IMPACT OF INCREASED LOAD CARRIAGE MAGNITUDE ON THE DYNAMIC POSTURAL STABILITY OF MEN AND WOMEN

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The impact of load carriage on dynamic postural stability affects the survivability of the Warfighter by influencing performance capabilities and injury incidence. Further, sex may interact with the relationship between load carriage and dynamic postural stability to further compromise survivability. **PURPOSE:** To investigate the effect of load carriage magnitude on dynamic postural stability of men and women and its relationship to jumping ability. **METHODS:** 32 subjects (16 men, 16 women) were investigated for maximum jump height and dynamic postural stability. Dynamic postural stability was assessed by subjects jumping a horizontal distance of 40% their height over a 30cm hurdle, landing on one leg on a force plate (sample rate = 1200 Hz). 3 trials were completed for 3 load conditions: +0, +20 and +30% body weight (BW). Dynamic postural stability was determined from ground reaction force data during landings, by calculation of the dynamic postural stability index (DPSI). Maximum jump height was assessed by subjects performing 3 countermovement jumps (sample rate = 1000 Hz). Two-way mixed measures ANOVA were used to compare mean DPSI scores between sexes and conditions ($\alpha = 0.05$). Pearson's Correlation Coefficients were used to determine the relationship between jump height and change in DPSI scores between conditions ($\alpha = 0.05$). **RESULTS:** Load condition significantly affected DPSI ($F(1.387, 43.004) = 100.304$, $p = 0.001$). DPSI scores increased between the 0% (0.359 ± 0.041), 20% (0.396 ± 0.034) and 30% (0.420 ± 0.028) BW load conditions. No significant effect of sex on DPSI was found ($F(1, 30) = 0.131$). No significant sex by load interaction on DPSI was found ($F(1.360, 40.801) = 0.393$). No significant correlations were found between jump height and change in DPSI scores between conditions. **CONCLUSION:** Increased load was found to negatively affect dynamic postural stability, most likely as a result of modifying the demands of the task. Therefore, the dynamic postural stability of men and women changes comparably in response to increased load carriage magnitude. Future research should focus on the effects of load on dynamic postural stability under higher loads and during more military-specific tasks.

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1.0 INTRODUCTION

Load carriage, an essential component of numerous military tasks,[55, 56, 74] has gained significant attention in recent years due, in part, to the increased loads carried by Warfighters in Operation Iraqi Freedom and Operation Enduring Freedom.[74] During dynamic tasks, the increased load carriage magnitude challenges the postural control system, decreasing the dynamic postural stability of the Warfighter.[7, 37, 39, 53, 55, 65, 67, 86, 101] Both increased load carriage and decreased dynamic postural stability decrease performance and increase injury risk.[9, 33, 41, 42, 63, 66, 74] Few studies have directly investigated the interaction between load carriage and dynamic postural stability.[98] By better understanding the impact of load carriage on dynamic postural stability, training programs may be targeted to attenuate the effects of load carriage on dynamic postural stability and increase the survivability of the Warfighter. With the recent expansion of the role of women in the armed forces, women may now take on combat-centric roles with high load requirements. Therefore, the influence of sex on the interaction between dynamic postural stability and load carriage must also be investigated. Women recruits have a greater risk of injury than men;[4, 57, 81] the extent to which this difference is related to trainable factors rather than non-trainable, sex-dependent factors needs further investigation. Differences in fitness-related factors such as strength and aerobic capacity contribute to injury risk as do differences in anthropometric factors such as leg length.[4, 81] Further research is needed to investigate possible sex differences in further trainable factors and to understand the extent to which any differences may be addressed through training.

1.1 POSTURAL STABILITY AND CONTROL

Postural stability refers to the ability of an individual to maintain their center of mass within their base of support through coordinated reactive and anticipatory mechanisms.[88] When an individual is maintaining the position of their center of mass over their base of support they are said to be in postural equilibrium.[88] Static postural stability is this process during stationary tasks where neither the base of support nor the individual is moving.[88] Dynamic postural stability is the ability of an individual to maintain stability throughout the transition from a dynamic to a static state of movement[113] which requires the initiation of anticipatory (feed-forward) and corrective (feedback) postural adjustments.[88]

The successful completion of dynamic tasks especially those such as landing[113] and cutting maneuvers[14] that challenge the postural control system rely on dynamic postural stability. Diminished dynamic postural stability can lead to decreased performance and increased risk of injury, especially of the ankle.[16, 41, 42, 111, 113] Therefore, the impact of decreased dynamic postural stability on sport and military operations is significant; in military operations the survivability of the Warfighter may be compromised as a result.[9] An improved understanding of postural control is needed to improve dynamic postural stability training methods and attenuate performance decreases and injury increases particularly as they relate to the Warfighter.

1.1.1 Postural Control Mechanisms

Postural control is a complicated process involving the coordination of the sensory, motor and nervous systems.[88, 89] Sensory information about body position and movement, environmental factors and task parameters from the visual, vestibular and somatosensory sensory channels is integrated by the nervous system.[34, 88, 89] A coordinated motor response is executed according to the integration of sensory information.[34] Traditionally two primary motor control patterns have been defined as the means of maintaining postural stability: the ankle and hip stabilization strategies.[21] In the ankle strategy, ankle musculature is activated producing a torque at the ankle that serves to stabilize the body, while in the hip strategy the more proximal hip musculature is activated producing a torque at the hip that serves to stabilize the body.[21] During a dynamic stabilization task women exhibited increased activation of the ankle musculature compared to men.[21, 77] Recent studies have investigated the contributions of additional joints to postural control providing a more global understanding of the process[24, 43, 46, 51] The different systems contributing to postural control and the different mechanisms of maintaining stability allow for different assessment methodologies.

1.1.2 Assessing Dynamic Postural Stability

Dynamic postural stability is frequently assessed during single leg landing and stabilization tasks using one of two measures: time to stabilization (TTS) or the dynamic postural stability index (DPSI).[26, 95, 98, 110, 111, 113] Both TTS and DPSI analyze ground reaction forces during the initial contact phase of landing however, the DPSI provides measures of stability along three axes (anterior-posterior, medial-lateral and vertical) and provides a composite score of these measures making it a more functionally useful measure.[113] The DPSI (ICC 3, 1 0.96) provides greater test-retest reliability than the TTS (ICC 3, 1 0.66-0.80).[113] The single leg landing and stabilization tasks used involve subjects jumping bilaterally and landing and stabilizing unilaterally on a force plate.[25, 95, 98, 110, 111, 113] Jump distance and jump height are normalized or standardized depending on the protocol used.[95, 113] Differences in the landing mechanics utilized by and the jumping ability of men and women may lead to differences in dynamic postural stability assessed using the landing and stabilization task.[108, 110] The impact of landing mechanic differences on postural stability adjustments under different conditions[89] (load carriage,[97] fatigue[12], jump height[108]) warrants further investigation.

1.2 MILITARY LOAD CARRIAGE

As the Warfighter carries a range of loads under various conditions, there is considerable interest in the performance implications of load carriage. Load carriage has been linked to injury in the lower back and leg,[55, 74] leading to the recommendation that loads not exceed 30% of an individual's body mass.[63] In absolute terms, the Army has recommended that combat and marching loads not exceed 22kg and 33kg respectively.[37] However, these recommendations are not always practical given the demands of military tasks, such as emergency tactical operations that require loads in excess of 60kg.[63] Warfighters train carrying as little as half the load they will carry in the field which may not allow them to adequately prepare for the true demands of military operations.[81] The wide range of loads carried by Warfighters, the wide range of tasks performed when carrying these loads, and the implications of carrying these loads has led to an abundance of military-related load carriage research.

