

Last but certainly not least, to all my friends and family, thank you for your undeniably amazing support and love throughout my time here at Pitt. To Anne Beethe, your constant inspiration and support is invaluable. To my roommates/Battle Buddies – I can say with 100%

certainty that I could not have gotten through this without you. Because of your endless companionship, support and compassion, I always knew everything would be fine regardless of the situation. Finally, to my parents Jim and Theresa Lane, you are my rocks. Your unconditional love and never ending support have made me into the person that I am today. Thank you for pushing me to be my best and pursue my dreams. I love and appreciate you more than words could say.

1.0 INTRODUCTION

Military personnel are often required to carry heavy loads for long distances over unpredictable and changing terrain.[1] A soldier's load is usually comprised of clothing, protective equipment (body armor, helmet), combat equipment (weapon systems, ammunition, power sources, radio) and sustainment stores (food and water).[2] The United States Army recommends combat loads according as either fighting/patrol load (18-22 kg), approach march load (32-35 kg) and emergency approach march load (>35 kg).[3] Supplies and equipment carried during both training and combat situations create many biomechanical and postural challenges for military individuals.[4] The added mass of a loaded backpack makes it more difficult to initiate motion and requires greater moments about the axes of rotation to control motion.[4] Additional load carriage has the potential to influence postural control mechanisms,[4-6] which may in turn alter the risk of falls and injury.

Fatigue has been demonstrated to play a part in the increasing rate of musculoskeletal injuries sustained in athletics as well as in military populations. Tasks such as exhaustive marches have been shown to increase injury rates,[7-9] which has the potential to not only adversely affect an individual's mobility, but reduce the effectiveness of an entire unit as well.[8] Within sports, injuries to the knee and ankle are common, and are most predominant in sports with intermittent bouts of high-intensity exercise and multiple changes of direction and jumping.[10,11] Injuries also tend to be more prevalent during later stages of practices, periods, games and seasons when fatigue is more prevalent.[12-14] Although many of these injuries are the result of direct blows, non-contact mechanisms of injury such as incorrect landings also frequently occur.[11,15,16] Successful landings require strength, stability and balance, which are also essential to protection against joint injury. It is possible that injuries seen during jumping and cutting maneuvers are the result of poor strength or impaired stability and balance.[11]

Neuromuscular control plays a key role in dynamic joint stability and the body's natural protection from injury,[11,17] and neuromuscular fatigue can impair this control and stability.[11,18,19] Dynamic postural stability tasks such as the NeuroCom Sensory Organization Test is an assessment of neuromuscular control that challenge both sensory and mechanical systems.[20] Given that injury rates increase when individuals are fatigued, and deficits in postural control are risk factors for lower limb injury, fatigue-induced postural stability deficits may be expected to contribute to the incidence of injury.[10] Previous research has investigated the results of fatigue on postural stability and balance in athletes,[11,16,21,22] however the effect of loaded fatigue on postural stability is limited, especially in military populations. Additionally, the effect of load carriage on postural stability has been studied extensively, however there are no studies identifying the effect of loaded fatigue on loaded condition of postural stability.

1.1 DEFINITION OF POSTURAL STABILITY

Postural stability is defined as an individual's ability to maintain a state of equilibrium by sustaining their center of mass within a base of support.[23,24] It is the detection of body motions and integration of sensorimotor information to execute musculoskeletal responses in order to establish balance between stabilizing and destabilizing forces.[24] Postural stability can be measured and explained by both static and dynamic processes. Static postural stability can be defined as maintaining steadiness on a fixed, firm, unmoving base of support, keeping the body as motionless as possible.[24] Static assessments can be quantified with laboratory equipment such as a force platform, or valid and reliable clinical scales such as the Balance Error Scoring System or the Berg Balance Scale.[25] Though static measurement of postural stability provides advantageous clinical information,[26] the principal task of standing stationary may not translate to movement tasks demanded during physical activity.[25]

For young, healthy, physically active individuals, dynamic postural stability tasks may be more suited for challenging balance skills associated with physical activity participation. Dynamic postural stability can be defined and measured by the assessment of an individual's ability to maintain balance while transitioning from a dynamic to a static state.[20,24] Dynamic postural stability can be assessed by disturbing the testing support surface, change of position or location of a subject while attempting to maintain balance, or by unplanned movement of the individual. Commonly used measurements of dynamic postural stability include the Star Excursion Balance Test, the Multiple Single-Leg Hop-Stabilization test, the Dynamic Postural Stability Index and the Sensory Organization Test. These assessments are laboratory and clinical based tests in which the goal of all methods is to expose underlying sensorimotor control issues.[24]

1.2 MILITARY LOAD CARRIAGE

Load carriage is defined as locomotion while bearing a mass on the torso supported by shoulder straps and/or a hip belt, and is an integral element in some occupational settings such as military or emergency services.[8,27] Carrying a backpack remains the most economical and convenient ways of transporting an external load, especially in military contexts where vehicles may be restricted.[27] With technological advancements, loads carried by soldiers in terms of increased firepower and protective equipment have progressively increased. During operation Desert Shield and Desert Storm, American soldiers carried loads up to 45.5 kg[28] and continued to carry loads between 45.5 to 54.5 kg in Iraq and Afghanistan.[2,29,30] A recent comprehensive study of the 82nd Airborne Division, on Operation Enduring Freedom III found that soldiers carried loads upward of 73% of their body mass.[2,31] The risk of injury increases with the magnitude of load carriage exposure in terms of increased weight, increased duration, or increased frequency. Over the last two millennia, though the nature of warfare has changed, the soldier's load had not reduced. Relying on improved equipment and load carriage logistical aides may not be the solution to reducing injury risk in soldiers.[2]

Negative consequences of excessive load carriage can include decreased mobility, increased fatigue, foot blisters, spinal injury and degeneration, muscle tightness, and soreness of the shoulders, back, legs, feet.[32] Load carriage has also been shown to negatively impact dynamic postural stability during jumping tasks,[6] and landing kinematics during drop landing maneuvers,[33] increasing the likelihood of unintentional musculoskeletal injury. Roy et al.[34] conducted a study on 263 soldiers during their deployment in Afghanistan, and concluded that wearing loads exceeding 36.6kg may increase physical demands, leading to a greater potential for musculoskeletal injury.[34] Though wearing an external load can be detrimental to a soldier's health and performance, exercising during load carriage can increase these negative effects. Changes in locomotion, high metabolic and mechanical energy requirements caused by load carriage lead to neuromuscular fatigue. This exercise related decline can affect both central and peripheral systems, which can cause failure to adequately drive motoneurons and alterations in excitation-contraction coupling.[35] The decrease in muscular function due to fatigue can lead to further negative effects including decreased maximal voluntary contraction,[35,36] mobility,[37] and further detrimental biomechanical changes[38] which can increase the likelihood of sustaining an unintentional musculoskeletal injury.

Given the high rate of non-battle related musculoskeletal injuries (25% of all injuries requiring medical evacuations in Operation Enduring Freedom)[39] there is a need for improved military fitness levels. Nindl et al. suggest testing and physical employment standards should include a soldier's ability to tolerate and operate under heavy loads for long periods of time.[40]

1.3 IMPLICATIONS OF FATIGUE

1.3.1 Fatigue and Injury

Fatigue has been widely studied with varying definitions, but is most commonly described as the inability to maintain a required force production or power output for a given intensity. Muscular fatigue is an inevitable part of high intensity exercise, and is associated with reduced power output and work capacity of skeletal muscle.[41] Fatigue induced impairments in muscle function are believed to be a potential cause of increased injury rates during the latter stages of athletic activities and performances.[13] Military studies have also shown that strenuous marching while carrying heavy equipment loads can be associated with acute injuries (ligament strains, back problems, blisters) which may lead to excessive morbidity.[9,42] In a prospective study, Reynolds et al.[9] monitored injuries sustained in Army infantry soldiers during a 161km road march as a part of routine training. Soldiers marched approximately 32km each day for five consecutive days, with several rest periods taken throughout the march. 36% of all soldiers suffered one or more injuries, leading to a total of 69 days of limited duty.[9] Results from this study were in accordance with other studies identifying injuries sustained during military marches of varied lengths and intensities. Knapik et al.[42] conducted a single day, passive surveillance during a 20km road march with 45kg of load carriage. 24% of soldiers reported injuries, resulting in 44 days of limited duty and 4% of injured soldiers unable to complete the march.[42] Fatigue related injuries experienced within the military has similarities within civilian sports. In athletics, an epidemiological study conducted by Ekstrand et al.[15] presented that there is a higher incidence of lower body injuries sustained in soccer players towards the end of each half of competition.[15] Similarly, additional studies in like populations[12,14] show that injuries occur more frequently during a game or performance, as well as closer to the end of the day and season suggesting an effect of fatigue over time.[43]

Failure to produce maximal muscular force from fatigue is the consequence of 1. peripheral fatigue resulting from failure at the neuromuscular junction and beyond and 2. central fatigue resulting from a failure to drive motor neurons to activate muscles voluntarily. Peripheral and central fatigue induced changes further impair neuromuscular control and performance.[13] These fatigue induced impairments in neuromuscular control may negatively alter joint proprioception,[13,19,44,45] joint laxity,[19,44,46] kinematics,[44,47,48] biomechanics, and other necessities of optimal performance. Understanding that safe and successful execution of motor tasks rely on optimization of these factors, the influence of fatigue can potentially limit performance and increase risk of injury during high intensity exercise. Although there is currently a lack of direct epidemiological evidence demonstrating that fatigue increases the risk of injury, there is research suggesting the validity of this relationship.[43] Fatigue has been shown to negatively affect postural control of the knee in healthy males by changing the degree of agonist-antagonist co-activation, and cause a delay in hamstring and quadriceps muscular activation in response to knee perturbations commonly occurring in sporting activities.[13] Fatigue has also been associated with negative changes in lower body biomechanics specific to non-contact ACL injury. An increase in knee valgus moment, decreased knee flexion,[49] increased anterior tibial translation,[44,47,48] and increased internal tibial rotation[44,50] have all been associated with fatigue. Fatigue has also been associated with decreased peak ankle dorsiflexion[44,50,51] and decreased hip flexion[51] during landings, and negative changes in knee proprioception[19,46] indicating an increased risk of lower body injury.[44,50,51]

1.3.2 Fatigue and Postural Stability

It has been suggested that fatigue reduces neuromuscular and sensorimotor control, and that the occurrence of these decrements may contribute to an increased risk of injury. The relationship has been investigated and partially supported by several studies that have examined postural stability changes after fatigue protocols.[22] Research examining the relationship between fatigue and postural stability has shown mixed results, most likely due to fatigue protocol implemented and postural stability testing method.[10] To date, studies assessing the impact of fatigue on postural control have focused primarily on static postural stability.

In the U.S. Army, service members are required to complete both aerobic and anaerobic tests and training to ensure proper physical fitness levels. Pendergrass et al.[52] conducted a military specific fatigue protocol and identified its effect on static postural sway in healthy individuals. The authors found that after a two-mile run, there was a significant increase in stability scores as measured by the Biodex Stability System, indicating postural sway was negatively influenced by the fatigue experienced after the run.[52] Though there is limited research looking at military specific fatigue and its effects on postural control, there has been extensive research in athletic populations.

The exact influence of sport specific fatigue on dynamic postural stability remains unclear. Studies that have utilized measurements of dynamic postural stability after fatigue have implemented fatigue protocols not specific to the population in question. Incremental treadmill runs in volleyball players,[16] treadmill runs alongside weighted barbell step-ups in handball athletes.[22] Two studies tested dynamic postural stability after functional fatigue protocols in healthy athletic individuals.[10,11] One of which utilized the Star Excursion Balance Test (SEBT) as a means to test dynamic postural stability after a high-intensity, intermittent exercise protocol (HIIP). The HIIP resulted in similarly elevated heart rates and distances covered during bouts of high-intensity intermittent activity in soccer. Researchers found that HIIP fatigue induced negative changes in dynamic postural stability.[10] Peak vertical ground reaction forces (vGRF), and time to stabilization (TTS) were measured by Wilkstrom et al.[11] to determine if isokinetic fatigue and functional fatigue effected dynamic stabilization in healthy individuals. The functional fatigue protocol was designed to mimic common movements that would occur on the field or court, and was found to negatively affect GRF and TTS suggesting diminished postural stability.[11] Due to lack of consistent research, more investigation is required to solidify the relationship between sport and military specific fatigue, dynamic postural stability and injury risk.

1.4 POSTURAL STABILITY AND INJURY

The use of prospective postural stability assessments as a possible risk factor for injury is limited. The majority of prospective studies have examined ability of postural stability tests to predict ankle joint injury in sports,[11,53-56] however results are inconsistent. A systematic review done by McKeon et al.[57] in 2008 reported discrepancy in results when using static postural stability as a predictor of lateral ankle sprain.[57] In two studies analyzed, researchers used center of gravity (COG) excursions measures as the singular predictor of ankle injury risk. Consistent predictive results were found, and established that diminished postural control is a risk factor of ankle injury.[54,55] However, when COG excursion measurements were analyzed along with multiple predictors of ankle sprain risk- such as muscle strength, joint laxity and reaction time- diminished postural stability was not found to be predictive of ankle injury.[53,58] Lack of uniformity may be attributed to the utilization of static measures of postural stability which may not provide sufficient discriminatory and predictive capabilities of detecting injury risk.[24] Due to the fact that they are too simple and do not appropriately represent advanced athletic movements typically associated with non-contact injuries,[24,59] measurements in dynamic postural stability may be more suited for predicting non-contact injury in healthy, highly trained populations.[24]

Though measurements of dynamic postural stability may be more suitable for measuring postural control in more experienced individuals, there is significantly less research utilizing dynamic postural stability as a predictor of lower extremity injury. One group of researchers utilized an SEBT to predict lower extremity injury in high school basketball players. They found that diminished postural stability was a reliable predictive measure of lower extremity injury, including both knee and ankle sprain.[60] Other studies that have utilized force plates found that poor postural control is predictive of secondary ACL injury following reconstruction[61] and that poor balance may be predictive of ACL rupture.[62] While there is countless research utilizing static postural stability as a risk factor for injury, there is a significantly less amount of research examining dynamic postural stability measures as a risk factor of injury. In addition, there are no studies that prospectively utilize a dynamic postural stability test such as the sensory organization test in military populations to identify potential risk factors for injury. This lack of utilization could stem from the numerous types of dynamic postural stability testing methods, and a lack of availability and inconvenience of laboratory based measurements for the military. It is important to establish the relationship between postural control and injury risk in military populations due to the high incidence of injuries sustained in non-battle situations.

1.5 DEFINITION OF THE PROBLEM

Musculoskeletal injuries are a common issue in the United States Armed Forces, and account for the largest portion of medical visits in the population.[39] Lower extremity injuries accounted for 49% and 35% of all injury-related musculoskeletal conditions treated at outpatient services and conditions requiring hospitalization, respectively.[63] One of the major unavoidable physical challenges for soldiers is the requirement to carry an external load. Negative consequences of excessive load carriage can include decreased mobility, increased fatigue, muscular tightness, alongside a number of other musculoskeletal injuries.[40] As loads increase, there are systematic decrements in the performance of tasks such as short sprints, agility runs, ladder climbs and obstacle courses.[8] Lower extremity musculoskeletal injuries have been reported during loaded exhaustive marches[9] and it is speculated that carrying heavy loads during strenuous activities would likely result in fatigue and reduced ability to maintain balance. The physiological effects of load carriage have been well documented, and the effects of fatigue in different modes on postural stability has also been established. To our knowledge, there have been no studies looking at the effect of a loaded fatiguing protocol on loaded postural stability.

1.6 PURPOSE

The primary purpose of this thesis was to establish if a loaded fatigue protocol influences loaded postural stability. Secondly, to determine if any component of the sensorimotor system (vestibular, visual or somatosensory) is negatively impacted by loaded fatigue. Lastly, to determine the differences in baseline to post-fatigue changes in loaded postural stability after a loaded fatigue protocol when stratifying for sex. Postural stability will be measured by the Sensory Organization Test (SOT) protocol used in the NeuroCom Balance Manager Smart EquiTest.

1.7 SPECIFIC AIMS AND HYPOTHESES

Specific Aim 1: To examine if differences exist in loaded postural stability, as measured by the NeuroCom SOT, following an incremental loaded fatigue protocol.

Hypothesis 1: Loaded NeuroCom SOT scores will be decreased following a loaded fatigue protocol.

Hypothesis 1a: Loaded NeuroCom SOT component scores will be decreased following a loaded fatigue protocol.

Hypothesis 1b: Loaded NeuroCom SOT component raw force plate data (SDvGRF and TotSway) will be increased following a loaded fatigue protocol.

Specific Aim 2: To determine if differences exist between baseline to post-fatigue changes in Neurocom SOT component scores or component raw force plate data.

Hypothesis 2: There will be no significant differences between pre- to post-fatigue changes of Neurocom SOT component scores or component raw force plate data.

Specific Aim 3: To determine if differences exist in baseline to post-fatigue changes in loaded postural stability between sex in as measured by the NeuroCom after a loaded fatigue protocol.

Hypothesis 3: Between-sex differences will be demonstrated from pre- to post-fatigue for Neurocom SOT composite, component, and component raw force plate data.

1.8 PROJECT SIGNIFICANCE

Previous research has shown that fatigue can negatively alter postural stability in military and athletic populations. Research has also shown that increased load carriage can be taxing on both the musculoskeletal and aerobic systems, leading to an increased risk of injury in soldiers. However, the effects of a loaded fatigue protocol on loaded postural stability has not been identified. The results of this study could potentially aid in future military recommendations for postural stability screening, training and other strategies for injury prevention during load carriage activities. This study will be the first to demonstrate the relationship between a loaded fatigue protocol on loaded postural stability measurement.

2.0 REVIEW OF LITERATURE

A review of the literature will provide an overview of previously published literature related to the current study. The first section will begin by discussing postural stability and how it pertains to numerous factors such as injury risk, fatigue and load carriage. The second section will include lower extremity injury epidemiology, rates and associative risk factors. The third section will describe the components of the sensorimotor system and examine its connection with lower extremity injury. Fatigue will then be discussed in relation to its mechanisms, and relationships with the sensorimotor system and injury risk. Finally, the methodology for this study will be considered thoroughly.

2.1 POSTURAL STABILITY

2.1.1 Static and Dynamic Postural Stability

Static postural stability can be defined as maintaining steadiness on a fixed, firm, unmoving base of support.[24,64] Steadiness is described as the ability to keep the body as motionless as possible.[65] Static postural stability testing can be assessed during single or double legged tasks, while performing the task with eyes open or eyes closed. Static postural stability has been utilized to prospectively investigate its capability of predicting ankle injury[53-55,58,66] and has shown to be a predictor of acute lateral ankle sprains, although results are not unanimous.[24,57] In a study performed by McGuine et al.,[54] after testing unilateral static postural stability in high school basketball players, investigators found that higher postural sway scores corresponded to increased ankle sprain injury rates (p=0.001). They also found that those who demonstrated poor postural stability suffered nearly seven times as many ankle sprains as subjects who had good static postural stability.[54] Though this study was in agreement with other static postural stability research looking at ankle injuries in athletes[11,55] it does not agree with other outcomes in similar studies.[53,58] This inconsistency may be due mainly to the use of static postural stability, which may not have the discriminatory capabilities required to predict injury risk in healthy populations.[24] This knowledge has caused a shift away from static postural stability measurements within sports medicine research and towards the use of dynamic postural stability measurements, as it may be more functional and specific to athletic populations.