1.2.1 Effect of Load Carriage Parameters on Dynamic Task Performance

Load carriage has a negative effect on a Warfighter's ability to perform dynamic tasks through its influence on numerous factors: the metabolic cost of tasks,[30, 69, 86] time to fatigue,[10, 33] spatiotemporal parameters,[7, 53, 67, 69] joint mechanics,[7, 14, 53, 63, 86] ground reaction forces (GRFs)[53, 97, 98] and muscle activation variables.[10, 39, 61] Specific adaptations depend on the population studied, task performed and load carriage conditions but are, in general, made to attenuate load-related decreases in stability and increases in required force dissipation.[7, 14, 30, 55, 99] Further, the distribution of load on the body influences metabolic cost of load carriage and joint mechanic changes in response to load carriage.[55, 86, 100] Load asymmetry (increased posterior distribution when wearing a backpack) results in kinematic adjustments that reorient the center of mass in order to maintain stability.[7, 19] However, many of the adaptations, such as the altered joint kinematics, increase musculoskeletal strain and decrease time to fatigue during dynamic tasks, leading to performance decrements and increased injury risk.[74]

1.2.2 Factors that Influence Load Carriage Performance

Multiple studies have investigated individual differences in performance under load carriage conditions.[66, 67] Sex differences have been reported in spatiotemporal, kinematic and kinetic variables using load carriage protocols that required all subjects to carry the same absolute load.[67] The observation of similar performance characteristics with body mass normalized loads suggest the influence of other individual factors.[99] Two ostensible factors are muscular strength and power which are strongly correlated with performance on high-intensity military-specific load carriage tasks (r=0.62, 0.67 respectively).[66]

1.3 EFFECT OF LOAD CARRIAGE ON POSTURAL STABILITY

Many studies have quantified the physical reactions that compensate for reduced postural stability during load carriage, without directly measuring postural stability.[7, 14 18, 19, 39, 56, 99-101] Increased magnitude of load carriage requires more deliberate and coordinated corrective adjustments to stop the movement of the center of mass away from the base of support and to realign it over the base of support.[94] The addition of load decreases postural stability during quiet standing as well as during dynamic tasks such as a single leg landing and stabilization task.[37, 94, 98] Sex differences in dynamic postural stability may be exacerbated under load carriage conditions as the postural control system is placed under increased strain, however further investigation is needed.[67] Further investigation is needed to understand the interaction between load carriage magnitude and changes in dynamic postural stability.

1.4 DEFINITION OF THE PROBLEM

Load carriage is associated with decreased postural stability;[7, 14, 55] however, the relationship between load carriage and dynamic postural stability has not been extensively studied.[98] The interaction between the load carriage and dynamic postural stability is significant due to their impact on Warfighter mobility and injury risk.[9, 81] Men and women exhibit differences in load carriage ability and dynamic postural stability that contribute to differences in performance and injury rates among Warfighters.[4, 67, 81, 110] Sex-specific differences in load carriage ability and dynamic postural stability may be due to differences in fitness (strength, aerobic capacity) and anthropometrics.[4] Sex differences in dynamic postural stability have not been extensively studied especially under conditions that challenge the postural control system such as load carriage. Understanding the interactions between sex, load carriage magnitude and dynamic postural stability will allow for the development of training programs that can be specifically designed to improve the ability of Warfighters to adapt to increased loads.

1.5 PURPOSE

The purpose of this study was to investigate the relationship between increased military-related load carriage magnitude and dynamic postural stability during a single-leg landing task using load magnitudes normalized to subject BW. The DPSI scores under each load condition were assessed to see if any performance differences were related to differences in sex or jumping ability.

1.6 SPECIFIC AIMS AND HYPOTHESES

Aim 1: To investigate the effect of load carriage conditions of 0, 20 and 30% body weight on dynamic postural stability as measured using the DPSI

Hypothesis 1: Statistically significant decrements in dynamic postural stability would be observed as load magnitude increases relative to body weight

Aim 2: To investigate sex differences associated with the effects of load carriage conditions of 0, 20 and 30% body weight on dynamic postural stability using the DPSI

Hypothesis 2: Statistically significant differences in dynamic postural stability would be observed between men and women as load magnitude increases relative to body weight.

Aim 3: To investigate differences in the effects of load carriage conditions of 0, 20 and 30% body weight on dynamic postural stability, assessed using the DPSI, associated with individual differences in jumping ability.

Hypothesis 3: Differences in dynamic postural stability under load carriage conditions would be associated with individual differences in jumping ability.

1.7 STUDY SIGNIFICANCE

Both load carriage and dynamic postural stability impact a Warfighter's survivability by affecting task demands, task performance and injury risk.[9, 41, 42, 66, 81, 104] A better understanding of this interaction and the extent to which it may be addressed during training for men and women recruits could provide support for increased incorporation of load carriage and balance training into armed forces training programs. Further, future research efforts can focus on the contribution of different fitness variables or sex-related anthropometric variables on dynamic postural stability under load carriage conditions.

2.0 REVIEW OF THE LITERATURE

This review will examine the effects of load carriage on dynamic postural stability. Postural control mechanisms will be described especially relating to the intake of sensory information and the execution of motor responses. The effect of load carriage on biomechanical variables, spatiotemporal parameters and muscle activation patterns during the performance of dynamic tasks will be detailed with a focus on how these variables influence stability. Investigations directly examining the influence of load carriage on dynamic postural stability will then be reviewed.

2.1 POSTURAL STABILITY AND CONTROL

Essential to the successful completion of dynamic tasks is dynamic postural stability.[98] Dynamic postural stability is an individual's ability to maintain the position of their center of mass over a moving base of support or over a static base of support experiencing an external perturbation through the coordination of different joints, importantly the ankle, knee and hip.[28, 49, 95, 98] The sensorimotor system is responsible for maintaining postural control and describes the cooperative function of the sensory, motor and central nervous systems.[88, 95] The visual, vestibular and somatosensory sensory systems work together to detect information about the surrounding environment and body movements.[88, 95] This sensory information is integrated and processed by the central nervous system so appropriate muscular responses can be initiated by the motor system.[88, 95] Motor responses are executed according to perceived task demands, environmental constraints and individual capabilities.[21, 35, 90, 111] To maintain postural stability, motor responses must maintain individual joint stability through the targeted and graded activation of specific muscles.[89, 98]

Postural stability has significant implications on injury occurrence.[41, 42] Athletes with lower levels of postural stability at the beginning of the season are more likely to experience an injury during the season, especially of the ankle joint.[41, 42] Ankle sprains are the most prevalent time loss injury reported in athletic populations.[90] Similarly ankle sprains are the most common preventable musculoskeletal injury reported in Warfighters.[4, 50] Constraints, such as fatigue, previous injury and load carriage can challenge the postural control system contributing to decreased performance and increasing injury risk.[4, 111, 113] The external load worn by Warfighters compromises their postural control capabilities,[37, 98] however further research is needed to elucidate the nature of the relationship between the external load and dynamic postural control specifically and to then understand how to mitigate any load related deficits in postural control.

Balance and plyometric training programs can improve postural stability and attenuate deficits associated with different constraints.[29, 41, 71] The training programs improve neuromuscular control which contributes to reduced hazardous joint mechanic patterns.[29, 41, 71] Traditionally military training programs have not incorporated balance and plyometric training but rather have focused on aerobic training and strength development.[73, 96] The incorporation of load carriage into the performance of military-related dynamic tasks challenges the postural control system of the Warfighters.[36, 37, 84, 94, 98] By better understanding how postural stability and control change under load carriage conditions, the challenges faced by the Warfighter can be better understood and future studies can investigate ways to mitigate these challenges.

2.1.1 Sensory System Function

The ability of the visual, vestibular and somatosensory sensory channels to pick up information about the environment and relay relevant information to the appropriate destination is essential to postural control.[88, 89] The availability of accurate information from each sensory system depends on environmental conditions and task demands.[45] Each sensory channel is optimized or compromised under different circumstances.[45] The sensory information that is most accurate and most relevant to maintaining postural control is more heavily weighted and provides a greater contribution to maintaining postural control.[45]

For visual sensory information, the successful control of and appropriate direction of gaze determines the quality of sensory information contributed to postural control.[106] If an individual sees an oncoming perturbation (i.e. a tackler in a rugby match, uneven ground they will have to navigate) they can initiate appropriate anticipatory postural adjustments to prepare for the perturbations.[20, 111] For example, during jump landing, preparatory kinematic changes that aid shock dissipation and decrease initial contact vertical GRFs are initiated before the landing when there is sufficient visual input.[93] When there is a lack of (eyes closed conditions)or reduced visual information(diminished lighting), anticipatory postural adjustments are not initiated. As a result, more hazardous landing patterns are adopted reflected in increased vertical GRFs[23, 93] There is also greater movement uncertainty when visual input is compromised, reflected in a greater degree of coordination pattern variability and decreased stability.[38, 93, 106] Input can also be compromised if vision of foot-strike is partially obstructed such when wearing or carrying something anteriorly. Further, helmets, commonly worn by Warfighters, firefighters, athletes among others, negatively impact the ability to track visual information and adjust the position of the head and neck as needed for the efficient intake of visual information and to maintain postural equilibrium.[82, 83] Depending on the nature and difficulty of the task, the vestibular and somatosensory channels can compensate for compromised visual input.[93]

The role of the vestibular system is to maintain center of mass position and to coordinate stable head motion.[105] To redirect gaze and reorient the body efficiently during large and whole body movements, the head, eyes and trunk must move in a coordinated fashion.[106] The redirection of gaze and reorientation of the body is essential to maintaining stability especially during change of direction and agility tasks.[82, 83, 106] During faster pace tasks, such as running or jogging, the influence of the vestibular system on postural stability is reduced.[31] The importance of the vestibular system to trunk coordination and movement is of particular importance in the hip coordination pattern used to maintain postural stability and discussed in greater detail in the next section. In short, individuals with vestibular deficits had greater difficulty maintaining postural equilibrium due to an inability to effectively coordinate motion at the hip with that of the other joints contributing to postural control.[24] In healthy individuals balance is maintained through the coordinated and redundant motion of joints at different points along the kinetic chain.[24, 43] Individuals with vestibular deficits were less able coordinate their trunk and leg motion leading to increased trunk sway and decreased postural stability.[24, 45] Therefore, a disruption in vestibular input may not only affect postural control capabilities but also postural control strategy.[45]

The third sensory channel contributing to postural control is the somatosensory system, which conveys afferent information from peripheral mechanoreceptors, thermoreceptors and pain receptors to the central nervous system.[88] One component of the somatosensory system is proprioception, afferent information from peripheral mechanoreceptors that contributes to postural control, joint stability and voluntary muscle movement.[88] Ruffini receptors, Golgi tendon organs and muscle spindles collectively provide information about joint, limb and muscle movement and location in space essential to maintaining joint stability and postural stability.[88] Muscles spindles are mechanoreceptors embedded in muscles fibers which are activated by lengthening of muscles.[47] If a postural disturbance causes a muscle to lengthen unexpectedly the muscle spindles may activate and initiate a corrective motor response.[47] Proprioception of the foot is especially important to the maintenance of postural stability and as such footwear influences postural stability by impacting the foot's proprioceptive capabilities at the foot-ground interface.[11] Mechanoreceptors in the foot, thought to be the slow adapting mechanoreceptor with myelinated afferents, sense plantar shear and stimulus directions contributing substantial information to the foot's kinaesthetic sense.[11, 92] The cushioning effect of footwear compromises the sensory feedback available to these mechanoreceptors.[11, 92] When performing single leg landings under shod and unshod conditions, postural stability was negatively affected by footwear.[11] Further, individuals experienced decreased peak vertical forces and loading rates in the unshod conditions.[11] Foot mechanoreceptors are sensitive to footwear but the addition of footwear alters the foot-ground interface impacting the accuracy of the proprioceptive information contributing to postural control.[4, 11] Each sensory channel provides information needed to maintain stability and execute dynamic tasks but this information alone cannot maintain stability; the successful integration of this information and the execution of an appropriate muscular response are needed to maintain stability.[88, 89]

2.1.2 Motor Response in Postural Control

At the muscle, there are multiple mechanisms acting to maintain postural stability. Muscle tissue and the connective tissues at the joint have some intrinsic passive stiffness which helps maintain joint stability.[47, 58] However, this passive stiffness does not provide enough mechanical stability to maintain postural stability on its own.[47, 58] Muscular activation provides a greater contribution to maintaining postural stability through reflexive activation and more coordinated responses via the central nervous system.[47] The magnitude, pattern and timing of muscular activation determines the ability of the muscular system to maintain postural stability

Muscle Activation and Stiffness Muscle activation is inherently linked with stiffness, which has significant implications in postural stability.[19, 89] Stiffness, in general, is defined as the ratio of change in force per change in length[89] and can apply to muscles, entire joints or specific structures. Joint stiffness is influenced by all structures crossing a joint, including muscles and passive connective tissue structures, and protects the joint by increasing mechanical joint stability which decreases risk of injury.[111] Increased joint stiffness enhances joint stability by increasing rigidity and decreasing compressibility.[44, 89] Muscular stiffness reflects muscle activation; increased stiffness and activation improve the ability of the muscles and muscle spindles to react to perturbations quickly by ‘priming’ the muscles to respond.[47, 89] Through this postural control is improved.[89] The contribution of active and passive stiffness to overall joint and muscular stiffness depends on muscle activation, joint angle and the angular velocity of motion at the joint.[32] Further the contribution of active and passive stiffness to postural stability depends on the nature of the task.[44, 58] During static postural stability tests, stiffness is maintained. The demands of the task remain relatively constant and having the muscles ready to react to sudden changes in length, helps to maintain postural stability and to prevent a fall. During other more dynamic tasks, such as landing from a jump or hopping, stiffness is more variable.[44] The demands and nature of such tasks change throughout their completion.[44] Hopping, for example, requires a continuous storage and release of energy.[44] Increased active stiffness may indicate that the muscles are "primed" and ready to respond to a perturbation.[47, 58] Passive stiffness will also play a role in ensuring the muscle is primed to respond during challenging postural tasks.[58] Increased passive stiffness of the muscle and passive connective tissue structures will improve proprioceptive feedback and the response of proprioceptive mechanoreceptors.[47, 58] Increased stiffness can contribute to anticipatory and simultaneous postural responses.

Motor Control and Stabilization Strategies Two primary motor response patterns used to maintain postural stability and ensure postural control have been defined: the ankle and hip strategies. In the ankle strategy, the ankle musculature is preferentially activated to absorb energy and control body motion about the ankle joint.[22, 64] In the hip strategy, reciprocal movement at the ankle and hip joints maintains stability using the more proximal hip musculature.[6, 22] The ankle strategy is preferred when responding to perturbations of relatively small magnitudes and velocities because it induces small displacements in the center of gravity that do not further compromise postural stability.[22] The hip strategy contributes to relatively large center of gravity displacements which perpetuate postural instability; however, the hip musculature is less fatigable and more powerful than the smaller, distal ankle musculature increasing the preference for the hip strategy when the postural control system is placed under increased stress such as during long duration physical activities and larger perturbations.[22] Further the higher velocity movement at the hip may activate Golgi tendon organs initiating a reflexive muscular response, further enhancing postural control.[6] When presented with a perturbation while standing on the ground individuals favored the ankle strategy but when presented with the same perturbation while standing on a narrow beam, where feelings of instability and anxiety may be increased, they favored the hip strategy.[40] Women show a preference to use ankle strategy compared to men, indicating either improved postural control or a preference for different postural control strategies between the sexes.[77] If the postural control system is further challenged the ankle or hip strategy alone may not be sufficient to maintain postural stability forcing the individual to step or hop to prevent falling in order to reposition the center of mass over the base of support[21, 40]

Postural control is inherently a complicated and multivariate process incorporating multiple systems and involving responses at multiple joints.[24, 43, 46, 51] The focus on the mechanics of the ankle and hip simplifies the study of postural control by not specifically studying the mechanics at other joints which may still contribute to postural control. Various models are used to study postural control based on this focused approach. The inverted pendulum model focuses solely on the ankle modeling the body as one rigid segment rotating about the ankle joint.[21] Use of this model provides an oversimplification of postural control and does not allow for an accurate understanding of the global motor response used to maintain postural equilibrium.[43, 51] The hip and knee make significant contribution to the maintenance of postural equilibrium and their contributions are not taken into account using the inverted pendulum model.[21, 24, 43] The double pendulum model models the body as two segments rotating about the hip and ankle joints.[21, 43, 51] Critics of this model contend that by only viewing postural stability and control through two joints a significant amount of understanding is lost.[43, 51] Hsu and colleagues studied postural control during quiet stance using a six degree of freedom model which took into account motion at the ankle, knee, hip, lumbosacral, C7-T1, cervical spine and atlanto-occipital joints.[43] Joint motion was coordinated across the six studied joints to minimize fluctuations in COM position; neither the hip nor the ankles were determined to play a more significant role in minimizing COM movement than any of the other joints.[43] By studying postural control and stability through more degrees of freedom a better understanding as to the true multivariate and global nature of the processes can be gained.[43, 51]