Dynamic postural stability can be defined as the ability to transfer the vertical projection of the center of gravity around the supporting base.[65] There are numerous ways to test dynamic postural stability including both laboratory and clinical based tests, which incorporate methods using sophisticated technology and basic cost effective tools. More information on dynamic postural stability tests will be covered in greater detail in the following sections. Researchers have investigated the relationship between static and dynamic tests, resulting in a lack of agreement in outcomes.[24,67-69] Two studies found weak yet significant relationships between static and dynamic tasks,[67,68] however later studies found no relationship.[24,70]

Nakagawa et al.[68] examined postural control in healthy controls and individuals suffering from recurrent ankle sprain utilizing static and dynamic clinical tests. The investigators measured static balance as the total center of pressure excursion during a unilateral stance, and assessed dynamic balance with a novel task. The task required subjects to take a lateral step onto an unstable surface situated on top of a force plate, which measured total center of pressure excursion. A four direction SEBT was also used to measure dynamic postural stability. Results of the study found a statistically significant, yet limited relationship between static and dynamic tasks (r=0.10), static and functional tasks (r = 0.05) and between dynamic and functional tasks (r = 0.12).[68] Similarly, a study conducted by Clark et al.[67] compared static balance using a single leg stance and a modified Balance Error Scoring System (mBESS) test with dynamic balance using the SEBT. The single leg stance test performed was in accordance with the Trojian protocol, using pass or fail as a resulting measurement.[71] Results of the study showed a significant, but limited relationship between the SEBT and both the mBess (r = -0.35) and the single leg stance (p = 0.025).[67] The authors of both studies suggested that the outcome insinuates that the modalities may be interrelated but might not assess similar components of the sensorimotor system.[67,68]

Later studies investigating the relationship between static and dynamic measures of postural stability found dissimilar results to those by Nakagawa et al.[68] and Clark et al.[67] Researchers investigated the relationship between three measurements of single leg postural stability in recreationally active college students. Riemann et al.[70] measured dynamic postural stability by using the SEBT and a single leg hop stabilization test. Static postural stability was assessed as center of pressure velocity using firm and multiaxial surfaces, with eyes both opened and closed. Unlike the prior studies, the authors found no significant relationship (r = 0.371 to 0.624) between measures of static postural stability and either of the dynamic postural stability measures.[70] Comparably, a study conducted by Sell[24] showcased the relationship between static and dynamic postural stability tests utilizing force plate measurements. Static postural stability was assessed during a single-leg standing task measuring the standard deviation of the ground reaction forces, while dynamic postural stability was measured using two single leg jumping tasks with outcomes quantified by the dynamic postural stability index (DPSI). Results of the study indicated a lack of correlation between the different postural stability measurements.[24] The lack of correlation between static and dynamic postural stability measurement conditions in these studies is likely due to the challenge, or lack thereof, imposed on the systems necessary for maintaining postural stability. The differences suggest measures of postural stability should be chosen carefully according to the population being studied. The greater challenge posed by dynamic tasks may indicate that they are a better tool for analyzing postural stability in athletes and other individuals who have highly developed sensorimotor systems.[24]

2.1.2 Laboratory and Field Measures of Postural Stability

Postural stability testing in athletics is imperative for evaluating injury risk, deficiencies in motor control after injury and quantifying improvements after injury treatment. These assessments can be measured in numerous static and dynamic tasks, both in clinical and laboratory settings. Laboratory based measures of postural stability include the DPSI test, and Time-to-stabilization (TTS) test assessed during a single leg landing task. In a clinical or field setting, qualitative tests such as the Simple Balance Test, the Balance Error Scoring System (BESS) and the Star Excursion Balance Test (SEBT) are often used. The Sensory Organization Test (SOT) is often used in laboratory based settings, but can also be utilized in clinical settings as well.

Laboratory Based Measures

The quantification of postural stability through laboratory testing is essential for quick determination of balance intervention or effectiveness of interventions meant to progress postural stability.[72] Three key laboratory tests to measure postural stability are measuring TTS, calculating DPSI based on force platform data, and the SOT. The DPSI is a reliable and precise measure of motor control of the lower extremity, dependent on proprioceptive feedback, reflexive, preprogrammed and voluntary muscle responses.[20] The test consists of two dynamic jumping tasks in the anterior-posterior (AP) and medial-lateral (ML) directions. Participants perform the jumps from a set distance over a small hurdle onto a force plate. The goal of the test is to jump over the hurdle and land without excessive sway and to stabilize as quickly as possible.[24] DPSI has been found to have good inter-session reliability with ICC values of 0.86 and 0.92 in the AP and ML directions respectively.[24] Additionally, Wikstrom et al.[20] found that the reliability of the DPSI and its directional components was higher than that for the TTS scores calculated in the same investigation.[20]

Time to Stabilization is an objective postural control measure that is used in combination with a functional jump or step down protocol. It is defined as the time required to minimize resultant GRFs of a jump or drop landing to within a range of the static baseline GRF. It is a measure of motor control of the lower body, dependent on proprioceptive feedback, reflexive and voluntary muscle responses and preprogrammed muscle patterns.[11,73] It has been used to evaluate the effects of fatigue,[74] motor control during drop jumps,[59] differences amongst healthy and ACL deficient knees,[75] and functional ankle instability.[11,20,59] The jumping stabilization test consists of performing a single one-leg hop onto a force plate over a small barrier and stabilizing as fast as possible. The step-down stabilization test consists of individuals stepping off a platform and landing on a force plate on one foot, stabilizing as quickly as possible. GRF and moment data in the vertical, medial-lateral and anterior-posterior positions are measured in both testing conditions.[75] Though the TTS test has been found to be reliable and precise[59,75] there it has several inherent flaws. Due to force measurements in three directions, researchers have multiple separate measures of postural stability which may prevent clinicians from observing global changes in lower body dynamic postural stability. Unequal baseline comparisons between healthy and injured populations in TTS tests poses another issue with using this protocol. Lastly, preforming data reduction and analysis on three separate directions is a tedious and limiting flaw.[20]

The SOT is a quantitative and objective assessment of the sensorimotor system and the integration and adaptive mechanisms of the central nervous system.[76] NeuroCom consists of several testing protocols including the SOT, the Motor Control Test (MCT) the Adaptation Test (ADT) and the Limits of Stability (LOS) test. A key test in the NeuroCom dynamic posturography system is the SOT, which provides information about the integration of the visual, vestibular and somatosensory components of balance. The overall equilibrium score (ES) reflects the global coordination of these systems by measuring timing, direction and amplitude of corrective responses. The test consists of six conditions, each manipulating sensory information to systematically assess the effectiveness of the human balance system. Table 1 indicates the visual and somatosensory input for each of the six conditions in addition to which sensory system is being perturbed in each condition. Within the area of sports medicine, the NeuroCom has been used widely within concussion research[77-80] as well as ankle stability and ankle injury studies.[54,81] Though the NeuroCom and other laboratory based postural stability tests have been found valid and reliable, their equipment may not be readily available to clinicians. Clinical based postural stability measurements have been established to offset this setback in order to test balance in the field.

Table 1: NeuroCom SOT Conditions

Condition	Vision	Surface	Disadvantaged System	System Used
1	Eyes Open	Fixed		Somatosensory
2	Eyes Closed	Fixed	Visual	Somatosensory
3	Sway	Fixed	Visual	Somatosensory
4	Eyes Open	Sway	Somatosensory	Visual
5	Eyes Closed	Sway	Somatosensory and Visual	Vestibular
6	Sway	Sway	Somatosensory and Visual	Vestibular

Field Based Measures

Field tests focus on non-instrumented measures that quantify balance.[82] There is a large amount of balance assessments available for testing postural stability in a clinical setting, however some of the more widely used tests include the Simple Balance Test, BESS test and the SEBT. The Simple Balance Test is performed under four testing conditions on a compliant floor surface. Subjects are instructed to keep balance in a single leg stance for one minute in each condition. Conditions tested include eyes open and eyes closed for both legs. The number of failures and time to first failure are counted towards the postural stability outcome.[83] The BESS test provides a quantitative static measure of balance using an error score.[82] The test combines a variety of stances on a firm surface and an unstable surface. Stances tested include double legged (feet side-by-side), single legged, and tandem (one foot placed directly behind the heel of the contralateral foot) on both firm and foam surfaces. Participants are instructed to keep their eyes close with their hands on their hips during testing. Participants aim to remain as motionless as possible for 20 seconds and to minimize balance errors during testing. Errors are classified as lifting hands off iliac crest, opening eyes, stepping, stumbling or falling, moving hip into more than 30° of flexion or abduction, lifting forefoot or heel, and remaining out of test position for more than five seconds.[64,82] A high total error score on the BESS test has previously identified balance deficits associated with chronic ankle instability.[84] The SEBT is a reliable clinical test consisting of a series of eight lower extremity reaching tasks that challenge subjects' postural control, strength, range of motion and proprioceptive abilities.[26] Individuals stand at the center of a grid consisting of eight lines extending at 45° increments from the center of the grid. A single-leg stance is maintained while reaching with the contralateral leg to touch as far as possible along the chosen line. Reach distance is measured three times and normalized to leg length on both legs.[26] The SEBT is claimed to detect functional performance deficits associated with lower extremity pathology in otherwise healthy individuals.[26,60,85]

There are advantages and disadvantages to all postural stability tests. There is still a lack of research incorporating dynamic postural stability tests within a military population, especially while incorporating potential factors of increased injury risk.

2.1.3 Postural Stability and Load Carriage

Poor postural stability has been identified as a risk factor for lower extremity musculoskeletal injury in athletic populations, and is likely a risk factor for injury in the military as well.[6] The effects of load carriage on gait[86,87] and physiological functions[35,36,88,89] have been identified, however the effect of load carriage on postural stability in soldiers is not well established.[6] Previous literature has primarily used static postural stability testing, which fail to replicate the dynamic movements and tasks military personnel experience during training and operations.[24] Shiffman et al.[5] analyzed the effects of three different loads on static postural stability in US Army men. Loads measuring 6, 16 and 40kg were applied in an increasing manner while taking static postural sway measurements on force plates. Researchers found that each of the traditional measures of sway was significantly affected by the load weight variable ($p<0.001$), and that ability to maintain balance while quietly standing was altered by the external load.[5] Heller et al.[4] demonstrated similar decrements in static postural stability when testing load carriage in females. While wearing an 18.1kg military backpack, center of pressure length increased 64%, medial-lateral excursion increased 131%, anterior-posterior excursion increased 54% and center of pressure area increased 229%. The data show that wearing an external load significantly increases postural sway in females, potentially increasing the likelihood of musculoskeletal injury.[4] Results of these studies coincide with similar findings of increased postural sway with addition of an external load in static postural stability assessments.[1,8]

Although the effect of load carriage appears to be detrimental to static postural stability, the effect of load carriage on dynamic postural stability is largely unidentified. A singular study by Sell et al.[6] aimed to establish the relationship between external load and dynamic postural stability in soldiers. 36 subjects were recruited from the Army 101st Airborne Division to perform several DPSI tests with and without an external load. The load carriage amount that was chosen to be the minimum load soldiers carry while on missions and training, and measured to be 15.6 $\pm$ 4.2% of body weight. Subjects performed the DPSI test significantly worse under loaded conditions when compared to non-loaded conditions. Scores in the anterior-posterior, medial-lateral, vertical and overall scores were found to be significantly poorer when carrying a minimal external load. Researchers explained that this significant decrease while wearing body armor may increase the risk for sustaining a lower extremity musculoskeletal injury. They further rationalized that careful consideration should be given to develop proper military training programs that incorporate balance training with the addition of body armor to induce adaptations to help alleviate the negative outcomes of load carriage on dynamic postural stability.[6] The body of literature examining load carriage and postural stability, as well as load carriage and injury rates are currently lacking. Further research is needed to solidify these relationships, which can aid in future military training programs to help mitigate the risk of sustaining unintentional musculoskeletal injuries.

2.1.4 Postural Stability and Fatigue

Postural stability is undeniably an important physiological response that is greatly influenced by many factors including fatigue.[52] Within athletics, studies have shown that a large quantity of injuries in athletics occur in later stages of practices and games.[12,14,15] Altered postural stability due to fatigue has been identified as a possible causation of this statistic. In attempt to correct this issue, researchers have performed examinations on different types of fatigue and its effects on postural stability in athlete and military populations in order to find a correlation and potentially prevent future injury.

Within the military, service members are required to perform various aerobic activities during both training and deployment circumstances. Pendergrass et al[52] looked at the effect of a two-mile run on postural sway in healthy subjects to correlate results to physical fitness requirements within the United States Army. Subjects completed a two-mile run on a flat surface as quickly as possible in order to keep with the requirements of the biannual Army test. Immediately post run, subjects were tested on the Biodex Stability System (BSS) for their overall stability index. The overall stability index measured by the BSS post two-mile run revealed a significant increase in postural sway ($p<0.05$). Similar results have been shown within civilian athletic populations.[52]

Brazen et al.[90] looked at the effect of a functional fatigue protocol on dynamic balance from a single-leg drop landing in recreational athletes. Time to stabilization (TTS) was measured in the medial-lateral, anterior-posterior and vertical directions. Results showed an increased TTS in the anterior-posterior and vertical directions following fatigue.[90] Though a clear pattern of TTS change in the medial-lateral direction was not observed, there was a significant interaction following fatigue. The authors hypothesized that the dynamic balance task was a possible limitation and could have hindered potential results. The little motion required in the medial-lateral direction of single-leg drop landings lead them to believe that the task did not pose a significant challenge to the body, resulting in the interaction effect observed.[90] Years later, researchers implemented more sophisticated methods in order to effectively measure postural stability changes after fatigue in athletes. Kuni et al.[16] implemented a jump test onto a force plate following a 30 minute, participant specific running protocol on a treadmill. Dynamic postural control was significantly impaired within the first minute after running in all participants ($p = 0.043$), including high performance athletes included in the study. Failed trials of the jump test were also recorded and noted between recreationally active subjects and high performance subjects. Recreationally active subjects failed more trials per person than the high-performance subjects, but differences between groups were not significant. These outcomes lead researchers to conclude that fatigue may cause trouble in fulfilling complex tasks seen in sport activity, leading to an increased chance in sustaining injury.[16]

Recently, researchers aimed to study the effect of high-intensity, intermittent exercise on dynamic postural control in civilian university athletes. Prior to a study conducted by Whyte et al.[10] there had been no prospective investigations into this correlation. Participants completed a high-intensity, intermittent exercise protocol followed by an eight direction SEBT. There was a negative effect on dynamic postural control in all directions seen after the fatigue protocol (p <

0.001) in both male and female participants.[10] Results showed greater fatigue-induced postural stability changes than in previous studies utilizing different methods of fatigue.[21,73,91] They also highlighted that their results disagreed with previous studies applying other techniques of on setting fatigue to investigate the effects on postural control. Closed kinetic chain dynamometry,[73] cycling,[21] step-up with resistance,[22] and continuous treadmill running all showed conflicting results to the current study.[21,22] The inconsistency in outcomes may be due to methodologic variations, more specifically that fatigue and its effects depend on the exercise.[10,21,92]

A decline in performance after fatigue may be the result of a change in coordination, in the functional capacity to produce force, or both. Postural stability performance has been proven to be diminished after fatigue, leading to a higher potential of injury. However, more research needs to be done to solidify this relationship in order to potentially prevent injury or implement sufficient injury prevention programs.

2.1.5 Postural Stability and Injury Risk

Most injuries sustained in the military as well as sport activities are unintentional, musculoskeletal injuries. A large amount of these injuries sustained are non-contact in nature. The ability to prepare, maintain and restore postural stability is believed to be essential to avoiding high risk positions that may increase non-contact injury risk.[20,93] Studies have been performed to test the relationship between postural stability and injury risk in civilian athletes to potentially diminish the amount of injuries sustained in this manner.

McGuine et al.[54] conducted a study examining the ability of preseason balance measurements and to predict ankle injury in high school basketball players. Balance was measured from postural sway scores via unilateral static balance tasks with eyes open and eyes closed, and ankle injuries were recorded throughout the season during two consecutive years. Results showed that higher postural sway scores corresponded to increased ankle sprain rates (p = 0.001), and subjects who demonstrated higher postural sway scores (and therefore poor balance) sustained nearly seven times as many ankle sprains as subjects who had good balance (p = 0.0002).[54] In agreement with this study, Willems et al.[94] found that some postural control parameters measured by a NeuroCom Balance Master could predict ankle injury in male subjects. This prospective study found a positive association between balance and ankle injury with a p-value of 0.037 in the LOS test.[94] More recently, Dingenen et al.[93] utilized a center-of-pressure displacement from a blinded, double-leg to single-leg transition task to measure postural stability in 53 female athletes. The main outcome variable was measured during the first three seconds after the time to a new stability point was reached during the single-leg stance. For one year after balance measurements were taken, non-contact lower extremity injuries were recorded. Results showed the center-of-pressure displacement during the first three seconds after the time to the new stability point was significantly increased in injured (p = 0.30) and non-injured (p = 0.009) legs of those who reported injury compared to the non-injured group.[93] This study agreed with other prospective studies that have reported decreased postural stability in relation to increased injury risk,[21,48,94] however contradictory results have also been reported.[58,74] The extensive assortment of testing modalities may be one of the factors contributing to these varied findings. Despite reports claiming that these postural stability measures may relate to each other, it remains difficult to compare outcomes across different studies.[93] Also, static postural stability measurements may be as discriminatory in skilled individuals due to their less challenging nature.[37] Though many studies correlate outcomes with athletes to military populations, there is a gap in the literature concerning direct prospective studies of postural stability and its correlation with injury in the armed forces. More dynamic postural stability measurements need to be implemented in prospective studies in military populations in attempt to identify if reduced postural control is a risk factor for injury.