Temporal Constraints on Motor Responses Postural control success and strategy are influenced by the time available to recognize and react to a potential perturbation. The relative contribution of anticipatory postural adjustments (feed-forward controls), simultaneous postural adjustments and compensatory postural adjustments (feedback controls) to postural control vary based on the time available to sense and respond.[88, 94] Anticipatory postural adjustments act before a postural disturbance through the preparatory activation of postural muscles.[90] During single-leg landing and stabilization tasks, increased anticipatory muscle activation increases the likelihood of a successful landing.[111] The early activation prepares the individual to land and allows them to land and stabilize using a more optimal muscle activation pattern.[111] Simultaneous postural adjustments maintain postural stability during voluntary movements.[90] Compensatory postural adjustments involve the activation of postural muscles and, in some cases, the initiation of movement strategies such as a step or a hop to restore postural stability in response to the perturbation.[90] When an individual is unaware of or does not have sufficient time to react to an impending postural disturbance, appropriate anticipatory adjustments cannot be made and more reliance is placed on compensatory strategies decreasing stability.[114] Wikstrom and colleagues investigated muscle activation differences between successful and failed single-leg landing and stabilization trials.[111] During successful trials lower extremity muscles activated earlier and to a greater extent than during failed trails.[111] Increased anticipatory muscle activation contributes to increased muscle stiffness during landing.[72] Furthermore, the muscle activation pattern of the successful stabilization trials differed from that of the failed trials.[111] During successful trials the vastus medialis activated first followed by the semimembranosus, long head of the gastrocnemius and tibialis anterior.[111] In failed trials, however, the long head of the gastrocnemius activated first followed by the semimembranosus, tibialis anterior and vastus medialis.[111] During the successful trials the vastus medialis activated significantly earlier while during the failed trials the ankle musculature activated earlier.[111] The significance of anticipatory activation of different musculature is related to the complexity of the task being performed. During a simpler dynamic stabilization task, the transition from a single to double leg stance the timing of gluteus medius activation did not play a significant role in preventing excessive pelvic drop or minimizing the knee abduction moment while activation magnitude did.[52] During the simpler task, the hip musculature plays less of a role in maintaining stability as stability can be maintained using the ankle musculature.[6]

2.1.3 Methods of Testing Postural Stability

There are many different tests used to assess postural stability. Tests of quiet standing assess static postural stability[3, 37, 77, 94] whereby test difficulty is manipulated by altering the base of support or visual input.[77] Testing static postural stability is helpful to assess the postural stability of older individuals or those with balance disorders/deficiencies; however it may not challenge the postural control system of healthy, active individuals and therefore may not test the limits of their postural control capabilities. Furthermore, static postural stability tests do not provide a measure of postural stability during dynamic tasks and therefore may not provide a relevant measure of postural stability for active individuals.[95, 98] Therefore, for active individuals dynamic postural stability is often assessed. Tasks such as the transition from double to single leg stance, stepping off of a box and a single leg landing are commonly used.[26, 82, 83, 95, 98, 109-111, 113] During the single leg landing and stabilization tasks, subjects jump bilaterally then land and stabilize unilaterally on a force plate without hopping or touching down their contralateral limb.[95, 113] These tasks assess the individual's ability to control and stabilize their center of mass.[113] According to one protocol, subjects complete anterior-posterior jumps of 70cm to a height equivalent to 50% maximum jump height.[110, 111, 113] In a second protocol, subjects complete anterior-posterior jumps of 40% body height over a 30cm hurdle and medial-lateral jumps of 33% body height over a 15cm hurdle.[95, 98] The protocol has demonstrated good intersession reliability (anterior-posterior jump ICC=0.86, medial-lateral jump ICC=0.92).[95] The differences between the protocols challenge individuals differently. The use of standardized jump heights or distances mean that individuals of different heights and jumping ability will be challenged to different extents.[110] The different challenges placed on different individuals may further compromise performance on the dynamic tasks by influencing landing mechanics.

Jumping Ability The landing and stabilization tasks used to assess dynamic postural stability involve landing and stabilizing following a jump.[26, 95, 110-113] Therefore, the individual's jumping ability may impact their performance on the test particularly if jump heights and distances are not scaled according to individual ability. Sex differences is dynamic postural stability exist when all individuals are required to jump the same absolute distance due to women jumping a distance that is relatively further for them based on their reduced jumping ability and height.[110] Sex differences in jumping ability exist and may contribute to observed differences in dynamic postural stability.[87, 108] Men jump higher during countermovement jumps than women.[87] This is due, in part, to increased knee extensor power in men related to a greater expression of type II muscle fibers, the fiber type responsible for muscle force generation and power output.[49, 87] The expression and recruitment of type II muscle fibers in women can be increased through a training program which incorporates resistance and load carriage.[73] When men and women are matched according to strength differences in relative power generated during the concentric phase of the countermovement jump exist but no differences exist in relative force output or relative jump height.[87]

Landing Mechanics Proper landing mechanics allow for efficient energy dissipation and shock absorption; force transmission to the joints is significantly affected by joint position and body posture during the initial contact of landing and walking.[68, 83] The amount of potential energy dissipation that can occur without changing landing mechanics is limited.[83] If the energy needed to be dissipated is increased, as it is with load carriage, changes in coordinative patterns may be initiated as protective mechanisms to aid in shock absorption and attenuate increases in shock that would otherwise be transmitted up the kinetic chain.[83]

Sex-related differences in landing mechanics have been extensively studied due to the proposed link with the increased incidence of non-contact ACL injury in women.[3, 15, 44, 108] Limited consistent kinematic differences have been found which may be attributed to the different populations studied and different landing tasks performed. Depending on the nature of the landing women land with increased hip flexion angle, hip abduction angle, hip adduction moment or knee valgus angle. Kinematic differences vary with different populations and when studying different landing tasks. During a stop-jump from 40% body height and a drop-jump from 0.51m, women 101st Airborne Division Soldiers landed with greater hip flexion and knee valgus than the men.[3] Similarly, during drop jumps from 30cm women team sport athletes exhibited greater peak knee valgus angles than men team sport athletes and than men and women dancers.[78] During landings from 30cm, 40cm, 50cm and a height equivalent to individual maximum jump height, recreationally active women displayed greater hip abduction during the unilateral landings from 50 cm, but no other sex differences in hip, knee or ankle mechanics were observed.[108] When performing countermovement jumps, women volleyball players demonstrated an increased range of motion of the hip, knee and ankle during landing than men volleyball players.[44] When landing from lower heights, women absorbed more energy at the ankle than men, indicating a preference to stabilize using the ankle.[108]

The kinematic and energetic sex differences contribute to observed sex differences in stiffness and stability during landing tasks. Women consistently land with decreased absolute leg stiffness than men due to their decreased body mass.[15, 44] According to the spring-mass model, leg stiffness is directly related to body mass.[15] When normalized to body mass, the sex differences in stiffness were minimized and were task dependent.[15] No differences in relative stiffness were observed during repetitive landings in hopping tasks but women had decreased relative leg stiffness during landing from volleyball block jumps.[15, 44] Hopping is a repetitive task that requires the continual storage and usage of energy necessitating that stiffness is maintained while landing requires energy dissipation and therefore a reduction in leg stiffness.[44] The decreased leg and knee stiffness women land with may be due to a reduced capacity to generate stiffness or may be a protective mechanism adapted by the experienced volleyball players used in the study to reduce landing GRFs.[15, 44] The decreased stiffness is associated with increased range of motion of the hip, knee and ankle joints during the landing; the joints are more collapsible.[44] The impact of decreased stiffness on the musculoskeletal system and on postural stability needs further investigation. The hopping task did not sufficiently challenge the stiffness generating capabilities of women to elicit sex differences during the task while the landing task did.[15] However, women have also been found to have increased stiffness compared to men during different landing tasks.[64] During landing, a higher co-activation of the ankle and knee right before initial contact resulted in higher limb stiffness at landing.[64] Women had reduced lower extremity dexterity, the ability to regulate end-point force magnitude and direction which contributes to an individual's ability to control and reorient the center of mass.[64] Increased stiffness may contribute to anticipatory postural adjustments and may compensate for decreased dexterity.[64] Differences in landing mechanics may relate to differences in stabilization strategies and stabilization capabilities but further investigation is needed.[110]