2.2 LOWER EXTREMITY INJURY EPIDEMIOLOGY

With the participation of athletics and exercise on the rise, the resulting risk of injury is a cause for concern. Athletic and military populations are suffering not only from pain and injury, but also from time lost and financial consequences. Injury may result in hospitalization, inability to participate in training and competition, and decreased quality of life. There is also possibility of loss of income to a professional, steep financial costs for medical care and job limitations depending on the severity and type of injuries sustained.[95] According to the National Institute of Health, in the United States roughly three million injuries occur annually from participation in sports, with about 770,000 of these resulting in physician visits and 90,000 requiring hospital care.[96] The amount spent for the acute treatment of these injuries has been estimated at 1.3 billion dollars.[96] Similarly, a recent epidemiological study found that within the United States Military, 19.5% of those surveyed suffered at least one non-battle injury, with 38% of those troops sustaining multiple injuries. The leading cause of these "severe" non-battle injuries was participation in sports/athletics and heavy gear/lifting (22.3% and 19.6% respectively).[97] An epidemiological study conducted by Jones et al.[63] highlighted medical injuries sustained within all branches of the US military in 2006. "Derangements of joints" (meniscal tears, articular cartilage injuries, loose bodies) accounted for 47% of hospitalizations and was the most common condition reported. Following this category, “pain and inflammation” injuries were reported as the second leading category of injury-related musculoskeletal conditions. This encompassed patello-femoral syndrome, Achilles tendonitis, bursitis and plantar fasciitis, and accounted for 25% of all hospitalizations.[63] The knee is one of the most common sites of musculoskeletal injury in the military,[33] accounting for up to 35% of all injuries among all branches of the US military.[98]

Lower extremity injuries caused the rate of medical visits for the Department of Defense (DoD) to be almost 900 per 1000 person-years over a six-year time period.[63] Looking at injuries treated in outpatient facilities reveals that sprains and strains are the largest unintentional musculoskeletal issue causing 49% of visits, with more than 265,000 injuries treated. Based on this number, authors stated that prevention of sprains and strains needs to be a priority within the US Military.[63] Ruscio et al.[99] approached the issue of injury prevention priority with estimating numbers of limited duty days for each type of injury seen in the Barell Matrix and injury-related musculoskeletal matrices. Across the entire DoD, it was estimated that acute and overuse injuries together resulted in over 25,000,000 days of limited duty in 2005. Lower extremity sprains and strains led to more than 1,800,000 days of limited duty, lower extremity overuse conditions (pain and inflammation) lead to an estimated 3,800,000 days of limited duty.[100]

When breaking down injuries sustained by each branch of the US Military, the US Army showed the highest rates of medical encounters, while the US Navy shoes the least.[63,101] Of 2,391 Army recruits surveyed between May 2010 and July 2011, 34% and 67% of males and females respectively, sustained at least one injury during basic combat training.[102] Similarly, an older study focusing on male US Army infantry basic training found an injury incidence rate of 37%, with 80% of those injuries related to an unintentional lower extremity injury.[103] A study identifying injury rates of US Air Force trainees showed 12.5% of all 67,525 individuals in basic training sustained at least one injury during a two year time period. The majority of all musculoskeletal injuries sustained involved the lower extremity (78.4%) with a total cost from all injuries exceeding $43.7 million.[104] Due to the overwhelmingly high amount of injury incidence in all branches of the armed forces, authors have concluded that non-battle, nonfatal unintentional injuries are the largest preventative health problem for the military.[63]

Similar to military populations, the lower extremity is the most common site for injuries sustained in sport.[105-107] According to a study published by Hootman et al.,[105] more than 50% of all reported injuries in 15 different collegiate sports were to the lower extremity, with knee and ankle injuries accounting for the majority of these injuries. ACL injuries were reported at an average of more than 2000 per year within these 15 activities. 88% of these injuries resulted in more than ten days off training and competition. Ankle sprains showed similar results at a reported average of 1700 per year, however contrasting ACL injuries, days of time loss over ten was only 20%.[105] Similarly, sport specific research including rugby, soccer, lacrosse and basketball have reported lower extremity injury rates of 35.9%,[108] 32.9%,[109] 30%,[110] and 65%[111] respectively of all injuries sustained within the past ten years.

Although requirements differ between sport and military, unintentional injuries sustained in both populations are limiting to their functional capabilities. Due to the prevalence and severity of military and sports injuries, research surrounding risk factors and injury prevention is key in order to diminish the detrimental outcomes of unintentional injury.

2.2.1 Risk Factors for Lower Extremity Injury

Due to the high frequency of injury to the lower extremity during sport participation, research has investigated possible mechanisms and risk factors which may lead to these injuries. The identification of risk factors is crucial in able to implement prevention and intervention strategies in attempts to lower the incidence of injury.

Numerous risk factors have been identified as contributors to lower extremity injury in athletics. These characteristics can be broadly divided into intrinsic and extrinsic risk factors.[112] Intrinsic risk factors can be defined as those inside the body, and extrinsic as those outside of the body. Intrinsic risk factors include age, sex, previous musculoskeletal injury, musculoskeletal or joint characteristics (strength, joint laxity, flexibility, range of motion), aerobic fitness, reaction time and postural stability. Extrinsic risk factors include weather, playing surfaces, level of competition, equipment, and the environment.[112] Risk factors can also be classified as modifiable and non-modifiable as well. Many sports medicine researchers have investigated non-modifiable risk factors such as age, gender or anatomical alignment, however modifiable risk factors are of more importance due to the potential for injury prevention interventions. Fatigue has been shown to negatively impact multiple intrinsic modifiable risk factors, and may contribute to lower extremity injury during training or competition. Studies investigating unintentional injuries in sports and athletics have identified fatigue as a contributing factor of injury during training and competition.[12,14,15,113,114] Epidemiological studies have shown that a large number of sport related injuries occur in later stages of practices and games[12,14,15] suggesting that fatigue could be related to injury.[43] Analysis of NCAA injury surveillance data shows that the rate of injuries sustained during competition (13.8 per 1000 athlete-exposures) was 3.5 times higher than the rate of practice injuries (4.0 per 1000 athlete-exposures).[105] This data also showed that of those injuries sustained during practice, preseason practices accounted for the highest rate of injury over an entire sport season. Preseason practices showed 2.5 to 3 times higher rates of injury when compared to in-season practice rates, and 4.6 to 5.5 times higher compared to postseason practice injury rates.

Variability in intensity and fatigue within these environments may contribute to the differences seen in injury rates across athletic seasons. Some athletes go into preseason poorly conditioned, which leads to higher stress during high-intensity, high-load preseason training.[105]

An epidemiological study performed by Ekstrand et al.[12] discovered similar outcomes in which more soccer injuries were sustained later in games and seasons which supports the idea of fatigue as a potential factor for injury. Within a span of seven consecutive seasons, 23 professional male European soccer teams were investigated to describe the incidence and nature of musculoskeletal injuries during match play and practice. Injury incidence during match play showed an increasing tendency of traumatic injury over time in both the first and second halves. A similar trend was observed for ligament sprains ($p=0.011$) and muscle strains ($p=0.005$) which account for two of the three most common injury subtypes experienced during match play. The authors speculated that fatigue may be an explanation to these findings, which support previous consensus agreements within soccer injury research.[7,12] Similar results were found when looking at the epidemiology of ice hockey injuries. Of all injuries sustained during game play, 42% occurred in the third period, leading researchers to conclude that the increased injury rate later in game play was due to an increased intensity and player fatigue.[115] A study investigating incidence, site and nature of injuries in amateur rugby players showed comparable results when focusing on when injuries occur during match play and within the competition season. Muscular injuries were the most common type of injury, and were sustained in latter stages of the season, with most injuries occurring within the second half of matches compared to the first (70.8% vs 29.2%). These findings suggest that fatigue or its associated effects may source a significant contribution to injuries in amateur rugby.[116]

There are numerous studies looking at certain biomechanical and physiological parameters after fatigue that can be associated with increased injury risk, but there is a lack of research identifying the exact lower extremity injury prevalence due to fatigue in military populations. Lower extremity injuries can cause significant time loss of involvement in sports and military operations, as well as other negative issues during later stages of life in general. Identifying and understanding injury risk factors such as fatigue is essential in order to possibly improve injury prevention strategies.

2.2.2 Load Carriage as a Risk Factor for Lower Extremity Injury

Medical problems associated with load carriage can adversely affect an individual's mobility, and in a military situation, reduce the effectiveness of the entire unit. The body of literature associated with load carriage and injury usually fall under two types; injury incidence after a single military excursion, or a report on a specific injury type and its association with load carriage. Although loads carried and distances traveled vary, the majority of injuries sustained involve the back or lower extremities.[8,63]

During military basic training, vigorous training protocols expose military recruits to significant muscular fatigue. Additionally, walking with a heavy load is always an important aspect of training. Large volumes of repetitive high ground reaction forces encountered during basic training could further increase the risk for lower extremity overuse injuries in the military.[38] Common overuse injuries documented in the military include knee pain, back pain and stress fractures.[8,38,63] Severe injuries such as stress fractures require extended periods of recovery and high medical costs.[38] Knapik et al.[42] conducted a small scale study looking at injuries after a single day loaded 20km road march. Authors reported a 0.6% incidence of knee pain in soldiers following a strenuous march. Although there were only two reported cases out of 335 soldiers, the cases resulted in a total of 14 days of disability.[42] Nine out of 85 Army soldiers who reported injury after a 100 mile infantry road march in sustained knee injuries, including sprains and strains.[9] Though the mechanisms responsible for knee injuries in the military has not been distinctly outlined, they are believed to be similar to the mechanisms responsible for knee injuries in athletes.[33]

The addition of load carriage to physiological stresses experienced during training and missions might lead to different mechanics and can potentially lead to higher incidence of lower extremity injury. Most non-contact traumatic knee injuries occur during tasks including sudden deceleration, landing, and pivoting maneuvers in athletics, which are also prevalent in military training and tactical operations.[33] Landing from a raised height is one of the most crucial and common tasks in the military which can incorporate possible detrimental biomechanical changes with an addition of an external load. A study conducted by Sell et al.[33] aimed to identify the effects of additional weight on knee kinematics and ground reaction forces during two-legged drop landings in air assault soldiers. Methods were conducted with a potential implication on lower extremity musculoskeletal injury using similar biomechanical models previously employed in athletes.[45,117,118] Researchers found that with the addition of weighted equipment, maximum knee flexion angles, maximum vertical ground reaction forces and time from initial contact to maximum values all increased significantly. With this in mind, the authors stated that additional weight carried by soldiers has the potential to alter kinematics and kinetics during tasks done during training and operations, therefore increasing the risk of unintentional musculoskeletal injuries.[33] Additional research has shown that carrying a military rucksack (approximately 15-30% of the soldier's body weight) can cause compensatory kinetic response at the knees,[88] and may alter landing kinematics and ground reaction forces as well.[33,38,87] Military load carriage can also increase ground reaction forces during walking,[37,38,119] alter pelvic and hip angles during standing,[86,120] and decrease balance and postural stability.[4-6,33]

Load carriage not only negatively influences soldiers in an injury perspective, it also can cause decrements in performance of military tasks during training and combat. As load increases, there are systematic decrements in the performance of tasks such as short sprints, ladder climbs, agility runs and obstacle courses.[121,122] Greater load volume can inhibit movement around obstacles, and distribution of load can also influence certain task performance as well.[8,121] Strenuous marches leading soldiers to walk 20km distances at maximum speeds with loads up to 61kg can lead to decrements in rifle marksmanship,[123,124] grenade throw distance,[125,126] and lower body muscular power.[8,127]

2.3 THE SENSORIMOTOR SYSTEM

2.3.1 Components of the Sensorimotor System

While standing, somatosensory, vestibular and visual inputs provide information about the body's orientation in space. The contribution and coordination of these sensory systems by the central nervous system (CNS) produces motor commands according to postural stability needs occurring in different sensory environments. The coordination of sensory information and motor commands occurs via the sensorimotor system.[128] This system is a subcomponent of the motor control system of the body and is comprised of the afferent, efferent and central integration and processing components involved in maintaining functional joint stability (FJS) and postural control during movement.[129] FJS is defined as the state of a joint remaining or promptly returning to proper alignment through an equalization of static and dynamic components. Static components include ligaments, joint capsules, friction, cartilage and bony geometry. The dynamic components include feedforward and feedback mechanisms, which can be influenced by biomechanical and physical characteristics of muscles surrounding the joint such as strength, endurance and range of motion. Feedforward control describes anticipatory mechanisms utilized prior to a stimulus, while feedback is described as actions occurring in a corrective response.[129] A combination of feedforward and feedback systems are necessary to allow for proper postural control and FJS.[69]

Somatosensory information concerning proprioception and the status of joints and associated structures is essential for neuromuscular and postural control. This information arises from joint mechanoreceptors in the muscle, tendon, ligament, joint capsule, fascia and skin. Mechanoreceptors are specialized sensory receptors responsible for translating the mechanical events occurring in tissues into neural signals.[130] Specific receptors can be found in both static and dynamic areas of joints. Static structures contain Ruffini receptors, Pacinian corpuscles, Golgi tendon organ-like receptors and free nerve endings, while muscle spindles and Golgi tendon organs (GTO) are found in dynamic structures. Ruffini receptors are considered to behave as both static and dynamic receptors due to their low-threshold, slow adapting characteristics. However Pacinian corpuscles are considered exclusively dynamic due to its low-threshold and rapidly adapting characteristics.[129,131] GTOs located within musculotendinous junction and the muscle spindles located in muscle tissue provide the CNS with feedback concerning muscle tension. GTO have very low threshold and high dynamic sensitivity which allows for the signaling of active muscle tension developed during contraction.[129,132] Muscle spindles consist of afferent nerve endings and are responsible for transmission of information about change or rate of change in muscle length.

Muscle spindles contain specialized nerve endings which wrap around muscle fibers, called intrafusal fibers.[129,133] These intrafusal fibers are peripherally innervated by gamma motor neurons (γ-MN) which are sensitive to changes in other peripheral mechanoreceptors. Collectively, this afferent information from the peripheral receptors is known as proprioception.[69,129] This proprioceptive feedback facilitates the efferent response and neuromuscular control of joints. The information stemming from these peripheral mechanoreceptors in the articular, cutaneous and muscle tissue join, increasing the activation of the γ-MN, and ultimately enhancing sensitivity of muscle spindles to length changes.[69,129,133,134] Enhanced muscle spindle sensitivity increases the excitability of the motor-neuron pool, which in turn increases the reflexive activation of a muscle.[129,134] This increased activation allows for added muscle stiffness around a joint, leading to further increased joint stiffness and stability, which play an essential part in maintaining dynamic joint stability.[69]

Balance relies on information stemming not only from proprioceptive cues, but vestibular and visual cues as well. These signals, along with cortical and cerebellar inputs are integrated at the level of the vestibular nuclei in the brainstem to optimize a motor response for balance maintenance.[135] The vestibular system plays an especially crucial role as it detects motion and orientation of the head in space.[136] Located within the inner ear, the vestibular apparatus encodes the orientation and motion of the head with respect to the external world, providing the CNS with important cues used in implementing standing balance. The CNS must be able to detect head movement in three-dimensional space with respect to whole body orientation. Multisensory integration of signals concerning head-on-feet posture is necessary to interpret and transform vestibular signals to allow appropriate whole-body postural responses. This transformation of vestibular signals allows for functions spanning the perception of self-motion and orientation reflexes that are relied upon for gaze and balance.[137-139] Further signal integration to enable appropriate full-body postural responses comes from the optokinetic, or visual system. The optokinetic system is a visual subsystem for motion detection based on optic flow. The brain uses eye movement signals to factor out the optic flow component related to self-motion, and can directly affect the perception of body motion, even in the absence of optic flow. While the vestibular and visual systems operate in different frequency domains, there is evidence that the brain integrates both of their information pathways when navigating through the environment.[136] The sensorimotor system encompasses all of the sensory, motor and central integration and processing components involved with maintaining postural stability during bodily movements.[129] It is important to understand the different systems in charge when investigating postural control in order to make appropriate conclusions and recommendations for improvement.

2.3.2 The Relationship Between the Sensorimotor System and Injury

Changes in neuromuscular activity is a primary source of kinematic changes and decreased dynamic joint stability during movement.[69] Decreases in proprioception and neuromuscular control can lead to altered sensation of joint movement, leading to motor control deficits and functional instability. This functional instability could further result in acute trauma or repetitive injury during sport.[17] Fatigue associated changes to neuromuscular control stem from decreased proprioception feedback, further impairing sensorimotor function and functional joint stability, inherently creating an environment more susceptible for injury to occur.[140]

Altered motor control has also been quantified during jumping and landing tasks to determine its effects on known risk factors for lower extremity injuries. Impairments in motor control and joint stability can be measured by postural stability, muscle activation patterns, and kinematic changes during dynamic movement.[69] Fatigue stimulated neuromuscular changes have been investigated through EMG to identify muscle activation patterns during functional tasks.[45,141] Knee injuries typically ensue at or near full joint extension during acceleration or deceleration motions with excessive quadriceps contraction and reduced hamstring co-contraction.[140,142]

Studies identifying different forms of sensorimotor deficits that contribute to ankle instability (FAI) have found significant differences between groups with stable and unstable ankles. These include balance[143] and strength deficits,[144] muscle response time to inversion perturbation,[145] motor neuron pool excitability[146] and time to stabilization after landing.[147] Contrasting findings when looking at ankle proprioception elicit the need for more research, mainly aiming to reproduce functional movement speeds, joint ranges of motion and muscle forces.[148-151]

2.4 FATIGUE

2.4.1 Mechanisms of Fatigue

Fatigue is commonly described as the decrease in physical performance associated with an increase in the real and/or perceived difficulty of a task or exercise.[152,153] More specifically during muscle exercise, fatigue is defined as the eventual incapacity to produce a required level of force.[152,154] Fatigue is a complex, multifactorial occurrence whose mechanisms are influenced by the characteristics of the task performed.[152] The degeneration potentially involves processes at all levels of the motor pathway from the brain to the skeletal muscle. By determining where the fatiguing mechanism is located, i.e. in the exercising muscle, or in the nervous system, the differentiation between central nervous system (CNS) and peripheral fatigue can be made.[155]

Central Fatigue

In general, central fatigue can be defined as a progressive, exercise-induced degradation of the muscle voluntary activation.[152] Going further, according to Davis and Bailey,[154] CNS fatigue can be defined as "a subset of fatigue associated with specific alterations in CNS function that cannot be reasonably explained by dysfunction within the muscle itself." Reduction of CNS drive to motor neurons can be described by two theories; a reduction in the corticospinal (descending) impulses reaching the motor neurons and/or an inhibition of motor neuron excitability by neutrally mediated afferent feedback from the muscle.[154] Accumulation or depletion of certain neurotransmitters such as serotonin during exercise has been highly investigated as a mediator of CNS fatigue. Serotonin is known to impact lethargy, sleepiness, and mood that may contribute to altered perceptions of effort and muscular fatigue. During prolonged exercise, serotonin levels increase in the brain, limiting central neural drive and motor unit recruitment.[156] Serotonin cannot cross the blood-brain barrier, which causes the brain's neurons to synthesize the compound from its precursor, tryptophan. In plasma, tryptophan competes with branched chain amino acids (BCAAs) for transport to the brain, and thus when the brain synthesizes serotonin during exercise, the plasma free tryptophan/BCAA ratio rises. Prolonged exercise causes BCAAs to be used by active muscles to produce energy, causing a fall of plasma BCAAs, which results in a greater level of free plasma tryptophan and an increased feeling of lethargy.[152] Central fatigue can be influenced by other neurotransmitter activity as well. A study conducted in human subjects utilizing transcranial magnetic stimulation assessed excitability from the motor cortex to the alpha-motor neuron. Results showed that the magnitude of motor responses in the muscle produced by the transcranial magnetic stimulation decreased after fatiguing exercise, which lead researchers to propose that reduced central drive likely involved the accumulation and depletion of neurotransmitters in the CNS pathways located upstream from the corticospinal neurons.[156]

At the spinal level, central fatigue may be caused by several mechanisms. The inhibitory afferents from intramuscular receptors may be involved in the loss of motor neuron activity.[152] Bigland-Ritchie et al.[157] have shown that firing rates of motor neurons can be regulated by peripheral reflexes in response to fatigue-induced metabolic variations within active muscles. Group III and IV muscle afferents or metaboreceptors may be sensitive to muscle byproducts that accumulate during fatigue such as potassium and lactate.[152,157] They later proposed that this ultimately influences muscle spindle sensitivity and the limitation of alpha-motor neurons activity, leading to a decrease in muscle force production to allow for the safest and most economical pattern of muscle activation.[157]

Peripheral Fatigue

Neuromuscular fatigue also manifests through the peripheral nervous system in which the neural activation of muscles is reduced due to a limited response of the muscle to a stimulus. Factors involved in peripheral fatigue include alterations in neuromuscular transmission, muscle action potential propagation, excitation-contraction coupling and other related contractile mechanisms.[152] Amongst the many metabolic changes linked to prolonged muscle contraction, an increased concentration of hydrogen ions and inorganic phosphate appears to negatively influence the myofibril’s force generation capacity during fatigue.[152,158] Hydrogen ions accrue as a result of the hydrolysis of adenosine triphosphate (ATP) and the production of lactic acid during exercise, and are associated with a decrease in intracellular pH. This reduction in pH disturbs other chemical reactions needed for ideal neuromuscular contraction.[152,159] Reduced force generation can also potentially be explained by inorganic phosphate accumulation. Buildup could negatively influence force generation by decreasing the myofibrils' sensitivity to calcium (Ca^{2+}), thus acting directly on the cross-bridges contraction-relaxation cycles.[152,160,161] When muscle work is sustained, the resulting decline in force generation may be related to the reduced quantity of Ca^{2+} released by the sarcoplasmic reticulum. Ca^{2+} is released during exercise by the sarcoplasmic reticulum so it can bind to troponin and enable muscle contraction. Varied levels of inorganic phosphate and ATP seen after fatigue may be responsible for this impaired release of Ca^{2+}.[152,162] Lastly, the limitation of blood supply during prolonged exercise will decrease the oxygen delivery and promote activity of anaerobic metabolic pathways, thus allowing for rapid accumulation of inorganic phosphate, hydrogen ions and other metabolites associated with muscle contraction.[152]

Both central and peripheral fatigue have been hypothesized to occur within the active muscles due to insufficient energy supply. Irregular levels of ATP can influence afferent feedback to the CNS, limiting central inhibition to exercising muscles.[154] A buildup of ATP synthesis byproducts can also interfere with cross-bridge cycling and energy production, resulting in inhibition of muscle contraction.[163] More directly, carbohydrates and muscle glycogen are the primary fuel source for sustained high intensity exercise.[164] Carbohydrate oxidation allows for high rates of ATP production,[165] and as muscle fuel sources become exhausted, exercise intensity can no longer be sustained.[164] Neuromuscular fatigue occurs as a result of many different processes. It is important to understand these processes to offset the negative effects of prolonged exercise, and to delay fatigue to improve performance and prevent injury.

2.4.2 Fatigue and the Sensorimotor System

The central nervous system interprets joint signals at both the conscious and unconscious levels of motor control. Unconscious joint stabilization is achieved, in part, by collecting and processing information gained from the afferent system. The ability of the somatosensory system to detect forces imparted on articular structures and mediate protective muscle responses is especially important in providing for joint stabilization.[46] The onset of fatigue may negatively influence components of the sensorimotor system, including diminished proprioception at the muscle and central nervous system level. Fatigue induced impairments in neuromuscular control may adversely after joint proprioception, and are thought to be a potential cause for increased injury rates during later stages of games and competitions. Fatigue has been related to diminished knee proprioception and increased joint laxity when compared to baseline values, putting an individual at an increased risk for unintentional injury.[13] Rozzi et al.[45] studied knee joint laxity, joint proprioception, balance, peak torque and muscle activity patterns in male and female soccer and basketball players after fatigue in attempt to identify potential risk factors for ACL injury. Female athletes demonstrate higher incidence of knee injuries when compared to their male counterparts, leading researchers to believe that knee joint stability and other factors may vary between gender. After testing, they discovered that women demonstrated higher values of knee joint laxity, and took greater time to detect passive knee extension; therefore, demonstrating poorer proprioception. Authors stated that motor reflex inadequacies caused by proprioceptive deficits and joint laxity may render a joint unable to sense and respond to joint stress, potentially resulting in unintentional injury. Joint-stabilizing muscle activity is influenced by proprioceptive, kinesthetic, visual, and vestibular system information as well as by cortical and spinal-nerve motor commands.[45] In a more recent study, researchers found that fatigue caused delayed knee muscle activation during perturbation when testing for postural control of the knee after a fatiguing protocol in recreationally active males. The onset of muscle activation after fatigue was significantly delayed for both knee extensors and flexors (both $p<0.05$) in comparison to baseline activation values.[13] At the central level, fatigue may induce a failure of excitation of the motor neurons caused by changes in the nervous system, resulting in an inability to maintain desired force output to help maintain posture. Regardless of origin, fatigue can reduce kinesthetic awareness and impair motor control,[166] leading to an increased risk of unintentional musculoskeletal injury.

2.4.3 Fatigue and Injury Risk

Numerous studies examining risk factors for unintentional musculoskeletal injuries have identified that fatigue may contribute to injury during training and competition. Research identifying the link between fatigue and neuromuscular injury has been done primarily within civilian athletic populations. Fatigue is an extrinsic risk factor affecting the musculoskeletal and neurologic systems[44] and is an inevitable part of high intensity activity.[13] Fatigue has been connected to decreased muscular work capacity, decreased joint proprioception, increased joint laxity, poor biomechanics and kinematics, all of which have been linked to unintentional musculoskeletal injury.

Muscle fatigue is associated with reduced power output and work capacity of the skeletal muscle.[41] Failure to produce maximal force is the consequence of peripheral fatigue resulting in failure at the neuromuscular junction and beyond, and central fatigue resulting from a failure to activate the muscle voluntarily.[166] A study conducted by Hassanlouei et al.[13] looked at the relationship between exercise induced fatigue, strength and postural control of the knee. Nine recreationally active males performed tests of postural sway after completing high intensity exercise on a bicycle ergometer. Muscle activity of the knee extensor and flexor muscles were recorded via surface electromyographic signals during postural sway testing as well. Researchers found that immediately after exercise, the maximal force of knee extensor muscles decreased by 63% and knee flexor muscles decreased by 66% ($p<0.0001$). The authors stated that their findings indicated that muscle fatigue induces a reduction and delay in the activation of both the hamstring and quadriceps muscles in response to rapid destabilizing computer based perturbations, potentially leaving the knee vulnerable to strain and injury.[13] Previously, metabolic accumulation and substrate utilization have been considered as the origin of the loss in force output following fatigue. In particular, changes in the glycolytic and creatine phosphate pathways have been described as the cause of fatigue in an intermittent sprint model.[167] However, studies have shown that the decrements in force are not closely correlated with these metabolic imbalances, suggesting that other factors such as neural control mechanisms, are more important determinants.[168]

Chappell et al.[44] researched risk factors for non-contact injuries in attempt to provide biomechanical evidence that fatigue may be a risk factor for non-contact ACL injuries. Dynamic knee motion analysis and force production were measured in male and female recreational athletes during stop-jump tasks after completion of a fatiguing exercise. The fatigue protocol used for this study was designed to induce volitional exhaustion with general aerobic fatigue from sprints and localized lower extremity muscle fatigue with repetitive squat jumps. Results showed that both male and female subjects had significantly higher peak proximal tibial anterior shear forces ($p=0.01$), increased knee valgus moments ($p=0.03$) and decreased knee flexion angles ($p=0.03$) during fatigued landings. Fatigue was shown to cause altered motor control strategies during stop-jump landings, therefore putting an individual at greater risk of anterior tibial translation and unintentional ACL injury. When fatigued, muscle fibers have a decreased capacity to absorb energy, causing altered neuromuscular function, and in turn increasing the likelihood of injury.[44]

2.5 METHODOLICAL CONSIDERATIONS

This section will address the rationale behind the methods selected for testing. More extensive details regarding the procedures will be further detailed in Chapter 3.

2.5.1 NeuroCom Sensory Organization Test

Postural stability is the process of coordinating corrective movement strategies to remain in postural equilibrium.[70] Decreased postural stability has been identified as a risk factor for lower extremity injury in athletic populations.[38,54,58,59] The NeuroCom Sensory Organization Test (SOT) is designed to systematically disrupt the sensory selection process by altering available somatosensory or visual information or both while measuring a subject's ability to minimize postural sway.[79] The NeuroCom SOT was utilized for this study due to its ability to isolate individual sensory input systems. Reliability and validity for the NeuroCom SOT have not been identified for healthy, physically active or military populations due to its popularity among geriatric populations and other populations with increased risk of equilibrium deficits and falls. However, within these populations test-retest reliability has been demonstrated to be fair to good, with ICC values of 0.67 for the composite score and 0.35-0.79 for individual conditions.[169]

A variety of variables can be collected while using the NeuroCom SOT assessment. Selection of SDvGRF and TotSway for utilization in this study was because of their ability to display excursion data in a multitude of directions. SDvGRF was used to quantify vertical body oscillations[170] and is the standard deviation of the forces exerted on the subject by the support surface. TotSway indicates the horizontal amplitude of movement and is calculated by using center of pressure movement in the x and y directions.[170] Generally, the greater these values are, the poorer postural stability performance.

2.5.2 Fatigue Protocol

Fatigue has been shown to increase injury risk in athletic populations.[13,19,44,46-48] Understanding the onset of fatigue and its associated implications during exercise and activities is important for performance enhancement and injury prevention. A variety of different fatigue protocols have been utilized in previous literature within athletic and military populations.

Administrative (non-tactical) military tasks are typically undertaken at a moderate pace (i.e. 3.0-6.0 km/hour) while tactical military tasks may involve movement at various speeds from slow walking to sprinting all the while carrying an external load.[2] Previous literature has examined constant march paces, increasing march paces until volitional fatigue, and increasing load carriage weight. The 4mph speed was chosen as it is the speed required to pass foot march test (a 12-mile foot march within three hours) for the expert infantryman badge and expert field medical badge test.

3.0 METHODOLOGY

3.1 RESEARCH DESIGN

This study utilized a quasi-experimental, pre-test/post-test, within-subject design. Subjects performed both rested and fatigued loaded postural stability testing to act as their own control. The purpose of this study was to determine if loaded postural stability is altered following a loaded fatigue protocol. Sex-related differences were examined to establish if loaded postural stability in a fatigued state is influenced differently between males and females. Independent variables included sex and fatigue. Dependent variables under investigation included loaded SOT composite scores, visual, vestibular and somatosensory scores, and vertical ground reaction force and total sway raw force plate data.

3.2 PARTICIPANTS

Subjects for this study included 23 males and females aged 20-33. A physically active population was selected based on the specific aims of this study. Eligibility was determined by the following inclusion and exclusion criteria:

3.2.1 Inclusion Criteria

- Males and females between the ages of 18-35 years, inclusive
- Physically active- defined as currently participating in physical activity a minimum of four times per week, for at least 45 minutes per session including some high intensity activity (defined as Level I or II on the Noyes Sports-Activities Rating Scale[171]).

3.2.2 Exclusion Criteria

- History of any musculoskeletal injury (any impairment which causes restriction of activities of daily living for one week or required medical attention) to the lower body or lumbar spine six months prior to day one testing
- History of surgery or fracture of lower extremity one year prior to day one testing
- Any balance or vestibular disorder
- History of head injury or concussion within six months prior to day one testing
- Any history of pulmonary, cardiovascular or vascular condition contraindicated to vigorous exercise
- Taking medication known to effect balance or equilibrium
- Pregnancy in female subjects (validated via history and date of last menses)

3.3 SAMPLE SIZE CALCULATION

Sample size was estimated by using the G*power 3.1.7 (Heinrich Heine Universitat, Disseldorf, Germany) calculator to examine the difference between two dependent means. To attain a moderate correlation of 0.6, a total of 19 subjects were required to achieve a power of at least 80%. To account for 15% attrition, four individuals were added, bringing the subject total to 23.

3.4 INSTRUMENTATION

3.4.1 Anthropometric Measurements

Height was measured using a wall stadiometer (Seca North America, East Hanover, MD). Mass was measured using a weight scale (BOD POD Version 5.2.0, COSMED USA Inc., Chicago, IL).

3.4.2 Heart Rate Monitor

Heart rate (beats per minute) was collected via Polar heart rate monitor strap (Polar USA, Lake Success, NY). Heart rate was recorded immediately before and after completion of the fatigue protocol to ensure subjects are exercising at intensities appropriate to study design.

3.4.3 Treadmill

A treadmill (Woodway USA Inc., Waukesha, WI) was used during the fatigue protocol with varied grades and speeds.

3.4.4 Rating of Perceived Exertion

The OMNI scale for Rating of Perceived Exertion (RPE) was utilized to monitor the subject's perceived effort during the fatigue protocol. The OMNI scale quantifies perceived effort on a 0-10 scale using a chart with 0 corresponding to "extremely easy" and 10 corresponding to "extremely hard." The OMNI scale has previously been found to be a valid and reliable method of measuring effort in exercising adults.[172]

3.4.5 Blood Lactate

Blood lactate levels were measured using a Lactate Pro 2 (ARKAY Inc, Japan) test meter and strips before and after completion of the fatigue protocol. Blood lactate levels were measured as a physiological check to monitor that subjects were exercising at appropriate intensities. Measurements were taken immediately before and after the fatigue protocol. Lactate levels were measured from a small drop of blood obtained from a finger stick. This level of technology has been proven reliable and valid in exercising subjects.[173]

3.4.6 NeuroCom Sensory Organization Test

A NeuroCom Equitest System (NeuroCom International, Inc, Clackamas, OR) was used to measure the SOT. The NeuroCom Equitest is a computerized dynamic posturography tool which measures vertical ground reaction forces produced by the body's center of gravity moving around a fixed base of support.[79] It utilizes two parallel force plates which contain anterior and posterior force transducers, resulting in a total of four force transducers. The SOT is designed to systematically disrupt the sensory selection process by altering available somatosensory or visual information or both while measuring a subject's ability to minimize postural sway.[79] Previous research has found good reliability for the NeuroCom SOT. Dickin[174,175] demonstrated moderate to good test-retest reliability when tested on a single day, as well as on separate days in young adults and athletes.[174,175] A secondary study found fair to good test-retest reliability for the composite score (ICC=0.67) and the equilibrium score for each condition (ICC= 0.35-0.79).[169] Lastly, Teel et al.[176] more recently reported ICC reliability measures for SOT condition one (0.611), three (0.345), four (0.845), and six (0.514).[176] The sampling frequency of the NeuroCom SOT was 200Hz.

3.5 TESTING PROCEDURES

All procedures were conducted at the Neuromuscular Research Laboratory (NMRL) within the Department of Sports Medicine and Nutrition at the University of Pittsburgh. Testing procedures were done within one day of testing lasting approximately 90-120 minutes. During the visit to the lab, inclusion and exclusion criteria were reviewed with subjects to determine eligibility for the study. All subjects signed an informed consent to participate form, approved by the University of Pittsburgh Internal Review Board prior to participation of the study. Demographic information, anthropometric measurements were recorded and a familiarization loaded NeuroCom SOT was performed. After a 15-minute unloaded rest period, subjects completed the baseline loaded NeuroCom SOT followed by the incremental loaded fatigue protocol, and finished by a post-fatigue loaded NeuroCom SOT. Subjects were asked to refrain from exercise 24 hours prior to testing to control for any confounding factors.

3.5.1 Testing Schedule

- Informed consent
- Anthropometrics
- Familiarization loaded NeuroCom SOT
- 15-minute unloaded rest period
- Baseline loaded NeuroCom SOT
- Loaded fatigue protocol
- Post-fatigue loaded NeuroCom SOT

3.5.1.1 Informed Consent

Subjects were given the informed consent document prior to engaging in any research activities. The principal investigator explained the contents of the consent and allowed the subject to ask any questions regarding the study. Once subject gave informed consent, inclusion/exclusion criteria were reconfirmed prior to study enrollment.

3.5.1.2 Loaded NeuroCom Sensory Organization Test

For postural stability testing, the NeuroCom Equitest was powered on and the Sensory Organization Test was selected. Demographic data such as height and date of birth, and subject ID were used to input each subject into the system before testing. Subjects stepped barefoot onto the platform with one foot on each force plate facing the screen. Foot location was placed according to the methods described by Natus Balance and Mobility[177] The medial malleolus of each ankle was positioned in line with the bold horizontal marking on the two force platforms. The midline of the calcaneus of both feet were then lined up with a vertical line previously determined based on height by the software package. Rear foot position was then held stationary by the examiner while the subject adjusted their forefeet if desired.

The test protocol consisted of six conditions, with three trials apiece. Trials lasted for approximately 20 seconds in which subjects were asked to stand as motionless as possible with their feet in the previously specified positions. Three different visual conditions (eyes open, eyes closed, sway-referenced visual surround) were crossed with two different surface conditions (fixed, sway referenced). The first test consisted of the subject balancing on a fixed surface with their eyes open, testing the somatosensory system. The second test also tested the somatosensory system on a fixed surface, however eyes were closed, leading to a visual disadvantage. The third condition tested the somatosensory system while the participant balanced on a fixed surface with a sway reference. The sway reference involves the tilting of the support surface or visual surround (or both), and is based on the individual. When the subject sways forward on the force plate, the surround tilts forward.[79] The fourth condition required the subject to stand with eyes open while the platform sways, testing the visual system. Similar to the reference, the force platform tilts to follow the subject's anterior-posterior (AP) sway. The last two circumstances tested the vestibular system. The fifth condition required eyes closed on a swaying platform, and the sixth condition required eyes open, with both reference and platform sway. The six testing conditions can be found in the visual representation in Figure 1. Between trials subjects were permitted to relax, but were asked to maintain foot positioning. Measurements of loaded SOT were completed pre- and post-loaded fatigue. Post-fatigue measurements started within five minutes of loaded fatigue protocol completion. Subjects wore clothing of their choice, a loaded vest measuring 30% of subject's body weight, and a Polar heart rate monitor during pre- and post-fatigue SOT measurements.