2.1.4 Measurements of Postural Stability

Static postural stability is measured multiple ways including through postural sway, center of pressure (COP) trajectory and COP velocity. Postural sway provides a measure of COP trajectory and displacement.[91] The frequency characteristics of postural sway reflect the relative contribution of different sensory channels contributing to postural control; low frequencies (0.15-0.5Hz) indicate sensory system function, medium frequencies (0.5-2Hz) cerebellum function and high frequencies (2-6Hz) proprioception and reflex responses.[91] Frequency analysis is particularly useful for individuals with balance deficiencies to identify the source of the deficiency.[91] However, measures used to evaluate static postural stability are not applicable in the evaluation of dynamic postural stability.[95]

TTS and DPSI are two measures used to assess dynamic postural stability.[113] TTS is the time it takes for the resultant GRFs to return to within a specified range of baseline measures after the completion of a functional jump protocol.[113] TTS provides a measure of overall postural stability but does not allow for assessment of postural stability along individual axes..[109, 113] DPSI provides a functional measure of neuromuscular control by providing a composite score of the stability indices in the anterior-posterior (APSI), medial-lateral (MLSI) and vertical (VSI) directions.[113] The first three seconds of GRF data following initial contact are used to calculate the stability indices.[98] The directional stability indices reflect deviations in GRFs measured along each of the axes.[113] While the MLSI provides poor reliability (ICC 3,1=0.38), the APSI, VSI and DPSI provide excellent test-retest reliability (ICC 3,1=0.90, 0.97 and 0.96 respectively).[110]

2.2 LOAD CARRIAGE

In recent years Warfighters have been required to carry loads of increasing magnitudes often exceeding the Army recommendation of 21kg.[63] For example, during emergency tactical operations Warfighters may carry 60kg loads (equivalent to ~78% BW of the average man Warfighter).[27, 74] Load carriage makes dynamic tasks more difficult by increasing the momentum of the system and the GRFs experienced by the body.[28, 72, 97, 99, 101] In order to control and coordinate body movements, body musculature must do more work.[28, 72] For example, when walking under load carriage conditions, lower extremity muscles must generate a greater propulsive force during the second half of stance phase to overcome the increased inertia of the body and initiate forward motion.[99] Increased momentum also makes it more difficult for an individual to make postural adjustments.[28] Joint mechanics and movement pattern changes attempt to compensate for the load related decreases in stability, increases in task demands and increases in force acting on the body.[7, 14, 19, 28, 83, 86]

However, these adaptations also decrease locomotive ability and increase strain on the musculoskeletal system leading to greater risk of injury.[14, 97] Decreased locomotive ability is manifested as performance decrements; sprint velocity,[9, 63, 66] jumping ability[33] and velocity during a casualty drag[66] all decrease with the addition of load. Increased inertia of the body due to the addition of the external load decreases the ability of the Warfighter to accelerate when initiating movement and increases the metabolic cost of tasks.[9, 99] Decreased locomotive ability combined with increased injury risk has a negative effect on the survivability of the Warfighter in the field.[9] An increased occurrence of foot blisters, spinal injury and degeneration, muscle tightness and shoulder, back, leg and feet soreness is associated with load carriage especially in new recruits.[8, [74, 79] The injury profile of women and men Warfighters differs; women Warfighters are more than twice as likely to sustain a foot injury and are more likely to sustain a stress fracture of the hip than men Warfighters.[80, 103] The nature of military marching causes women to increase their stride length more than men, which alters how force is transmitted up the kinetic chain.[67] As they elongate their stride, more stress is placed on the neck of the femur leading to its fracture.[80] Further, the overall injury rate of women Warfighters is twice that of men Warfighters.[4, 57, 73] However, the strongest predictor of injury rate is aerobic fitness and when injury rates are normalized to fitness level, sex differences no longer exist.[4, 8, 57] Improved training programs and programs that incorporate load carriage may better prepare the Warfighters for the demands they will experience in the field and may reduce injury risk.[73] The combination of decreased locomotive ability and increased injury risk compromises the survivability of the Warfighter.[9, 74]

2.2.1 Effects of Load Carriage

Ground Reaction Forces and Joint Kinetics With the addition of an external load, GRFs increase and greater forces are transmitted to and therefore, must be absorbed by the joints.[10, 53, 97, 101] The three directional components of GRF are not impacted by load in the same manner, as seen during a prolonged duration loaded walking protocol.[53] GRFs in the anterior-posterior and medial-lateral directions did not change with the addition of 20% BW and 40% BW loads while those in the vertical direction increased.[53] The increased vertical GRF was accompanied by an increased vertical impulse.[53]

Increased load carriage magnitude consistently increases vertical GRFs however; the magnitude of the increased vertical GRFs is also, consistently less than the magnitude of the load increase.[48, 53, 99] With an evenly distributed anterior-posterior load, such as a vest or webbing, vertical GRFs increased 5-6% for every 10% increase in carried load during gait.[99] During a separate loaded gait investigation, vertical GRFs increased with load increases of 0-20% body weight and 20-30% body weight but did not increase from 30-40% body weight.[101] The differences between the percent increase in external load and GRFs is due to load accommodation.[48, 76] The increases in GRFs do not mirror the increases in load magnitude due to other adaptations occurring which serve to attenuate the increase in GRFs in order to protect the joints and body from injury.[48] Changes in spatiotemporal patterns at 40% body weight acted to attenuate the expected increase in GRF.[101] Spatiotemporal and kinematic changes attenuate some of the increased force transmitted to the body and protect against this increased force.[99, 101]

When increased forces are exerted on the body, increased forces are transmitted to the joints resulting in increased joint moments. Additional external load increases the overall upper, lower and net moments experienced by the body.[59] Peak knee extension and flexion and ankle plantarflexion moments increase during gait.[99, 107] Peak hip extension and adduction moments increase during gait and the stance phase of cutting maneuvers respectively.[14, 99, 107] Knee flexion moment increases during landing.[75] Load accommodation strategies attenuate the effects of load on individual joints.[48, 49, 59] However, the changes in the joint moments still increase the likelihood of neuromuscular impairment and load accommodation strategies induce changes in joint mechanics that further exacerbate the effects of fatigue and increase musculoskeletal strain.[7, 10] Neuromuscular impairment occurs as the increased force strains the musculoskeletal system and as the musculoskeletal system fatigues due to the increased task demands under load carriage conditions.[10] When neuromuscular function is impaired, the ability of the musculature to dissipate the increased GRFs is compromised.[86] Kinematic adjustments and neuromuscular impairment will be discussed in more detail in later sections.