The SOT can assess the subject's ability to ignore inaccurate information from the sway-referenced senses. A composite equilibrium score is a weighted average of the equilibrium scores from all 18 trials and describes the individual's overall level of performance, with higher scores indicating better stability performance. Scores range from 0 to 100, with a score of 0 indicating a fall, and a 100 indicating absolutely no movement during the test. NeuroCom SOT also includes sensory analysis of the three individual components of the sensorimotor system, center of gravity alignment and normative ranges. The composite equilibrium score, visual, vestibular and somatosensory individual scores, and SDvGRF and TotSway raw data were used for analysis in this study.

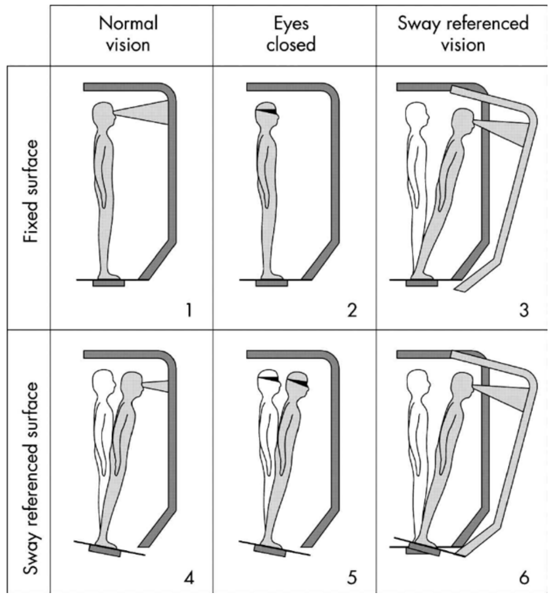

Figure 1: Testing Conditions of the NeuroCom Sensory Organization Test

3.5.1.3 Loaded Fatigue Protocol

A modified Astrand protocol[99] was used to implement fatigue in all subjects. While wearing a Polar heart rate monitor, loaded vest of 30% of their body weight, clothing and footwear of their choice, subjects were required to perform an incremental treadmill protocol to volitional fatigue. After proper explanation, each subject was instructed to complete a three-minute warm up on a Woodway treadmill at a speed of 2 mph and 0% grade. As soon as the warm-up period was completed, the speed was increased to 4mph (grade of 0%). Speed remained constant through the entirety of the test, and incline was increased by 2% every three minutes. Subjects were instructed to walk (or march) instead of running throughout the entirety of the test. Subjects continued the protocol until volitional termination due to fatigue. During the test, subjects were verbally encouraged to continue to exercise until exhausted. Blood lactate, OMNI RPE and heart rate were measured both before and after the fatigue protocol. A maximal effort was verified by at least one of the two physiological criteria: maximum heart rate within 10 bpm of age-predicted heart rate maximum achieved during the test, or blood lactate concentrations greater than or equal to 8 mmol/L, and by the perceptual criteria of the OMNI scale RPE. Within five minutes of fatigue protocol completion, subjects performed the loaded post-fatigue loaded NeuroCom SOT.

3.6 DATA REDUCTION

The composite and equilibrium scores were exported from the NeuroCom as .sum files and saved onto the lab network drive. The .sum files were then uploaded into Excel and saved into a file containing the component and composite scores for each subject. Data was then imported into SPSS for analysis.

Raw force plate data from the NeuroCom Balance Master was exported as a .txt file with left forefoot (lbs), left rearfoot (lbs), right forefoot (lbs), right rearfoot (lbs), shear (lbs), center of force in the x and y planes (in) and center of gravity in the x and y planes (in) variables with 2000 data points per variable, per condition trial. There were three trials for each of the six conditions. Files were checked to ensure that all data points were present for each subject. Data was discarded if data points were missing. The .txt files were processed with a custom MatLab script to create an Excel output file with standard deviation of the vertical ground reaction force (SDvGRF) and total sway (TotSway) for each condition. The equations for the raw data outcome variables can be reviewed in Table 2 below. The output data for all six conditions was then imported into SPSS for analysis.

Table 2: NeuroCom SOT Raw Force Plate Outcome Variable Formulas

Variable	Formula
SDvGRF	$SD\ \Sigma\ GRF_z$
TotSway	$\Sigma\ [\sqrt{(COPx_2\text{-}COPx_1)^2 + (COPy_2\text{-}COPy_1)^2}] / 1000$

3.7 DATA ANALYSIS

All procedures were done in IBM SPSS Statistics 21 (IBM Corporation, Armonk, NY). Descriptive statistics were calculated for all variables. Data were tested for normality by using the Shapiro-Wilk test. If the data were not normally distributed, appropriate nonparametric tests were performed. If assumptions of normality were met, paired t-tests were done to measure pre- to post-fatigue SOT scores for composite SOT, and individual component (vestibular, visual and somatosensory) scores, SDvGRF and TotSway scores. Independent sample t-tests were calculated between the mean values of loaded SOT score changes in males and females to describe any differences seen when stratifying for sex. Statistical significance was set at $\alpha=0.05$ *a-priori*.

4.0 RESULTS

The purpose of this study was to investigate the effect of loaded fatigue on loaded postural stability as measured by the NeuroCom Sensory Organization Test clinical outcome measures and kinetic force plate data.

4.1 SUBJECTS

4.1.1 Demographic Data

A total of 23 subjects expressed interested in study participation and met all criteria outlined in the initial screening process. Twenty-three subjects enrolled in the study and completed all data collection procedures. Power analysis for the significant correlations revealed that 19 subjects were needed to complete data collection, and a total of 23 subjects meeting all criteria participated in all study activities. Due to loss of data from the force plate during post-fatigue SOT testing of one subject, data from 22 subjects was used for kinetic data analysis in this study.

Subject demographics are presented in Table 3. The age range of study participants was 20-33 years of age. Of the 23 participants, there were 12 males and 11 female subjects.

Table 3: Subject Demographic Data

	N	Mean ± SD	Median	IQR
Age	23	24.1 ± 4.0	23.0	21.0, 27.0
Height (cm)	23	172.3 ± 11.1	171.8	161.2, 182.5
Weight (lbs)	23	162.2 ± 38.2	158.4	127.6, 192.6

N = Number of subjects
SD = Standard deviation
IQR = Interquartile range (first quartile, third quartile)

4.1.2 Loaded Fatigue Protocol

Results of the fatigue protocol are displayed in Table 4. Fatigue was quantified by perceptual and physiological assessments following termination of the march. As a group, subjects reached near maximal perceived exertion, reached above maximal criteria for blood lactate (>8.0 mmol) and reached within 10 bpm of age predicted heart rate max.

Table 4: Physiological Fatigue Data

	N	Mean ± SD	Median	IQR
HR (bpm)	23	184.04 ± 9.5	184.0	174.0, 189.5
RPE	23	8.74 ± 1.0	9.0	8.0, 9.3
Lactate (mmol)	23	10.06 ± 3.9	10.0	6.7, 13.0

N = Number of subjects
SD = Standard deviation
IQR = Interquartile range (first quartile, third quartile)
HR = Heart rate
RPE = OMNI Rating of Perceived Exertion
Lactate = Blood lactate

4.2 NEUROCOM SENSORY ORGANIZATION TEST

4.2.1 NeuroCom SOT Clinical Outcome Scores

Descriptive statistics for the SOT component and composite scores are presented in Table 5. Scores are based on the AP sway in relation to the LOS as discussed in the methodology of this study. Significant decrements were observed in COMP scores from baseline to post-fatigue after a loaded incremental march to fatigue.

Table 5: Descriptive Statistics for Baseline to Post-Fatigue Differences in Sensory Organization Test Output Data

	BASELINE				POST-FATIGUE				
	N	**Mean ± SD**	**Median**	**IQR**	**N**	**Mean ± SD**	**Median**	**IQR**	**Group Comparison p-value**
VEST	23	76.1 ± 9.3	76.9	71.3, 83.0	23	76.9 ± 7.8	79.1	69.3, 82.5	0.075*
VIS	23	93.2 ± 5.9	95.1	91.4, 97.5	23	92.3 ± 5.8	94.1	89.2, 97.5	0.056*
SOM	23	97.4 ± 2.2	96.8	95.9, 99.6	23	96.6 ± 2.2	96.8	95.4, 97.9	0.142
COMP	23	82.8 ± 4.7	83.0	80.0, 87.0	23	81.6 ± 5.2	82.0	78.0, 85.0	0.010^{+}

VEST = Vestibular component score
VIS = Visual component score
SOM = Somatosensory component score
COMP = Composite score
N = Number of subjects
SD = Standard deviation
IQR = Interquartile range (first quartile, third quartile)
* denotes the use of a non-parametric test
$^{+}$ denotes statistical significance

4.2.2 NeuroCom SOT Raw Force Plate Data

Raw force plate results for the SOT are presented in Tables 6 and 7 below. The standard deviation of the vertical ground reaction force and the total sway were calculated for each condition of the SOT. Several variables did not meet assumptions of normality, including TotSway of SOT condition 2, TotSway of SOT condition 4 and TotSway of SOT condition 6. Significant increases in SDvGRF were found in conditions 1-3 indicating somatosensory changes, and condition 6 relating to changes in the vestibular system. Significant increases in TotSway were also found in all conditions.

Table 6: Descriptive Statistics for Baseline to Post-Fatigue Differences in Raw Force Plate Data (Standard Deviation of the Vertical Ground Reaction Force) During the Sensory Organization Test

	BASELINE SDvGRF				POST-FATIGUE SDvGRF				
	N	**Mean ± SD**	**Median**	**IQR**	**N**	**Mean ± SD**	**Median**	**IQR**	**Group Comparison p-value**
C1	22	1.3 ± 0.5	1.2	1.0, 1.5	22	2.0 ± 1.0	1.9	1.3, 2.4	<0.001+
C2	22	1.4 ± 0.6	1.2	1.0, 1.5	22	1.9 ± 1.2	1.7	1.3, 2.4	<0.001+
C3	22	1.4 ± 0.5	1.2	1.0, 1.5	22	2.1 ± 1.8	1.7	1.3, 2.1	0.026+
C4	22	1.7 ± 1.2	1.4	1.0, 1.8	22	2.3 ± 2.2	1.9	1.3, 2.2	0.123
C5	22	2.4 ± 1.4	1.9	1.5, 2.6	22	3.6 ± 3.9	2.6	1.9, 3.8	0.060
C6	22	2.5 ± 2.2	1.9	1.5, 2.6	22	3.5 ± 3.2	2.1	1.9, 4.3	<0.001+

SDvGRF = Standard Deviation of the Vertical Ground Reaction Force
N = Number of subjects
IQR = Interquartile range (first quartile, third quartile)
C1 = Condition 1 (eyes open, no sway)
C2 = Condition 2 (eyes closed, no sway)
C3 = Condition 3 (eyes open, sway surround)
C4 = Condition 4 (eyes open, sway support)
C5 = Condition 5 (eyes closed, sway support)
C6 = Condition 6 (eyes open, sway surround, sway support)
+ denotes statistical significance

Table 7: Descriptive Statistics for Baseline to Post-Fatigue Differences in Raw Force Plate Data (Total Sway) During the Sensory Organization Test

	BASELINE TotSway				**POST-FATIGUE TotSway**				
	N	**Mean ± SD**	**Median**	**IQR**	**N**	**Mean ± SD**	**Median**	**IQR**	**Group Comparison p-value**
C1	22	0.0153 ± 0.0019	0.0154	0.0139, 0.0168	22	0.0180 ± 0.0035	0.0173	0.0157, 0.0194	<0.001⁺
C2	22	0.0195 ± 0.0046	0.0186	0.0165, 0.0212	22	0.0219 ± 0.0062	0.0202	0.0181, 0.0245	<0.001*⁺
C3	22	0.0180 ± 0.0039	0.0174	0.0150, 0.0192	22	0.0216 ± 0.0069	0.0200	0.0177, 0.0217	0.001⁺
C4	22	0.0211 ± 0.0047	0.0199	0.0174, 0.0235	22	0.0239 ± 0.0065	0.0215	0.0200, 0.0261	0.002*⁺
C5	22	0.0392 ± 0.0102	0.0350	0.0328, 0.0447	22	0.0457 ± 0.0162	0.0423	0.0344, 0.0523	0.013⁺
C6	22	0.0346 ± 0.0099	0.0336	0.0259, 0.0385	22	0.0394 ± 0.0114	0.0376	0.0296, 0.0471	<0.001*⁺

TotSway = Total Sway
N = Number of subjects
SD = Standard deviation
IQR = Interquartile range (first quartile, third quartile)
C1 = Condition 1 (eyes open, no sway)
C2 = Condition 2 (eyes closed, no sway)
C3 = Condition 3 (eyes open, sway surround)
C4 = Condition 4 (eyes open, sway support)
C5 = Condition 5 (eyes closed, sway support)
C6 = Condition 6 (eyes open, sway surround, sway support)
* denotes the use of a non-parametric test
⁺ denotes statistical significance

4.2.3 NeuroCom SOT Differences Between Sex

Sex-related differences in baseline to post-fatigue clinical outcome scores and kinetic force plate data were examined to assess if loaded postural stability influenced males and females to a different extent. Descriptive statistics for the baseline to post-fatigue differences in SOT component and composite scores are presented in Table 8, as well as differences in raw force plate data results (SDvGRF in Table 9 and TotSway in Table 10). Results were stratified for sex to determine any differences in postural stability changes between males and females. All variables violated assumptions of normality with exception of SDvGRF of SOT condition 2 and SDvGRF of SOT condition 3. Within group comparisons were calculated using the Mann-Whitney test for all values with exception of SDvGRF of SOT condition 2 and SDvGRF of SOT condition 3. Significant differences were found in SDvGRF of conditions 1 and 5, as well as TotSway of conditions 2 and 3. Baseline to post-fatigue changes in SDvGRF were greater in males than females in both conditions 1 and 5. Baseline to post-fatigue changes in TotSway of component scores 2 and 3 were significantly different between males and females, with males displaying greater changes in loaded postural stability following fatigue.

Table 8: Descriptive Statistics for Baseline to Post-Fatigue Changes in Clinical Outcome Scores in Males and Females During the Sensory Organization Test

	FEMALES				MALES				
	N	**Mean ± SD**	**Median**	**IQR**	**N**	**Mean ± SD**	**Median**	**IQR**	**Group Comparison p-value**
VEST	11	2.9 ± 9.9	1.1	-3.0, 4.01	12	-1.1 ± 5.0	-1.6	-5.8, 2.1	0.413
VIS	11	-0.4 ± 6.2	-0.7	-4.4, 0.1	12	-1.4 ± 2.9	-1.1	-3.7, 0.1	0.928
SOM	11	-0.3 ± 2.9	0.1	-1.4, 1.3	12	-1.2 ± 2.0	-1.5	-3.1, 1.1	0.316
COMP	11	-0.8 ± 2.2	-1.0	-3.0, 1.0	12	-1.5 ± 1.8	-1.5	-3.0, 0.0	0.468

N = Number of subjects
SD = Standard deviation
IQR = Interquartile range
VEST = Vestibular component score
VIS = Visual component score
SOM = Somatosensory component score
COMP = Composite score
* denotes the use of independent sample t-test
$^{+}$ denotes statistical significance

Table 9: Descriptive Statistics for Baseline to Post-Fatigue Changes in the Standard Deviation of the Vertical Ground Reaction Forces (SDvGRF) in Males and Females During the Sensory Organization Test

	FEMALES				MALES				
	N	**Mean ± SD**	**Median**	**IQR**	**N**	**Mean ± SD**	**Median**	**IQR**	**Group Comparison p-value**
SDvGRF_C1	10	0.5 ± 0.3	0.4	0.2, 0.6	12	1.0 ± 0.7	0.9	0.7, 1.2	0.003⁺
SDvGRF_C2	10	0.3 ± 0.2	0.3	0.2, 0.4	12	0.7 ± 0.9	0.5	0.4, 0.9	0.168*
SDvGRF_C3	10	0.3 ± 0.2	0.2	0.2, 0.23	12	1.1 ± 1.8	0.5	0.4, 0.8	0.178*
SDvGRF_C4	10	0.3 ± 0.2	0.3	0.2, 0.5	12	0.9 ± 2.5	0.6	0.3, 1.0	0.093
SDvGRF_C5	10	0.4 ± 0.3	0.3	0.1, 0.6	12	1.9 ± 3.8	0.8	0.4, 1.6	0.036⁺
SDvGRF_C6	10	0.4 ± 0.3	0.4	0.2, 0.6	12	1.4 ± 1.4	1.2	0.3, 2.2	0.059

N = Number of subjects
SD = Standard deviation
IQR = Interquartile range
SDvGRF_C1 = Standard Deviation of the Vertical Ground Reaction Force in condition 1 (eyes open, no sway)
SDvGRF_C2 = Standard Deviation of the Vertical Ground Reaction Force in condition 2 (eyes closed, no sway)
SDvGRF_C3 = Standard Deviation of the Vertical Ground Reaction Force in condition 3 (eyes open, sway surround)
SDvGRF_C4 = Standard Deviation of the Vertical Ground Reaction Force in condition 4 (eyes open, sway support)
SDvGRF_C5 = Standard Deviation of the Vertical Ground Reaction Force in condition 5 (eyes closed, sway support)
SDvGRF_C6 = Standard Deviation of the Vertical Ground Reaction Force in condition 6 (eyes open, sway surround, sway support
* denotes the use of independent sample t-test
⁺ denotes statistical significance

Table 10: Descriptive Statistics for Baseline to Post-Fatigue Changes in Total Sway (TotSway) in Males and Females During the Sensory Organization Test

	FEMALES				MALES				
	N	**Mean ± SD**	**Median**	**IQR**	**N**	**Mean ± SD**	**Median**	**IQR**	**Group Comparison p-value**
TotSway_C1	10	0.0022 ± 0.0018	0.0020	0.0007, 0.0032	12	0.0033 ± 0.0029	0.0028	0.0011, 0.0048	0.381
TotSway_C2	10	0.0010 ± 0.0020	0.0003	-0.0003, 0.0026	12	0.0039 ± 0.0031	0.0030	0.0015, 0.0064	0.014^{+}
TotSway_C3	10	0.0013 ± 0.0017	0.0013	-0.0003, 0.0025	12	0.0054 ± 0.0047	0.0041	0.0031, 0.0059	0.002^{+}
TotSway_C4	10	0.0013 ± 0.0027	0.0009	-0.0009, 0.0032	12	0.0039 ± 0.0038	0.0042	0.0013, 0.052	0.180
TotSway_C5	10	0.0022 ± 0.0051	0.0009	-0.0013, 0.0049	12	0.099 ± 0.0135	0.0086	0.0001, 0.0144	0.140
TotSway_C6	10	0.0039 ± 0.0051	0.0037	-0.0001, 0.0051	12	0.0056 ± 0.0062	0.0043	0.0015, 0.0109	0.539

N = Number of subjects
SD = Standard deviation
IQR = Interquartile range
TotSway_C1 = Total Sway in condition 1 (eyes open, no sway)
TotSway_C2 = Total Sway in condition 2 (eyes closed, no sway)
TotSway_C3 = Total Sway in condition 3 (eyes open, sway surround)
TotSway_C4 = Total Sway in condition 4 (eyes open, sway support)
TotSway_C5 = Total Sway in condition 5 (eyes closed, sway support)
TotSway_C6 = Total Sway in condition 6 (eyes open, sway surround, sway support)
* denotes the use of independent sample t-test
$^{+}$ denotes statistical significance

5.0 DISCUSSION

The purpose of this study was to investigate the effects of an incremental loaded march to fatigue on loaded postural stability measured by the NeuroCom Sensory Organization Test. Physically active, healthy males and females participated in two assessments of postural stability using the SOT in a single testing session. Means were compared to assess any baseline to post-fatigue differences in SOT component and composite clinical outcome scores as well as raw force plate kinetic data. Change in SOT component and composite clinical outcome scores, and raw force plate kinetic data differences were analyzed to describe any between sex differences of the SOT.

It was hypothesized that a loaded fatigue protocol would lead to lower loaded NeuroCom SOT scores (COMP). It was also hypothesized that there would be no significant differences between baseline and post-fatigue scores for loaded NeuroCom SOT component scores (VEST, VIS, SOM) or raw force plate data (SDvGRF and TotSway) after loaded fatigue. Lastly, it was hypothesized that males will display greater changes in loaded postural stability post-loaded fatigue when comparing outcomes between sex. Our hypothesis concerning overall SOT scores was accepted, as there were significant decrements in COMP scores from baseline to post-fatigue. Our hypothesis concerning component scores was accepted, as there were no significant differences found from baseline to post-fatigue in individual sensorimotor system components. Our hypothesis was partially accepted concerning raw force plate data (SDvGRF and TotSway) following loaded fatigue. Significant increases in SDvGRF values were found in SOT conditions 1-3, and TotSway significantly increased within all SOT conditions (1-6) following loaded fatigue. The last aim was partially accepted, as there were only four of 18 variables presenting that males had greater baseline to post-fatigue changes in postural stability compared to females.. Conditions with significant differences included SDvGRF of conditions 1 and 5, as well as TotSway of conditions 2 and 3. Fatigue protocol, postural stability assessment, limitations and future directions are discussed in the sections below.

5.1 LOADED FATIGUE PROTOCOL

Heart rate, blood lactate, and RPE were measured at the end of the loaded fatigue protocol to confirm that subjects were exercising at preferred intensities. With utilization and agreement of subjective and physiological fatigue assessments, we can validate the use of the current protocol to sufficiently induce fatigue. The fatigue protocol utilized by this study intended to induce general fatigue, which may not have caused excitation and activation within the CNS and impairment in peripheral neuromuscular control. Since direct measurement of peripheral or CNS fatigue is not possible, exact level of fatigue is not known. Due to the nature of termination from the fatigue protocol, certain subjects may not have reached a point of fatigue that would negatively influence their ability to coordinate muscle contraction, and therefore allowed sufficient muscle force to maintain upright, and stable standing.

5.2 NEUROCOM SENSORY ORGANIZATION TEST

5.2.1 NeuroCom SOT Clinical Outcome Score

Loaded postural stability was evaluated with the NeuroCom SOT to determine if a loaded fatigue protocol negatively influenced loaded postural stability. Loaded postural stability was measured before and after a loaded march to fatigue using the NeuroCom SOT in this study due to its ability to isolate the vestibular, visual and somatosensory systems and detect deficits in each. The closer a component score is to 100, the more optimal the use of the sensory system of interest. Changes in loaded postural stability scores following fatigue were calculated and demonstrated small differences in the VEST, VIS, and SOM systems, with significant decreases in COMP scores. Although the changes in individual component SOT clinical outcome scores were not statistically significant, we did discover a significant decline in COMP scores after a loaded march to fatigue. COMP scores are the weighted average of the scores of all sensory conditions, and characterizes the overall level of performance. It is calculated by independently averaging scores for conditions 1 and 2, adding these scores to the equilibrium scores from each trial of conditions 3-6 and dividing that sum by the total number of trials.[178] Through this calculation, differences in COMP scores from baseline to past-fatigue may be greater than any differences found in individual component scores following fatigue. Though there was a significant decrease in COMP scores following loaded fatigue, the mean value achieved post-fatigue was within a normative range of SOT outcome data. Post-fatigue results are within range of normative data previously identified establishing normative SOT values for healthy young adults (aged 20-22),[179] collegiate athletes[180] and military populations[181] in non-fatigued, unloaded states. Mean post-fatigue COMP scores were also higher than COMP values observed in Soldiers while carrying a tactical load in a non-fatigued state.[182] Due to the high values scored after loaded fatigue, the differences observed in the current study may not be indicative of poor postural stability performance following a loaded fatigue protocol.

The lack of significant differences within individual component scores following fatigue could possibly stem from a learning effect within the SOT. The primary procedure during testing was a familiarization loaded SOT in which subjects may have learned how to control perturbations occurring during each condition. The post-fatigue SOT was the third-time subjects performed the test, therefore the lack of significant decrements in individual sensorimotor system components may be attributed to a learning curve. However, subjects performed their best scores during the second SOT (Baseline), therefore a learning curve may not have significantly affected results.

5.2.2 NeuroCom SOT Raw Force Plate Data

Raw force plate data was also analyzed to determine if there were differences in baseline to post-fatigue loaded postural stability values after loaded fatigue. Changes in SDvGRF were calculated and demonstrated significant increases in conditions 1-3, and condition 6. The changes in SDvGRF observed portrayed inadequate somatosensory (conditions 1-3) and vestibular (condition 6) feedback when in a fatigued state. Given that testing conditions within the SOT can be considered either static or dynamic, greater SDvGRF values may not be attributed to fatigue induced postural stability decrements alone. Conditions 1 and 2 can be considered static conditions with 3-6 considered dynamic within the SOT testing procedures.[72] With subjects quietly standing on the fixed support surface with eyes open (condition 1) and closed (condition 2), the sensorimotor system might not be perturbed by testing procedures alone to produce significant somatosensory deficits following fatigue. Condition 3 incorporates a fixed surface with sway surround and therefore classified as a dynamic condition.[72] Subjects are challenged with inaccurate visual information, causing necessary postural compensation via the somatosensory system. Inadequacies within the somatosensory system following fatigue in conditions 1-3 were most likely caused by a decreased ability to detect forces imparted on articular structures and the inability to mediate protective muscle responses which provide joint stabilization.[46] Strenuous exercise and the onset of muscle fatigue may diminish proprioception by influencing the afferent spindle receptors in the muscles and can cause changes in the CNS, and at various spinal and supraspinal levels.[183] The collective effects of peripheral and CNS fatigue can result in reduced muscle-force output, that when combined with fatigue-induced decreased in sensorimotor afferent information[25] and delayed muscle contraction,[13] may lead to postural control deficits.[10,21,74] Previous research has shown that fatigue has been related to diminished knee proprioception and increased joint laxity when compared to baseline values, putting an individual at an increased risk for unintentional injury.[13]

Given the dynamic nature of condition 6, significant escalations of SDvGRF could be due to diminished vestibular feedback, or could be related to a coping mechanism to perturbations of the plate surface. Within the sixth testing condition, sway visual surrounds are crossed with a swayed platform surface, therefore putting the visual and somatosensory systems at a disadvantage and theoretically testing the effectiveness of the vestibular system. However, recent literature has identified more complex strategies of balance recovery during perturbation,[184] which may have caused the significant changes in SDvGRF. Authors stated that postural balance was obtained against AP perturbation; similar to NeuroCom SOT conditions featuring sway support surface, by lowering the body via ankle and knee flexion,[185] and through heel and sacrum accelerations.[184] The joint motions that occur together in attempt to dampen perturbations experienced during SOT dynamic conditions may have led to increased vGRF[184] values in condition 6. Since post-fatigue postural stability results were within a normative range, the cause of decrements observed in the current study are most likely the result of compensatory strategies from a changing base of support. However, if the sensorimotor system was in fact negatively influenced following fatigue, inadequate vestibular feedback may be ascribed to the continuous stimulation of the otholitic system during the fatigue protocol, which is sensitive to linear head accelerations. The prolonged stimulation may have led to a decreased sensibility threshold within the integrator centers of vestibular information.[186] Lepers et al.[186] found similar results when investigating the effects of prolonged running and cycling to fatigue on postural control. Authors also attributed postural control deficits following fatigue to the persistence of vestibular omission resulting from an adaptation to running movement into the recovery period post-exercise.[186]

Increased SDvGRF found in this study are consistent with results of other research studies utilizing different postural control tasks after fatiguing exercise to examine vertical ground reaction forces. In a previous study performed by Allison et al.[187] post-fatigue vGRF were significantly higher than pre-fatigue vGRF in males and females during quiet single leg standing following both anaerobic and aerobic fatigue.[187] Similarly, within studies identifying the effect of fatigue on dynamic postural stability, increased vGRF have been found following exercise.[16] Kuni et al.[16] presented that dynamic postural stability as measured by a stabilization task following sport specific jumping caused significantly greater vGRF following a run to fatigue.[16] Though previous and current studies utilize different methods of fatigue and postural stability tasks, similar increased vGRF outcomes can be associated with greater peripheral neuromuscular fatigue and impairment of the mechanisms of muscle excitation to contraction.[188]

Changes in TotSway were calculated and demonstrated significantly greater differences in all six conditions after loaded fatigue. TotSway refers to changes in the center of pressure during testing conditions and has been shown to be significantly affected by external load carriage. With greater sway during standing, the more likely the body's center of mass will approach the limits of the base of support and the less stable a person will be. In addition to greater sway with load carriage, neuromuscular fatigue and motor reflex inadequacies caused by proprioceptive deficits and joint laxity may render a joint unable to sense stress and respond appropriately causing more sway.[189] Results are in agreement with a previous study conducted by Berger et al.[190] examining postural control following unilateral ankle muscle fatigue in healthy male subjects. Sway was measured in both legs individually by COP displacement in the AP direction and ML direction, with calculation of the total sway area based on these trajectories. Significant increases were found in sway of both directions, as well as total sway area following fatigue of the lower leg musculature ($p < 0.01$).[190] Results are also consistent with previous literature examining postural sway after isokinetic fatigue of plantarflexor and dorsiflexor muscles. Yaggie and McGregor[191] found a significant increase in total sway along with other measures of postural stability during quiet standing on a force plate. Dependent variables including total sway, ML sway and displacement, and fore-aft sway and displacement were measured via force platform during quiet stance at baseline and at four recovery time points following fatigue. Fatigue was induced with isokinetic ankle fatigue using a dynamometer. Total sway was significantly higher immediately following fatigue, and continued to decline below baseline, therefore recover and improve for the duration of the test. Disturbances within ankle proprioception due to localized fatigue causes an inability to produce sufficient forces, leaving the joint unstable and causing an increase in postural sway.[191] Though fatigue protocols differ, when subjects were asked for a subjective reason for termination of the current study, majority of responses contained "lower extremity muscular fatigue" which may have included muscles of the ankle.

5.2.3 NeuroCom SOT Differences Between Sex

Differences between sex were also identified when looking at the same dependent variables. Significant differences were found in the changes of SDvGRF during conditions 1 and 5, with males exhibiting a larger negative difference between baseline and post-fatigue scores. Our results support the findings of Gribble et al.[192] and Whyte et al.[10] that fatigue negatively affects females less than males. This may partially result from the differences in muscle fatigue characteristics between sex, due to several interrelated processes.[10] Previous research has demonstrated that males have a lower rate of oxidative muscle metabolism than females, and a strength-dependent reduction in muscle perfusion. These physiological characteristics can lead to an accumulation of muscle metabolites, and a greater stimulation of inhibitory afferents resulting in a decreased motor response to posture perturbations.[193] Similarly, findings are also in agreement with one previous study which looked at postural stability differences between males and females measured with the NeuroCom SOT. Results showed that differences in postural stability were found between sex in condition 5, in that females performed better than males.[76] These outcomes support previous literature that showcases the postural stability superiority of female athletes in both static[194,195] and dynamic conditions.[196]

TotSway of conditions 2 and 3 also displayed a significant positive difference when stratifying results for sex; more specifically males had greater differences in TotSway post-loaded fatigue compared to females. These deficits illicit somatosensory system insufficiencies leading to greater postural sway when fatigued. The physiological differences between males and females in response to fatigue may have caused the discrepancies between sex. The musculoskeletal responses to fatigue in males may lead to decreased muscle activation, deterring the body from producing functional movements to maintain postural stability.[192] Previous studies identifying postural stability differences between males and females following fatigue is limited, therefore the current body of literature is mixed. Though the results of this study are in agreement with past findings[10,192] they disagree with studies that found males to have better postural stability than females,[197] and also conflict with those that found no difference between sexes.[195,198,199] The lack of uniformity in the current body of research can stem from different methods of measuring postural stability, as well as different age groups and varying levels of athletic abilities within subjects.

This is one of the first studies to examine loaded postural stability before and after a loaded fatigue protocol in physically active males and females. Since the mean SOT COMP scores for baseline (82.78 ± 4.65) and post-fatigue (81.61 ± 5.18) were comparable to SOT COMP scores of similarly aged healthy young adults (80.00 ± 2.49) reported in a study conducted by Borah et al.[200] and methods have been previously proven to be reliable,[174,175] we can conclude that the results of SOT testing are representative of their postural stability within the context of the current testing protocol. Current subjects likely had better scores than their healthy comparisons because of present history of athletic sport or training involvement. Postural stability was likely not influenced by the external load requirement because of the amount and distribution of the weight used. Morgan et al. [182] assessed SOT postural stability differences in Special Warfare Combatant-Craft (SWCC) crewmen with and without gear and found no change between testing conditions.[182] Their results were consistent with other literature that assessed center of pressure excursions between military training college students with and without load carriage which suggested that even distributions of weight could lead to improved postural stability by decreasing body sway.[201] Methodology of this study mandated even distribution of load, possibly leading to decreased body sway and higher postural stability scores during the SOT.

5.3 LIMITATIONS

This study has several limitations worth mentioning. Subjects used in this study were physically active males and females recruited from a greater university area, as opposed ideally to a military recruit or trainee population. The difference in demographics affects the ability to generalize results to military recruit or trainee populations. Additionally, subjects were excluded from participation if they had a lower extremity injury in the past six months. This did not include subjects with a history of ankle sprain prior to this time period, and those with a history of ankle sprains were included in this study. Ankle sprains have been shown to affect postural stability due to a change in functional stability of the ankle,[54,55] possibly influencing balance strategies and postural stability.

Limitations of the fatigue protocol should also be recognized. All subjects terminated the loaded fatigue protocol on their own accord, although verbal encouragement was used to motivate subjects to reach their maximum exhaustion. The protocol was a modified Astrand protocol, which is commonly used to assess the highest maximal oxygen uptake (VO_2max), however since subjects marched at constant pace with a load, it may be possible that lower extremity and low back musculature fatigued earlier before respiratory exhaustion was achieved. Secondly, instructions were given to participants before arriving in order to eliminate potential confounding variables that could affect loaded march performance. Subjects were instructed to refrain from any strenuous exercise prior to their testing session, so that residual soreness or fatigue would not influence any study results. Decrements in exercise performance could have been swayed by strenuous exercise performed prior to data collection due to higher levels of blood lactate.

Postural stability testing procedures should be mentioned concerning potential limitations. The order of conditions for all three NeuroCom SOT attempts was consistent for all subjects, potentially leading to an order effect within the procedure. The nature of progression during the SOT goes from easiest to hardest in difficulty of conditions, leading to an expected outcome of decreasing scores as the test goes from condition 1 to condition 6. Given that conditions 1-3 are considered "easier" than conditions 4-6, results from the current study may not be indicative of the full effect of loaded fatigue on loaded postural stability. Raw force plate variables showed significant increases post-fatigue in conditions 1-3, which potentially displays that postural stability may have been influenced to a greater extent earlier in the test compared to later in the test. Similarly, previous research has shown that following fatigue, postural stability can return to resting values within 10 to 15 minutes into a recovery period.[21,202-204] With post-fatigue SOT measurement starting within five minutes of fatigue protocol completion and the lengthy duration of SOT, total post-fatigue testing could have lasted up to 20 minutes. This disparity between fatigue recovery and SOT test duration may have led to a lack of significant differences during later stages of the SOT.

Lastly, limitations concerning the loaded vest should be noted when aiming to relate results of this study to military populations and the effect of load carriage on postural stability and potential injury risk. While loads used were similar to loads soldiers experience during training and tactical missions, the vest worn by subjects was for training, and was not military grade. There has been extensive research concerning the differences in posture utilizing different military pack load styles,[8,120,205] however we cannot correlate our results due to differences in load carriage conditions and distributions. The loaded vest was adjustable to the preferred comfort of each subject, however since it was not military grade or style, it is hard to make direct connections between previous military research and the results of this study. Military load carriage systems usually include backpacks, shoulder straps and belts to enhance the comfort and efficiency of transporting demanding loads.[205] Going further with loaded vest limitations, one of the main complaints and subjective reasons for fatigue protocol termination was lower extremity fatigue and back pain. It is possible that subjects did not reach full potential of peripheral nervous system fatigue because of other discomforts caused by the loaded vest.

5.4 FUTURE DIRECTIONS

Future research examining load carriage, fatigue and postural stability can explore many variations of the current study. The fatigue protocol used in this study was a modified Astrand which was selected to induce fatigue in each subject to the same level of perceptual and physiological fatigue by requiring participation until volitional fatigue. Future research may be more valid towards military populations by using one or multiple military physical fitness tests, or training modalities which are completed to fatigue. Furthermore, utilizing military grade load carriage such as belts, ruck sacks and other military implements during fatigue and postural stability testing might be another step further towards a more valid research experiment.

The addition of testing variables could be expanded to show the relationship between the change in loaded postural stability after a loaded march to fatigue and other physiological characteristics. Musculoskeletal strength has been shown to play an important role in attenuating external loads,[38] so the addition of lower extremity muscular strength testing could be beneficial to further identify this relationship during military centric training and operations.

Postural stability was only measured with the NeuroCom SOT, which can be modified in future experiments. Utilizing a true static postural stability measurement, dynamic postural stability measurement; such as the DPSI, as well as the NeuroCom SOT could give a better overall view of postural stability under load carriage conditions. Additionally, these postural stability measurements could be done under different load carriage conditions after fatigue to identify any possible interactions between increasing load, type of stability test and fatigue.

Lastly, different subject groups can be utilized in future studies. The age range and activity level of subjects in the current study aimed to be generalizable to a military recruit population. Since load carriage is essential to the military, inclusion of recruit populations or other individuals with load carriage experience might elicit different and more specialized results. Additionally, since not all recruits are physically active in similar volumes or intensities as current subjects, a broader range of activity levels could be included in future research. Finally, looking at differences in loaded postural stability before and after loaded fatigue following implementation of a load carriage training program aimed to improve postural stability, strength and endurance would provide necessary information towards injury prevention within the military.