In military load carriage, where a helmet is often worn, increased stress is placed on the neck.[7] The ability of the neck to contribute to dynamic balance and stabilization is then affected.[7, 83] The head and neck aid in reorienting the center of mass which is shifted during load carriage[7] and play a vital role in the pickup of visual information.[83] Compromising this ability impacts the available contribution of the visual and vestibular sensory channels to the maintenance of postural stability.[82]

The effect of increased GRFs is not isolated to an individual joint or region of the body, but rather, impacts joint moments all along the kinetic chain.[7, 14, 60] Increased GRFs and joint moments subsequently impact time to fatigue, neuromuscular function,[10] joint kinematics,[7, 99, 101] and spatiotemporal parameters.[53]

Spatiotemporal Parameters The effect of load carriage on gait parameters has been investigated during different walking and running protocols.[7, 14, 18, 19, 53, 56, 63, 67, 101] Changes in stride frequency and stride length are dependent in part on the walking speed used in the study protocol. Studies have investigated subjects walking at a variable self-selected pace,[7, 101] a constant self-selected pace[18, 19] and a study defined pace.[10, 14, 69] When subjects were able to self-select their walking pace, their walking velocity and cadence decreased with increased load.[101] Small load carriage magnitudes induced increases in stride length and stride frequency both of which decreased when loads exceeded 16kg.[7] However, when subjects walked at a constant pace for the entirety of the protocol, stride frequency was not affected by external load magnitudes up to 30% body weight.[18] However, when load magnitudes were systematically decreased from 40% BW, stride frequency decreased linearly with each magnitude decrease of 10% BW.[18] The stride length of women was more sensitive to increases in absolute load carriage magnitudes as these increases were greater relative to their body weight.[67]

Regardless of walking speed or duration, increased time spent in the stance phase of gait is consistently associated with load carriage.[7, 14, 18, 53, 67, 99, 101] Attwells and colleagues reported an initial decrease in stance time with a load of 8kg but then subsequent proportionate increases in stance time with subsequent increases in load magnitude.[7] At loads equivalent to 40% BW, stance time increased greater than was to be expected if a linear relationship was maintained.[18] Increased time in stance allows for the increased momentum of the loaded system to be slowed, controlled and stabilized before forward motion is continued.[7, 14] Load carriage of 22kg had no effect on the time spent in double support during a prolonged walking protocol in recreationally active men who were inexperienced with load carriage..[69] This finding was attributed to the load carriage magnitude not being challenging enough to the athletic population used to induce spatiotemporal changes.[69]

Kinematic Effects Changes in joint moments and spatiotemporal parameters occur concurrently to changes in joint kinematics. During many military-related load carriage investigations, a helmet is incorporated in the load carriage configurations.[7, 14, 82, 83] While the helmet does not contribute greatly to the absolute magnitude of the load carriage, it does induce a more forward head position impacting the performance of dynamic tasks.[7, 19, 82] The more downward head angle makes it more difficult to pick-up visual information by reducing the field of regard.[82] The field of regard is a dynamic definition of an individual's field of vision which takes head movements into account.[82] Furthermore, peak velocity of head movement increases which destabilizes head trajectory.[82] These changes reduce an individual's dynamic visual acuity and decrease their perception-action coupling capabilities which reduces their ability to maintain stable posture with load.[82] Load carriage increases the body's momentum during movements and increases the energy that must be dissipated in order to reorient the body in a stable manner; the changes seen at the head are indicative of the body's inability to properly dissipate all of this energy during a postural transition.[82]

Military load distribution consists predominantly of posterior load contained within a rucksack which shifts the COM posteriorly resulting in increased forward lean (trunk flexion).[7, 19, 70] Trunk flexion is resisted by eccentric contraction of the hamstrings and semispinalis muscles.[7] The eccentric contractions strain these muscles, contributing to the increased risk of leg and lower back musculoskeletal injury associated with load carriage.[33, 80] While it has been suggested that forward lean acts to reposition the COM over the base of support maintaining postural equilibrium,[7] it has also been argued that the purpose of this repositioning is to maintain the position of the COM relative to the ankle in the sagittal plane regardless of if postural equilibrium is maintained.[19] Walking is controlled falling where postural equilibrium is perpetually disrupted as the COM is not positioned over the base of support for the majority of the gait cycle.[19] The ankle serves as the axis of rotation for the body so its position relative to the COM contributes to the impulse generated at push-off, the angular momentum generated about the COM and the trajectory of the COM during walking and running.[19] Increased trunk flexion maintains COM trajectory until load reaches 40%.[19] In order to maintain COM trajectory the increased trunk flexion is coupled with increased ankle dorsiflexion at initial contact.[19, 53, 86, 99] The trajectory of the COM influences kinetic and potential energy transfer throughout the gait cycle affecting the metabolic cost of the movement.[19] COM trajectory is properly maintained throughout the gait cycle for loads ranging from 0-30% BW; however, a significant change in the vector occurs when load carriage magnitudes reach 40% BW.[19] The constant COM trajectory indicates invariance in the lower extremity and a reduction of the degrees of freedom that must be controlled.[19]

There are conflicting results about whether hip flexion increases[7, 65, 99] or remains constant[69, 86] during gait under load carriage conditions. The role of increased hip flexion has not been widely discussed but given the significance of the hip musculature in force absorption, the increased flexion likely aids in this process and serves as a protective mechanism.[7] Increased peak knee flexion is also associated with load carriage during prolonged walking[53, 86, 99] and landing.[97] One study reported that this increase was not present until load magnitude reached 30% BW;[86] however, a second study reported that this increase was present with loads equivalent to 20% BW.[101] The first study involved Army recruit men walking at a set velocity while the second involved women recreational hikers walking at a self-selected pace. Knee flexion is associated with quadriceps fatigue.[86] Based on the study population differences, load carriage experience, fitness level and sex may contribute to the kinematic adjustments made in response to load carriage.

The changes in the orientation of the knee and hip during load carriage are particularly significant; knee and thigh muscles act as shock absorbers during the initial contact period of landing and walking[53] with the knee joint being the primary location of energy absorption .[108] Therefore, the kinematic changes at the knee and hip alter the shock absorbing capabilities of the kinematic chain.[86] Furthermore, these kinematic changes contribute to increased stance time, an indication of decreased postural stability and decreased locomotive ability.[14]

Muscle Activation/Stiffness The locomotive ability and postural stability of the Warfighter is influenced by muscle activation and joint stiffness. Muscle activation of the soleus, gastrocnemius, lateral hamstrings, vastus medialis, vastus lateralis and rectus femoris increase with loads of 25kg.[10] During the first half of stance the increased activity of the quadriceps muscles helps support the increased weight of the body and during late stance the increased activity of the calf muscles helps to accelerate this increased load to continue locomotion.[10, 61] The active stiffness component of joint stiffness is due to muscle activity.[44] The co-contraction of antagonist muscle groups, associated with load carriage,[91, 111] increases joint stiffness by increasing the compression forces between joint articular surfaces.[89] Muscular stiffness increases linearly with increased load magnitude[18, 84, 99] until the load increases from 30 to 40% body weight where a greater than linear increase is observed.[18] The increased stiffness and increased muscle activation decreases the time to muscular fatigue and can induce neuromuscular impairment.

Neuromuscular Impairment Neuromuscular impairment refers to the decreased functioning of the musculature due to changes in the muscle’s contractile properties or in central nervous system control.[10] These changes are manifested as decreased force production, increased metabolic cost of exercise, decreased neuromuscular control and decreased sprint performance.[10, 33] Load carriage increases the GRFs acting on the body forcing the muscles to dissipate more force which increases the muscle damage leading to neuromuscular impairment.[10] Damage to the muscle fibers impairs excitation-contraction coupling and reduces calcium release from the sarcoplasmic reticulum leading to low-frequency fatigue.[10] Furthermore, the increased trunk flexion associated with posteriorly distributed load is counteracted by the eccentric contraction of the hamstrings and lower back muscles.[7] Eccentric contractions damage the muscle tissue increasing the susceptibility of the muscles to neuromuscular impairment.[33] During landing tasks the quadriceps muscles contract eccentrically to absorb and dissipate landing forces therefore, landing tasks that incorporate load carriage, such as Warfighters jumping down from a vehicle, place the Warfighters at a higher risk of neuromuscular impairment and further compromise performance.[97] Changes in central nervous system functioning correspond with changes at the muscles.[10] Following a long duration walking protocol, decreased maximal voluntary contraction of the knee extensors was coupled with decreased voluntary activation indicating that there was a central nervous system contribution to the observed neuromuscular impairment.[10]

2.2.2 Factors Affecting Load Carriage Performance

Some trainable factors such as strength and power impact how load carriage affects the Warfighter.[66] Recreationally active individuals who have greater upper and lower body strength as well as greater lower body power took significantly less time to complete a 30m sprint, 27m zig-zag run and a 10m casualty drag of 79.5kg while carrying a load of approximately 42kg.[66] Further, a study using maximum vertical jump height as a measure of lower extremity muscle power found increased muscle power to be associated with a decreased risk of injury related to load carriage in new police recruits.[79] Maximum vertical jump height is associated with lower extremity strength and power providing a functional measure of the two variables as well as of performance.[79, 115] Strength and power are both modifiable characteristics which, if targeted in training programs could attenuate some of the performance decrements and injury risk associated with load carriage.[66, 104]

2.3 POSTURAL STABILITY AND LOAD CARRIAGE

While numerous studies have reported on adaptations made to attenuate load carriage related postural stability decreases,[7, 14, 18, 19, 53, 55, 56, 63, 67, 69, 70, 99, 101] less have directly investigated the relationship between load carriage and postural stability.[36, 37, 84, 94, 98] Wearing an external load negatively affects static postural stability assessed using sway area and sway excursion.[36, 37, 84, 94] When sway area and sway excursion in the anterior-posterior and medial-lateral directions increase, reaching the limits of the base of support is more likely.[94] If the limits are reached, postural stability cannot be maintained; a compensatory movement such as a hop or step must occur to prevent a fall.[21] However, as previously stated static and dynamic postural stability are separate qualities, therefore the effect of load on static postural stability does not necessarily represent the effect load would have on dynamic postural stability.[95]

The effect of load carriage on dynamic postural stability has been investigated; however, the methodological differences in load carriage configuration/magnitude and dynamic postural stability assessment used make it difficult to make generalized conclusions. One study directly investigated the effect of load carriage on dynamic postural stability in 101st Airborne Division Soldiers using the Soldiers' personal interceptor body armor (IBA).[98] During the loaded condition, subjects performed a single-leg landing task with greater MLSI, APSI, VSI and DPSI scores than they did in the unloaded condition.[98] However, as the Soldiers used their own IBA, the load was not standardized (12.47 ± 2.56kg) or normalized (15.55 ± 4.18%).[98] The use of the Warfighters' own IBA strengthens the ecological validity of the study but makes it more difficult to make comparisons between individuals and to make generalizations about the exact relationship between load carriage and dynamic postural stability. The range of absolute and relative load carriage magnitudes carried by the subjects in the study demonstrates one of the complications when studying military-related load carriage; while absolute standards for load carriage exist the actual load carried by each Warfighter varies. A Warfighter may carry additional load based on specific mission needs, individual needs or individual capabilities. The decrement in dynamic postural stability associated with the IBA, a relatively light load compared to many of the loads Warfighters are required to carry, highlights the need for an improved understanding of how load carriage impacts dynamic postural stability and maneuverability.[27, 98]

Other dynamic postural stability assessments used include traversing a balance beam[17], obstacle negotiation[13] and stabilizing after stepping[83] or jumping[75, 76] off of a box. While these studies have used tasks targeted to test dynamic postural stability they have not directly measured dynamic postural stability but rather have analyzed variability in the movement patterns used to complete the tasks.[13, 75, 76, 83] Analyzing movement pattern variability provides insight about changes in postural affordances with the addition of external load.[82, 83] The term affordance refers to the possible actions an individual may perform defined by the interaction/intersection between their capabilities, the environment and the demands of the task.[35] The limits of afforded action are defined by the action boundaries of a task. In postural control tasks the action boundaries are the limits of the base of support, how far the COM can shift over the base of support before postural equilibrium can no longer be maintained.[83, 88] The effects of increased load carriage on postural affordances and the action boundaries defining these affordances are reflected in movement pattern variability.

During obstacle negotiation and landing tasks, movement variability decreased with the addition of load.[13, 75, 76, 83] With the additional load, the task becomes more difficult which reduces the postural affordances available to an individual; there are less successful ways for them to complete the task.[75, 83] For example, when stepping over a hurdle without an external load there are a wide range of step heights an individual can use to successfully step over the hurdle.[13] Under loaded conditions the range of step heights the individual can use to successfully complete the task is reduced, decreasing the variability in step heights used to complete the task.[13]

Reduced movement pattern variability can be further defined in relation to neuromechanical synergies. Neuromechanical synergies refer to the systematic coordination between muscles, limbs and joints that characterize a particular movement or task.[75] During unloaded drop landings, there is substantial inter- and intra-individual variability in joint mechanics and muscle activation patterns at initial contact between trials.[75, 76] When the same landings are performed under loaded conditions, the inter- and intra-individual variability in these landing patterns is significantly reduced.[75, 76] Fewer neuromechanical synergies are adopted because there are fewer potential motor patterns that can be used to successfully complete the task under the loaded conditions.[75, 76] These findings were replicated in two studies investigating changes in the movement patterns of Special Forces Operators when they stepped off of a 24-in. box.[82, 83] With increased load, there was less inter-individual variability in the coordination patterns used to step off the box and stabilize, reflecting the decreased available stabilization strategies that would maintain postural stability.[82, 83]

After stabilization, one investigation required the Special Forces Operators to locate and fire at a target located either directly in front of them or above their head and off to the side.[82] Increased load altered coordination patterns between the head, trunk and gun which decreased ability to pick-up optical information and decreased the ability to adapt to changes in target position.[82] The effects of load carriage on the intake of sensory information as well as on the coordination of the motor response reflect the multifaceted influence of load carriage on postural control.

2.3.1 Factors Affecting Load Carriage and Postural Stability

Load Distribution Adaptations made in response to load carriage depend not only on load magnitude but also on the distribution of this magnitude.[56] Symmetrical anterior-posterior distributions produce walking mechanics that more closely resemble those of unloaded walking,[53] but still restrict locomotive ability.[56] Double-packs split the load magnitude equally between the anterior and posterior sections of the pack and the relatively greater anterior distribution compared to a normal backpack negatively affects ventilatory function[36] and impairs postural control.[28, 56] The anterior load impairs visual input especially at foot strike decreasing the sensory information available to the individual.[28] Further, the inflexibility of the load restricts trunk mobility compromising the ability to make postural adjustments.[56] Asymmetric distributions produce more detrimental adaptations than symmetrical distributions.[56] The hazardous adaptations associated with anterior-posterior asymmetry due to a predominantly posterior load distribution have been described in previous sections but hazardous adaptations are also associated with medial-lateral asymmetry.

Many military-focused investigations have subjects carry a firearm-like object thereby inducing medial-lateral asymmetry;[7, 14, 33, 82, 83] however, few studies have investigated the effects of medial-lateral asymmetry.[20, 84] Park and colleagues found that medial-lateral asymmetry induced greater medial-lateral excursion of the COP and greater COP sway area than symmetric medial-lateral distributions.[84] The decreased stability may be caused by changes in muscle activation patterns related to asymmetry.[20] In healthy individuals, stability is usually maintained through reciprocal activation of the lower limb musculature; however, under asymmetric load conditions the muscles of the contra-lateral side co-contract decreasing the ability of the individual to maintain stability.[20]

Fatigue Fatigue decreases an individual's ability to maintain postural stability and load carriage exacerbates the effects of fatigue on postural stability. [12, 109] Postural stability requires that the body musculature control body momentum but fatigued muscles have decreased force producing capabilities and are less effective at responding to perturbations.[28] Fatigue may also increase joint stiffness altering the ability to generate an appropriate motor response to maintain postural control.[12] The sensory system is able to compensate for some of the effects of fatigue; following a fatigue protocol postural stability only decreased during the eyes closed conditions of a quiet standing assessment.[12] During a more challenging single leg landing and stabilization task, fatigued muscles were not able to efficiently dissipate force resulting in increased GRF and decreased dynamic postural stability measured with TTS.[109] Under load carriage, the forces the body must dissipate are increased and the muscles must generate more force to control body motion and make postural adjustments.[10, 28] The adaptations made in response to load carriage in combination with the increased task demands due to load decrease time to fatigue;[10] however, this fatigue may be attenuated through training.