5.5 CONCLUSIONS

The purpose of this study was to examine the effects of loaded marching to fatigue on loaded postural stability. It was hypothesized that loaded fatigue would lead to lower loaded NeuroCom SOT scores (COMP). It was also hypothesized that there would be no significant differences between baseline and post-fatigue scores for loaded NeuroCom SOT component scores (VEST, VIS, SOM) or raw force plate data (SDvGRF and TotSway) after loaded fatigue. Lastly, it was hypothesized that males will display greater changes in loaded postural stability post-loaded fatigue when comparing outcomes between sex. Although all our hypotheses were not fully accepted, results contribute useful information to the current load carriage knowledge base. The significant decrease in NeuroCom SOT composite scores following loaded fatigue demonstrates a change in postural stability performance and a potential for increased risk of injury. Though post-fatigue scores remained within normative value ranges, changes in postural stability were most likely the result of compensatory mechanisms to surface perturbations. The increased ground reaction forces and total sway displayed following loaded fatigue also reveal a change in loaded postural stability, potentially leading to increased injury risk. This study may provide beneficial information for the military towards the development of training programs that work to increase postural stability performance while carrying military loads and executing tasks to fatigue. Implementation of this type of training is essential for injury prevention, as well as performance optimization within the military.

BIBLIOGRAPHY

1. May B, Tomporowski PD, Ferrara M. Effects of backpack load on balance and decisional processes. *Mil Med.* 2009;174(12):1308-1312.

2. Drain J, Orr R, Billing D, Rudzki S. Human dimension of heavy load carriage. Land Warfare Conference; November 2010, 2010; Brisbane.

3. US A. Foot Marches. *Field Manual No. 21-18*. Washington, DC1990.

4. Heller MF, Challis JH, Sharkey NA. Changes in postural sway as a consequence of wearing a military backpack. *Gait Posture.* 2009;30(1):115-117.

5. Schiffman J, Bensel C, Hasselquist L, Gregorczyk K, Piscitelle L. Effects of carried weight on random motion and traditional measures of postural sway. *Appl Ergon.* 2006;37(5):607-614.

6. Sell T, Pederson J, Abt J, et al. The addition of body armour diminishes dynamic postural stability in military soldiers. *Mil Med.* 2013;178(1):76-81.

7. Hawkins R, Fuller C. A prospective epidemiological study of injuries in four English professional football clubs. *Br J Sports Med.* 1999;33:196-203.

8. Knapik J, Harman E, Reynolds K. Load carriage using packs: A review of physiological, biomechanical, and medical aspects. *Appl Ergon.* 1996;27(3):207-216.

9. Reynolds K, White J, Knapik J, Witt C, Amoroso P. Injuries and risk factors in a 100 mile infantry road march. *Prev Med.* 1999;28:167-173.

10. Whyte E, Burke A, White E, Moran K. A high-intensity, intermittent exercise protocol and dynamic postural control in men and women. *J Athl Train.* 2015;50(4):392-399.

11. Wikstrom E, Tillman M, Borsa P. Detection of dynamic stability deficits in subjects with functional ankle instability. *Med Sci Sports Exerc.* 2005;37:169-175.

12. Ekstrand J, Hagglund M, Walden M. Injury incidence and injury patterns in professional football: the UEFA injury study. *Br J Sports Med.* 2011;45(7):553-558.

13. Hassanlouei H, Arendt-Nielsen L, Kersting UG, Falla D. Effect of exercise-induced fatigue on postural control of the knee. *J Electromyogr Kinesiol.* 2012;22(3):342-347.

14. Inklaar H. Soccer injuries, I: incidence and severity. *Sports Med.* 1994;18:55-73.

15. Ekstrand J, Hagglund M, Walden M. Epidemiology of muscle injuries in professional football (soccer). *Am J Sports Med.* 2011;39(6):1226-1232.

16. Kuni B, Cardenas-Montemayor E, Bengert Y, et al. Impaired jump landing after exercise in recreational and in high-performance athletes. *J Strength Cond Res.* 2014;28(8):2306-2313.

17. Lephart S, Henry T. Functional rehabilitation for the upper and lower extremity. *Orthop Clin North Am.* 1995;26:579-592.

18. Forestier N, Teasdale N, Nougier V. Alteration of the position sense at the ankle induced by muscular fatigue in humans. *Med Sci Sports Exerc.* 2002;34:117-122.

19. Skinner H. Effect of fatigue on joint position sense of the knee. *J Orthop Res.* 1986;4:112-118.

20. Wikstrom E, Tillman M, Smith A, Borsa P. A new force plate technology measure of dynamic postural stability: the dynamic postural stability index. *J Athl Train.* 2005;40(4):305-309.

21. Wright K, Lyons T, Navalta J. Effects of exercise-induced fatigue on postural balance: a comparison of treadmill versus cycle fatiguing protocols. *Eur J Apply Physiol.* 2013;113(5):1303-1309.

22. Zech A, Steib S, Hentschke C, Eckhardt H, Pfeider K. Effects of localized and general fatigue on static and dynamic postural control in male team handball athletes. *J Strength Cond Res.* 2012;26(4):1162-1168.

23. Holden S, Boreham C, Doherty C, Wang D, Delahunt E. Dynamic postural stability in young adolescent male and female athletes. *Pediatr Phys Ther.* 2014;26(4):447-452.

24. Sell TC. An examination, correlation, and comparison of static and dynamic measures of postural stability in healthy, physically active adults. *Phys Ther Sport.* 2012;13(2):80-86.

25. Gribble PA, Hertel J, Plisky P. Using the Star Excursion Balance Test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *J Athl Train.* 2012;47(3):339-357.

26. Hertel J, Braham R, Hale S, Olmstead-Kramer L. Simplifying the star excursion balance test: analyses of subjects with and without chronic ankle instability. *J Orthop Sports Phys Ther.* 2006;36(3):131-137.

27. Faghy M, Brown P. Preloaded time trial to assess load carriage performance. *J Strength Cond Res.* 2014;28(12):3354-3362.

28. Porter S. The soldier's load. *Infantry.* 1992;82(3):19-22.

29. Team TFDCAA. The modern warrior's combat load. Dismounted operations in Afghanistan April-May 2003; 2003.

30. Scales R. Urban warfare: A solder's view. *Military Review.* 2005;85(1):9.

31. Dean C. The modern warrior’s combat load. Dismounted operations in Afghanistan, April–May 2003. US Army Center for Army Lessons Learned; 2004; Ft Leavenworth, KS.

32. Nindl BC, Castellani JW, Warr BJ, et al. Physiological Employment Standards III: physiological challenges and consequences encountered during international military deployments. *Eur J Appl Physiol.* 2013;113(11):2655-2672.

33. Sell T, Chu Y, Abt J, et al. Minimal additional weight of combat equipment alters air assault soldiers' landing biomechanics. *Mil Med.* 2010;175(1):41-47.

34. Roy T, Ritland B, Knapik J, Sharp M. Lifting tasks are associated with injuries during the early portion of a deployment to Afghanistan. *Mil Med.* 2012;177(6):716-722.

35. Grenier J, Millet G, Peyrot N, et al. Effects of extreme-duration heavy load carriage on neuromuscular function and locomotion: A military-based study. *PLoS ONE 78.* 2012.

36. Blacker S, Fallowfield J, Bilzon J, Willems T. Neuromuscular impairment following backpack load carriage. *J Human Kin.* 2013;37:91-98.

37. Harman E, Han K, Frykman P. Load-speed interaction effects on the biomechanics of backpack load carriage. Soldier Mobility: Innovations in Load Carriage System Design and Evaluation; 2000; Kingston, Canada.

38. Wang H, Frame J, Ozimek E, Leib D, Dugan E. The effects of load carriage and muscle fatigue on lower-extremity joint mechanics. *Res Q for Exerc Sport.* 2013;84:305-312.

39. Cohen S, Brown C, Kurihara C, Plunkett A, Nguyen C, Strassels S. Diagnoses and factors associated with medical evacuation and return to duty for service members participating in Operation Iraqi Freedom or Operation Enduring Freedom: a prospective cohort study. *Lancet 375.* 2010:301-309.

40. Nindl BC, Williams TJ, Deuster PA, Butler NL, Jones BH. Strategies for optimizing military physical readiness and preventing musculoskeletal injuries in the 21st century. *US Army Med Dep J.* 2013:5-23.

41. Pilegaard H, Domino K, Noland T, et al. Effect of high-intensity exercise training on lactate/H transport capacity in human skeletal muscle. *Am J Physiol Endocrinol Metab.* 1999;276(2):255-261.

42. Knapik J, Reynolds K, Staab J, Vogel J, Jones B. Injuries associated with strenuous road marching. *Mil Med.* 1992;157:64-67.

43. Liederbach M, Kremenic IJ, Orishimo KF, Pappas E, Hagins M. Comparison of landing biomechanics between male and female dancers and athletes, part 2: Influence of fatigue and implications for anterior cruciate ligament injury. *Am J Sports Med.* 2014;42(5):1089-1095.

44. Chappell JD, Herman DC, Knight BS, Kirkendall DT, Garrett WE, Yu B. Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *Am J Sports Med.* 2005;33(7):1022-1029.

45. Rozzi S, Lephart S, Gear W, Fu F. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *Am J Sports Med.* 1999;27(3):312-319.

46. Rozzi S, Lephart S, Fu F. Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. *J Athl Train.* 1989;24:106-114.

47. Lepers R, Hausswirth C, Maffiuletti N, Brisswalter J, Van Hoecke J. Evidence of neuromuscular fatigue after prolonged cycling exercise. *Med Sci Sports Exerc.* 2000;32:1880-1886.

48. Wojtys E, Wylie B, Huston L. The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. *Am J Sports Med.* 1996;24:615-621.

49. Pappas E, Hagins M, Sheikhzadeh A, Nordin M, Rose D. Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. *Clin J Sport Med.* 2007;17(263-268).

50. Nyland J, Shapiro R, Caborn D, Nitz A, Malone T. The effect of quadriceps femoris, hamstring, and placebo eccentric fatigue on knee and ankle dynamics during crossover cutting. *J Orthop Sports Phys Ther.* 1997;25:171-184.

51. Quammen D, Cortes N, VanLunen B, Lucci S, Ringleb S, Onate J. Two different fatigue protocols and lower extremity motion patterns during a stop-jump task. *J Athl Train.* 2012;47(1):32-41.

52. Pendergrass T, Moore J, Gerber J. Postural control after a 2-mile run. *Mil Med.* 2003;168(11):896-903.

53. Beynnon B, Renstrom P, Alosa D, Baumhauer J, Vacek P. Ankle ligament injury risk factors: a prosprective study of college athletes. *J Orthop Res.* 2001;19:213-220.

54. McGuine T, Greene J, Best T, Leverson G. Balance as a predictor of ankle injuries in high school basketball players. *Clin J Sport Med.* 2000;10:239-244.

55. Tropp H, Ekstrand J, Gillquist J. Stabilometry in functional instability of the ankle and its value in predicting injury. *Med Sci Sports Exerc.* 1984;16:64-66.

56. Wang H, Chen C, Shiang T, Jan M, Lin K. Risk factor analysis of high school basketball player ankle injuries: a prospective controlled cohort study evaluating postural sway. *Arch Phys Med Rehabil.* 2006;87:821-825.

57. McKeon P, Hertel J. Systematic review of postural control and lateral ankle instability, part I: can deficits be detected with instrumented testing? *J Athl Train.* 2008;43(3):293-304.

58. Willems TM, Witvrouw E, Delbaere K, Philippaerts R, De Bourdeaudhuij I, De Clercq D. Intrinsic risk factors for inversion ankle sprains in females--a prospective study. *Scand J Med Sci Sports.* 2005;15(5):336-345.

59. Ross S, Guskiewicz K. Examination of static and dynamic postural stability in individuals with functionally stable and unstable ankles. *J Sport Med.* 2004;14:332-338.

60. Pilsky P, Rauh M, Kaminski T, Underwood F. Star excursion balance test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther.* 2006;36(12):911-919.

61. Paterno M, Schmitt L, Ford K, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med.* 2010;38(1968-1978).

62. Vrbanic T, Ravlic-Gulan J, Gulan G, Matovinovic D. Balance index score as a predictive factor for lower sports results or anterior cruciate ligament knee injuries in Croatian female athletes-preliminary study. *Coll Anthropol.* 2007;31:253-258.

63. Jones B, Canham-Chervak M, Canada S, Mitchener T, Moore S. Medical surveillance of injuries in the U.S. military: Descriptive epidemiology and recommendations for improvement. *Am J Prevent Med.* 2010;38(1):S42-S60.

64. Riemann B, Caggiano N, Lephart S. Examination of a clinical method of assessing postural control during a functional performance task. *J Sport Rehabil.* 1999;8:171-183.

65. Goldie P, Bach T, Evans O. Force platform measures for evaluating postural control: reliabilty and validity. *Arch Phys Med Rehabil.* 1989;70:510-517.

66. McKeon P, Ingersoll C, Kerrigan D, Saliba E, Bennett B, Hertel J. Balance training improves function and postural-control in those with chronic ankle instability. *Med Sci Sports Exerc.* 2008;40(10):1810-1819.

67. Clark R, Saxion C, Cameron K, Gerber J. Associations between three clinical assessment tools for postural stability. *N Am J Sports Phys Ther.* 2010;5(3):122-130.

68. Nakagawa L, Hoffman M. Performance in static, dynamic and clinical tests of postural control in individuals with recurrent ankle sprains. *J Sport Rehabil.* 2004;13:255-268.

69. Riemann B, Lephart S. The sensorimotor system, part II: the role of proprioception in motor control and functional joint stability. *J Athl Train.* 2002;37(1):80-84.

70. Riemann B, Schmitz R. The relationship between various modes of single leg postural control assessment. *Int J Sports Phys Ther.* 2012;7(3):257-266.

71. Trojian T, McKeag D. Single leg balance test to identify risk of ankle sprains. *Br J Sports Med.* 2006;40:610-613.

72. Chaudhry H, Findley T, Quigley K, et al. Measures of postural stability. *J Rehab Res Develop.* 2004;41(5):713-720.

73. Johnston RI, Howard M, Cawley P, Losse G. Effect of lower extremity muscular fatigue on motor control performance. *Med Sci Sports Exerc.* 1998;30:1703-1707.

74. Wikstrom E, Powers M, Tillman M. Dynamic stabilization time after isokinetic and functional fatigue. *J Athl Train.* 2004;39(3):247-253.

75. Colby S, Hintermeister R, Torry M, Steadman J. Lower limb stability with ACL impairment. *J Orthop Sports Phys Ther.* 1999;29(8):444-454.

76. Olchiwik G, Tomaszewski M, Olejarz P, Warchol J, Rozanska-Boczula M, Maciejewski R. The human balance system and gender. *Acta Bioeng and Biomech.* 2015;17(1):69-74.

77. Broglio S, Sosnoff J, Ferrara M. The relationship of athlete reported concussion symptoms and objective measures of neurocognitive function and postural control. *Clin J Sport Med.* 2009;19(5):377-382.

78. Graves B. University football players, postural stability, and concussions. *J Strength Cond Res.* 2016;30(2):579-583.

79. Guskiewicz K, Ross S, Marshall S. Postural stability and neuropsychological deficits after concussion in collegiate athletes. *J Athl Train.* 2001;36(3):263-273.

80. Riemann B, Guskiewicz K. Effects of mild head injury on postural stability as measured through clinical balance testing. *J Athl Train.* 2000;35(1):19-25.

81. Broglio SP, Monk A, Sopiarz K, Cooper ER. The influence of ankle support on postural control. *J Sci Med Sport.* 2009;12(3):388-392.

82. Linens SW, Ross SE, Arnold BL, Gayle R, Pidcoe P. Postural-stability tests that identify individuals with chronic ankle instability. *J Athl Train.* 2014;49(1):15-23.

83. de Vries JS, Kingma I, Blankevoort L, van Dijk CN. Difference in balance measures between patients with chronic ankle instability and patients after an acute ankle inversion trauma. *Knee Surg Sports Traumatol Arthrosc.* 2010;18(5):601-606.

84. Docherty C, Valovich McLeod T, Shultz S. Postural control deficits in participants with functional ankle instability as measured by the balance error scoring system. *Clin J Sport Med.* 2006;16(3):203-208.

85. Hertel J, Miller S, Denegar C. Intratester and intertester reliability during the star excursion balance test. *J Sport Rehabil.* 2000;9:104-116.

86. Attwells R, Birrell S, Hooper R, Mansfield N. Influence of carrying heavy loads on soldiers' posture, movements and gait. *Ergonomics.* 2006;49(14):1527-1537.

87. Tilbury-Davis D, Hooper R. The kinetic and kinematic effects of increasing load carriage upon the lower limb. *Hum Mov Sci.* 1999;18:693-700.

88. Quesada P, Mengelkoch L, Hale R, Simon S. Biomechanical and metabolic effects of varying backpack loading on simulated marching. *Ergonomics.* 2000;43(3):293-309.

89. Beekley M, Alt J, Buckley C, Duffey M, Crowder T. Effects of heavy load carriage during constant-speed, simulated road marching. *Mil Med.* 2007;172(6):592-595.

90. Brazen D, Todd M, Ambegaonkar J, Wunderlich R, Peterson C. The effect of fatigue on landing biomechanics in single-leg drop landings. *Clin J Sport Med.* 2010;20(4):286-292.

91. Gribble P, Hertel J, Denegar C, Buckley W. The effects of fatigue and chronic ankle instability on dynamic postural control. *J Athl Train.* 2004;39(4):321-329.

92. Reimer R, Wikstrom E. Functional fatigue of the hip and ankle musculature cause similar alterations in single leg stance postural control. *J Sci Med Sport.* 2010;13(1):161-166.

93. Dingenen B, Malfait B, Nijs S, et al. Postural Stability During Single-Leg Stance: A preliminary evaluation of noncontact lower extremity injury risk. *J Orthop Sports Phys Ther.* 2016;46(8):650-657.

94. Willems T, Witvrouw E, Delbaere K, Philippaerts R, De Bourdeaudhuij I, De Clercq D. Intrinsic risk factors for inversion ankle sprains in male subjects: a prospective study. *Am J Sports Med.* 2005;33:415-423.

95. King DA, Hume PA, Milburn P, Gianotti S. Rugby league injuries in New Zealand: a review of 8 years of Accident Compensation Corporation injury entitlement claims and costs. *Br J Sports Med.* 2009;43(8):595-602.

96. NIH. Conference on sports injuries in youth.; 1992; Bethesda, MD.

97. Skeehan C, Tribble D, Sanders J, Putnam S, Armstrong A, Riddle M. Nonbattle injury among deployed troops: an epidemiologic study. *Mil Med.* 2009;12:1259-1262.

98. Kaufman K, Brodine S, Shaffer R. Military training-related injuries: surveillance, research and prevention. *Am J Prev Med.* 2000;18(3S):54-63.

99. Kang J, Chaloupka E, Mastrangelo M, Biren G, Robertson R. Physiological comparisons among three maximal treadmill exercise protocols in trained and untrained individuals. *Eur J Appl Physiol.* 2001;84(291-295).

100. Ruscio B, Smith J, Amoroso P, et al. DoD military injury oreventuon priorities working group: leading injuries, causes, and mitigation recommendations. 2006.

101. Hauret KG, Bedno S, Loringer K, Kao TC, Mallon T, Jones BH. Epidemiology of exercise and sports-related injuries in a population of young, physically active adults: a survey of military servicemembers. *Am J Sports Med.* 2015;43(11):2645-2653.

102. Knapik J, Graham B, Cobbs J, Thompson D, Steelman R, Jones B. A prospective investigation of injury incidence and injury risk factors among army recruits in military police training. *BMC MusculoSkel Disord.* 2013;14(32):1-11.

103. Jones B, Cowan D, Tomlinson J, Robinson J, Polly D, Frykman P. Epidemiology of injuries associated with physical training among young men in the army. *Med Sci Sports Exerc.* 1993;25(2):197-203.

104. Nye N, Pawlak M, Webber B, Tchandja J, Milner M. Description and rate of musculoskeletal injuries in air force basic military trainees, 2012−2014. *J Athl Train.* 2016;51(11):858-865.

105. Hootman J, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train.* 2007;42(2):311-319.

106. Junge A, Landevoort G, Pipe A, et al. Injuries in team sports tournaments during the 2004 Olympic Games. *Am J Sports Med.* 2006;34(4):565-576.

107. Conn J, Annest J, Gilchrist J. Sports and recreation related injury episides in the US population 1997-99. *Inj Prev.* 2003;2:117-123.

108. Swain MS, Lystad RP, Henschke N, Maher CG, Kamper SJ. Match injuries in amateur Rugby Union: a prospective cohort study - FICS Biennial Symposium Second Prize Research Award. *Chiropr Man Therap.* 2016;24:17.

109. Stubbe JH, van Beijsterveldt AM, van der Knaap S, et al. Injuries in professional male soccer players in the Netherlands: a prospective cohort study. *J Athl Train.* 2015;50(2):211-216.

110. Xiang J, Collins CL, Liu D, McKenzie LB, Comstock RD. Lacrosse injuries among high school boys and girls in the United States: academic years 2008-2009 through 2011-2012. *Am J Sports Med.* 2014;42(9):2082-2088.

111. Deitch JR, Starkey C, Walters SL, Moseley JB. Injury risk in professional basketball players: a comparison of Women's National Basketball Association and National Basketball Association athletes. *Am J Sports Med.* 2006;34(7):1077-1083.

112. Murphy D, Connolly D, Beynnon B. Risk factors for lower extremity injury: a review of the literature. *Br J Sports Med.* 2003;37(1):13-29.

113. Woods C, Hawkins R, Husle M, Hodson A. The Football Association Medical Research Programme: an audit of injuries in professional football: an analysis of ankle sprains. *Br J Sports Med.* 2003;37(3):233-238.

114. Woods C, Hawkins R, Maltby S, Hulse M, Thomas A, Hodson A. The Football Association Medical Research Programme: an audit of injuries in professional football-analysis of hamstring injuries. *Br J Sports Med.* 2004;38(1):36-41.

115. Molsa J, Kujala U, Snasman O, Lehtipuu T, Airaksinen O. Injury profile in ice hockey from the 1970s through the 1990s in Finland. *Am J Sports Med.* 2000;28(3):322-327.

116. Gabbett T. Incidence site and nature of injuries in amateur rugby league over three consecutive seasons. *Br J Sports Med.* 2000;34:98-103.

117. Sell T, Ferris C, Abt J, et al. Predictors of proximal anterior tibia sear force during a vertical stop-jump. *J Orthop Res.* 2007;25(12):1589-1597.

118. Lephart S, Ferris C, Riemann B, Myers J, Fu F. Gender differences in strength and lower extremity kinematics during landing. *Clin J Orthop Relat Res.* 2002;40(1):162-169.

119. Birrell S, Hooper R, Haslam R. The effect of military load carriage on ground reaction forces. *Gait Posture.* 2007;26:611-614.

120. Devroey C, Jonkers I, de Becker A, Leanaerts G, Spaepen A. Evaluation of the effect of backpack load and position during standing and walking using biomechanical, physiological and subjective measures. *Ergonomics.* 2007;50(5):728-742.

121. Holewijn M, Lotens W. The influence of backpack design on physical performance. *Ergonomics.* 1992;35:149-157.

122. Martin P, Nelson R. The effect of carried loads on the combative movement performance of men and women. *Mil Med.* 1985;150:357-362.

123. Knapik J, Johnson R, Ang P, et al. *Road march performance of special operations soldiers carrying various load distributions.* Natick, MA: US Army Research Institute of Enviornmental Medicine;1993.

124. Tharion W, Moore R. *Effects of carbohydrate intake and load bearing exercise on rifle marksmanship performance.:* US Army Research Institute of Enviornmental Medicine;1993.

125. Wilson W. Brachial plexus palsy in basic trainees. *Mil Med.* 1987;152:519-522.

126. Bessen R, Belcher V, Franklin R. Rucksack paralysis with and without rucksack frames. *Mil Med.* 1987;152:372-375.

127. Knapik J, Staab J, Bahrke M, Reynolds K, Vogel J, O'Conner J. Soldier performance and mood states following strenuous road marching. *Mil Med.* 1991;156:197-200.

128. McCollum G, Shupert C, Nasher L. Organizing sensory information for postural control in altered sensory enviornments. *J Theor Bio.* 1996;180(3):257-270.

129. Riemann B, Lephart S. The sensorimotor system, part I: the physiological basis of functional joint stability. *J Athl Train.* 2002;37(1):71-79.

130. Grigg P. Peripheral neural mechanisms in proprioception. *J Sport Rehabil.* 1994;3:2-17.

131. Wyke B. The neurology of joints. *Ann R Coll Surg Engl.* 1967;41(1):25-50.

132. Jami L. Golgi tendon organs in mammalian skeletal muscle: functional properties and central actions. *Physiol Rev.* 1992;72(3):623-666.

133. Gordon J, Ghez C. Muscle receptors and spinal reflexes; the stretch reflex. 1991.

134. Johansson H, Sjolander P, Sojka P. A sensory role for the cruciate ligaments. *Clin Orthop.* 1991;268:161-178.

135. McGeehan MA, Woollacott MH, Dalton BH. Vestibular control of standing balance is enhanced with increased cognitive load. *Exp Brain Res.* 2016.

136. Medendorp WP, Selen LJ. Vestibular contributions to high-level sensorimotor functions. *Neuropsychologia.* 2017.

137. Dalton BH, Rasman BG, Inglis JT, Blouin JS. The internal representation of head orientation differs for conscious perception and balance control. *J Physiol.* 2016.

138. Mergner T, Rosemeier T. Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions-a conceptual model. *Brain Res Rev.* 1998;28:118-135.

139. Angelaki D, Cullen K. Vestibular system: the many facets of a multimodal sense. *Annu Rev Neurosci.* 2008;31:125-150.

140. Griffin L, Angel J, Albohm M, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* 2000;8(3):141-150.

141. McNair P, Marshall R. Landing characteristics in subjects with normal and anterior cruciate ligament deficient knee joints. *Arch Phys Med Rehabil.* 1994;75:584-589.

142. Griffin L, Albohm M, Arendt E, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med.* 2006;34(9):1512-1532.

143. Arnold B, de la Motte S, Linens S, Ross S. Ankle instability is associated with balance impairments: a meta-analysis. *Med Sci Sports Exerc.* 2009;41(5):1048-1062.

144. Willems T, Witvrouw E, Verstuyft J, Vaes P, Clercq D. Proprioception and muscle strength in subjects with a history of ankle sprains and chronic instability. *J Athl Train.* 2002;37(4):487-493.

145. Konradsen L, Ravn J. Ankle instability caused by prolonged peroneal reaction time. *Acta Orthop Scand.* 1990;61(5):388-390.

146. McVey E, Palmieri R, Docherty C, Zinder S, Ingersoll C. Arthrogenic muscle inhibition in the leg muscles of subjects exhibiting functional ankle instability. *Foot Ankle Int.* 2005;26(12):1055-1061.

147. Munn J, Sullivan S, Schneiders A. Evidence of sensorimotor deficits in functional ankle instability: a systematic review with meta-analysis. *J Sci Med Sport.* 2009;13(1):2-12.

148. Witchalls J, Waddington G, Blanch P, Adams R. Ankle instability effects on joint position sense when stepping across the active movement extent discrimination apparatus. *J Athl Train.* 2012;47(6):627-634.

149. Brown C, Ross S, Mynark R, Guskiewicz K. Assessing functional ankle instability with joint position sense, time to stabilization, and electromyography. . *J Sport Rehabil.* 2004;13(2):122-134.

150. de Noronha M, Refshauge K, Kilbreath S, Crosbie J. Loss of proprioception or motor control is not related to functional ankle instability: an observational study. *Aust J Physiother.* 2007;53(3):193-198.

151. Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. *Clin Sports Med.* 2008;27(3):353-370.

152. Boyas S, Guevel A. Neuromuscular fatigue in healthy muscle: underlying factors and adaptation mechanisms. *Ann Phys Rehabil Med.* 2011;54(2):88-108.

153. MacIntosh B, Gardiner P, McComas A. *Skeletal muscle: form and function.* 2 ed. Champaign, IL, USA2005.

154. Davis M, Bailey S. Possible mechanisms of central nervous system fatigue during exercise. *Med Sci Sports Exerc.* 1997;29(1):45-57.

155. Martin V, Kerherve H, Messonnier LA, et al. Central and peripheral contributions to neuromuscular fatigue induced by a 24-h treadmill run. *J Appl Physiol (1985).* 2010;108(5):1224-1233.

156. Brasil-Neto J, Pascual-Leone J, Valls-Sole A, Cammarota A, Cohen L, Hallett M. Postexercise depression of motor evoked potentials: a measure of central nervous system fatigue. *Exp Brain Res.* 1993;93:181-184.

157. Bigland-Ritchie B, Thomas C, Rice C, Howarth J, Woods J. Muscle temperature, contractile speed, and motorneuron firing rates during human voluntary contractions. *J Appl Physiol.* 1992;73(6):2457-2461.

158. Westerblad H, Allen D, Bruton J, Andrade F, Lannergren J. Mechanisms underlying the reduction of isometric force in skeletal muscle fatigue. *Acta Physiol Scand.* 1998;162:253-260.

159. Westerbald H, Bruton J, Lannergren J. The effect of intracellular pH on contractile function of intact, single fibres of mouse muscle declines with increasing temperature. *J Physiol.* 1997;500:193-204.

160. McLester J. Muscle contraction and fatigue: the role of adenosine 5'-diphosphate and inorganic phosphate. *Sports Med.* 1997;23:287-305.

161. Stackhouse S, Reisman D, Binder-Macleod S. Challenging the role of pH in skeletal muscle fatigue. *Phys Ther.* 2001;81:1897-1903.

162. Allen D, Kabbara A, Westerbald H. Muscle fatigue: the role of intracellular calcium stores. *Can J Appl Physiol.* 2002;27:83-96.

163. Noakes T. Physiological models to understand exercise fatigue and adaptations that predict or enhance athletic performance. *Scand J Med Sci Sports.* 2000;10:123-145.

164. Bosch A, Dennis S, Noakes T. Influence of carbohydrate loading on fuel substrate turnover and oxidation during prolonged exercise. *J Appl Physiol* 1985;74(4):1921-1927.

165. Stepto N, Martin D, Fallon K, Hawley J. Metabolic demands of intense aerobic interval training in competitive cyclists. *Med Sci Sports Exerc.* 2001;33(2):303-310.

166. Gandevia S. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev.* 2001;81(4):1725-1789.

167. Nummela A, Vuorimaa T, Rusko H. Changes in force production, blood lactate and EMG activity in the 400-m sprint. *J Sports Sci.* 1992;10(3):217-228.

168. Lattier G, Millet GY, Martin A, Martin V. Fatigue and recovery after high-intensity exercise part I: Neuromuscular fatigue. *Int J Sports Med.* 2004;25(6):450-456.

169. Wrisley D, Stephens M, Mosley S, Wojnowski A, Duffy J, Burkard R. Learning effects of repetitive administrations of the sensory organization test in healthy young adults. *Arch Phys Med Rehabil.* 2007;88(8):1049-1054.

170. Karlsson A, Frykberg G. Correlations between force plate measures for assessment of balance. *Clin Biomech.* 2000;15(5):365-369.

171. Noyes F. The Noyes knee rating system. Cincinnati: Cincinnati Sports Medicine and Research Education Foundation; 1995.

172. Utter A, Robertson R, Green M, Suminski R, McAnulty S, Nieman D. Validation of the adult OMNI scale of perceived exertion for walking/running exercise. *Med Sci Sports Exerc.* 2004;36(10):1776-1780.

173. Pyne D, Boston T, Martin D, Logan A. Evaluation of the Lactate Pro blood lactate analyser. *Eur J Apply Physiol.* 2000;82(1):112-116.

174. Dickin D. Obtaining reliable performance measures on the sensory organization test: altered testing sequences in young adults. *Clin J Sport Med.* 2010;20(4):278-285.

175. Dickin D, Clark S. Generalizability of the sensory organization test in college-aged males: obtaining a reliable performance measure. *Clin J Sport Med.* 2007;17(2):109-115.

176. Teel E, Register-Mihalik J, Blackburn J, Guskiewicz K. Balance and cognitive performance during a dual-task: Preliminary implications for use in concussion assessment. *J Sci Med Sport.* 2013;16(3):190-194.

177. NBM S. Clinical integration seminar lecture notes. In: Clackamas, ed. Medical Incorporated 2005.

178. Zemkova E, Hamar D. Physiological mechanisms of post-exercise balance impairment. *Sports Med.* 2014;44(4):437-448.

179. Ferber-Viart C, Ionescu E, Morlet T, Froehlich P, Dubreuil C. Balance in healthy individuals assessed with Equitest: maturation and normative data for children and young adults. *Int J of Pediatr otorhinolaryngol.* 2007;71(7):1041-1046.

180. Guskiewicz KM, Riemann BL, Perrin DH, Nashner LM. Alternative approaches to the assessment of mild head injury in athletes. *Med Sci Sports Exerc.* 1997;29(7 Suppl):S213-221.

181. Pletcher ER, Williams VJ, Abt JP, et al. Normative Data for the NeuroCom Sensory Organization Test in US Military Special Operations Forces. *J Athl Train.* 2017;52(2):129-136.

182. Morgan P, Williams V, Sell T. Postural stability of special warfare combatant-craft crewmen with tactical Gear. *J Spec Ops Med.* 2016;15(4):7-11.

183. Shields R, Madhavan S, Cole K. Sustained muscle activity minimally influences dynamic position sense of the ankle. *J Orthop Sports Phys Ther.* 2005;35(7):443-451.

184. Hwang S, Tae K, Sohn R, Kim J, Son J, Kim Y. The balance recovery mechanisms against unexpected forward perturbation. *Ann of Biomed Eng.* 2009;37(8):1629-1637.

185. Hughes MA, Schenkman ML, Chandler JM, Studenski SA. Postural responses to platform perturbation: kinematics and electromyography. *Clin Biomech.* 1995;10(6):318-322.

186. Lepers R, Bigard AX, Diard JP, Gouteyron JF, Guezennec CY. Posture control after prolonged exercise. *Eur J Appl Physiol Occup Physiol.* 1997;76(1):55-61.

187. Allison K, Akins J, Sell T, et al. Heart rate and postural stability recovery are similar after aerobic and anaerobic exercise.: University of Pittsburgh.

188. Boyas S, Remaud A, Rivers E, Bilodeau M. Fatiguing exercise intensity influences the relationship between parameters reflecting neuromuscular function and postural control variables. *PLoS One.* 2013;8(8):e72482.

189. Schiffman JM, Bensel CK, Hasselquist L, Gregorczyk KN, Piscitelle L. Effects of carried weight on random motion and traditional measures of postural sway. *Appl Ergon.* 2006;37(5):607-614.

190. Berger LL, Regueme SC, Forestier N. Unilateral lower limb muscle fatigue induces bilateral effects on undisturbed stance and muscle EMG activities. *J Electromyogr Kinesiol.* 2010;20(5):947-952.

191. Yaggie JA, McGregor SJ. Effects of isokinetic ankle fatigue on the maintenance of balance and postural limits. *Arch Phys Med Rehabil.* 2002;83(2):224-228.

192. Gribble PA, Robinson RH, Hertel J, Denegar CR. The effects of gender and fatigue on dynamic postural control. *J Sport Rehabil.* 2009;18(2):240-257.

193. Hunter SK. Sex differences and mechanisms of task-specific muscle fatigue. *Exerc Sport Sci Rev.* 2009;37(3):113-122.

194. Sell T, Lovalekar M, Nagai T, Wirt M, Abt J, Lephart S. Gender differences in static and dynamic postural stability of Soldiers of the Army's 101st Airborne Division (Air Assault). *J Sport Rehabil.* 2017:1-17.

195. Howell DR, Hanson E, Sugimoto D, Stracciolini A, Meehan WP, 3rd. Assessment of the postural stability of female and male athletes. *Clin J Sport Med.* 2017;27(5):444-449.

196. Dallinga JM, van der Does HTD, Benjaminse A, Lemmink KAPM. Dynamic postural stability differences between male and female players with and without ankle sprain. *Phys Ther Sport.* 2016;17(Supplement C):69-75.

197. Wikstrom E, Tillman M, Kline K, Borsa P. Gender and limb differences in dynamic postural stability during landing. *Clin J Sport Med.* 2006;16(4):311-315.

198. Hageman PA, Leibowitz JM, Blanke D. Age and gender effects on postural control measures. *Arch Phys Med Rehab.* 1995;76(10):961-965.

199. Torres SF, Reis JG, de Abreu D. Influence of gender and physical exercise no balance of healthy young adults. *Fisioter Em Mov.* 2014;27:399-406.

200. Borah D, Wadhwa S, Singh U, Yadav S, Bhattacharjee M, V S. Age related changes in postural stability. *Indian J Physiol Pharmacol.* 2007;51(4):395-404.

201. Park H, Branson D, Kim S, et al. Effect of armor and carrying load on body balance and leg muscle function. *Gait Posture.* 2014;39(1):430-435.

202. Bryanton MA, Bilodeau M. Postural stability with exhaustive repetitive sit-to-stand exercise in young adults. *Hum Mov Sci.* 2016;49:47-53.

203. Ishizuka T, Hess RA, Reuter B, Federico MS, Yamada Y. Recovery of time on limits of stability from functional fatigue in Division II collegiate athletes. *J Strength Cond Res.* 2011;25(7):1905-1910.

204. Fox ZG, Mihalik JP, Blackburn JT, Battaglini CL, Guskiewicz KM. Return of postural control to baseline after anaerobic and aerobic exercise protocols. *J Athl Train.* 2008;43(5):456-463.

205. Knapik J, Reynolds K, Harman E. Soldier load carraige: historical, physiological, biomechanical and mdical aspects. *Mil Med.* 2004;169(1):45-56.