Sex The recent expansion of women's role in the United States Armed Forces has increased the focus on sex-related differences in military task performance. Of importance is the extent to which physiological, biomechanical and performance differences are associated with sex rather than other modifiable, fitness-related factors. Relevant to load carriage capabilities is the existence of strength differences between men and women which are only partially explained by differences in body mass.[3] Strength has been identified as one of the critical fitness components contributing to the successful completion of typical military tasks[73] and strength deficits were found when women were compared to men even when values were normalized to body mass.[3] Therefore, even if a load is relative to body mass a woman Warfighter may need to use a greater relative amount of her strength to carry the load.[3] This could decrease time to fatigue and increase injury risk of the woman Warfighter.[3] When carrying loads of equal absolute magnitudes these effects could be exacerbated. Increases in absolute load affect women's stride length more than men's stride length, indicative of different demands placed on men and women.[67] Differences in load carriage capabilities can be attenuated through proper training.[73] Training that targeted enhanced motor unit and muscle fiber recruitment and activation was able to successfully enhance type II motor unit and muscle fiber activity leading to improved performance.[73]

Sex differences in dynamic postural stability and postural control are task dependent. Women typically have better static postural stability than men.[26] They also typically have a lower COM than men which enhances their ability to control the system and maintain postural stability.[3,

[26] However, mixed results have been reported on sex differences in dynamic postural stability. In one investigation using a single leg landing and stabilization task, women landed with greater hip flexion at initial contact and had better dynamic postural stability than men.[26] This may be a function of women's lower COM, of an improved capability to dissipate force or a combination of the two factors.[26] However, a second investigation using a similar single leg landing and stabilization task reported men to have improved dynamic postural stability compared to women.[110] The study used a single leg landing and stabilization task that required all subjects to jump the same distance but to jump a height based on their jumping ability.[110] The standardized jump distance was relatively further for the women subjects causing them to land with greater horizontal kinetic energy decreasing dynamic postural stability.[110] When DPSI composite scores were normalized to landing energy, sex differences were no longer observed.[110] Whether or not true differences in dynamic postural stability exist between men and women must be studied using tasks that place the same relative demands on each subject.

Sex differences in dynamic postural stability under loaded conditions have not been extensively studied but warrant further investigation. Investigations of sex related differences in gait with external load reveal that the stability of women may be influenced by load to a greater extent than that of men.[67] Stride parameters, such as stride length, that are more sensitive to changes in load in women reflect an increased challenge placed on the postural control system; adaptations to gait had to be made to control the COM and maintain stability of movement.[67] With load, the difficulty of the task increases inducing the deviation from the preferred coordinative pattern.[7, 82, 83, 97] To gain an improved understanding of how load carriage impacts dynamic performance a foundational understanding of its impact on dynamic postural stability and any differences in the response of men and women to the load carriage is needed.

2.3.2 Implications of Load Carriage and Postural Stability on Injury Risk

Decreased postural stability increases the risk of injury to individuals and the negative effect of load carriage on postural stability may further increase this risk.[2, 41, 42, 74, 81] The altered mechanics and increased strain placed on the musculoskeletal system during loaded walking and landing tasks have been well described.[10, 28, 56, 75, 76] Reduced variability in the movement patterns used to complete tasks targeting dynamic postural stability results in increased repetitive loading on joints and connective tissue structures.[75, 76] The increased loading and repetitive nature of the loading increases the susceptibility of the structures to overuse injury.[75, 76] Reduced movement pattern variability reflects reduced postural stability[83] which is associated with an increased risk of injury of the lower extremity in athletes, especially of the ankle joint.[41, 42] Load carriage-related injuries are most often musculoskeletal injuries to the back and leg.[50, 81] The interaction between load carriage, dynamic postural stability and injury risk warrants further investigation.

Training programs to address factors relating to military performance and load carriage ability may decrease the injury risk of the Warfighter.[73] Programs that target improving postural stability reduce the adoption of hazardous joint mechanics,[41, 71] such as valgus motion at initial contact of landing which is associated with noncontact anterior cruciate ligament ruptures.

3.0 METHODS

3.1 RESEARCH DESIGN

A lab-based quasi-experimental within-subject study design was used to investigate changes in dynamic postural stability with increased load. A lab-based quasi-experimental between-subject study design was used to investigate differences in dynamic postural stability under load carriage conditions associated with sex and jumping ability. Dynamic postural stability was investigated during a single leg landing task and was assessed with the dynamic postural stability index (DPSI). The number of failed landing task trials also were used to provide a measure of the ability to complete the landing task with increased load. Subjects were tested under load carriage conditions equivalent to 0, 20 and 30% of their body weight (BW).

3.1.1 Independent Variables

- Sex
- Height (in)
- Body weight (lbs)
- Maximum jump height (in)
- Load carriage magnitude (lbs)

3.1.2 Dependent Variables

- DPSI composite score
- Anterior-posterior stability index score (APSI)
- Medial-lateral stability index score (MLSI)
- Vertical stability index score (VSI)
- Number of failed trials

3.2 SUBJECTS

A sample of 32 recreationally active adults (16 men, 16 women) participated in the study (Table 1). A power analysis completed using G*Power version 3.1.9.2 (Heinrich Heine, Universität Dusseldorf, Germany) determined that 28 total participants were needed to have a power of 0.8 and an effect size of 0.25 with a two-sided α of 0.05 for a mixed measures ANOVA statistical test investigating within and between subject interactions. To account for possible 10% attrition and to create equal sized groups of men and women, 32 subjects were recruited and completed all testing.

To be included in the study subjects needed to be recreationally active as defined by the American Colleges of Sports Medicine (30 minutes of moderate intensity physical activity at least 3 times a week for at least 3 months),[85] between 18-39 years old to correspond to the possible age range of military recruits[1] and had to be comfortable carrying a load equivalent to 30% of their body weight. Subjects were excluded if they had a history of back or lower extremity injury within the past three months that would influence their performance of the study procedures, any history of back or lower extremity surgery, history of concussion in the previous year, any history of neurological or vestibular disorders or past military experience as these factors all influence load carriage ability and/or dynamic postural stability. An injury was defined as a condition other than a contusion or laceration that altered the completion of activities of daily living or athletic activities for more than one day regardless if medical treatment was sought.[2]

3.3 INSTRUMENTATION

3.3.1 Anthropometric Data

Height (in) was collected using a stadiometer (Seca North America; East Hanover, MD). Body weight (lbs) was collected using a scale (BOD POD Version 5.2.0, COSMED USA Inc.; Chicago, IL).

3.3.2 Force Plate Data

A piezoelectric force plate (Model 9268A, Kistler Instrument Corp.; Amherst, NY, USA) was used to assess maximum jump height and dynamic postural stability. The force plate measured ground reaction forces in the vertical, anterior-posterior and medial-lateral directions. This signal underwent analog to digital conversion using an analog to digital converter and was recorded using Vicon Nexus Software 8.5 application (Vicon Motion Systems LTD; Centennial, CO). Jump height data was sampled at 1000Hz[54, 102] and dynamic postural stability data at 1200Hz.[95, 98]

3.4 TESTING PROCEDURES

3.4.1 Informed Consent

Before individuals were recruited as subjects they were screened by the primary investigator to ensure that they met the inclusion/exclusion criteria. Upon meeting the criteria, subjects were scheduled for one testing session to take place at the University of Pittsburgh Neuromuscular Research Laboratory (NMRL). Before starting the testing session subjects reviewed and signed an Informed Consent form that had been approved previously by the University of Pittsburgh Institutional Review Board.

3.4.2 Subject Preparation

Subjects reported to the NMRL for one testing session lasting approximately 60-90 minutes. Height and weight were measured and collected for each subject. Subjects put on the combat boots which were worn for the remainder of testing. Their booted weight was measured. Subjects then completed tests of jumping ability and dynamic postural stability. Jumping ability was only assessed during the unloaded condition and was assessed using a test of maximum jump height. The dynamic postural stability assessments were completed under three conditions: unloaded, wearing 20% BW and wearing 30% BW. The dynamic postural assessment required that subjects jump over a short hurdle off of both feet and land on only their dominant limb on the force plate. Subjects completed three practice and three successful testing trials of the landing task under each of the three load carriage conditions.

3.4.3 Maximum Jump Height

Maximum jump height was assessed by having subjects perform three unloaded maximum countermovement jumps on a force plate. The countermovement jumps consisted of subjects starting in an upright position with the hands on the hips and feet placed shoulder width apart. When ready, subjects squatted to a self-selected depth[54] before initiating the upward propulsion phase of jumping. Subjects landed in the same position from which they took off. Subjects were able to complete practice jumps to become familiar with the jumping form. A 30 second rest period was given between jumps.

3.4.4 Landing Task

The single-leg landing task used in the study has been previously described by Sell *et al.*[97] The task required subjects to perform a bilateral takeoff from a distance equivalent to 40% of body height and land in a unilateral stance with the dominant limb on a force plate while jumping over a 12in hurdle placed halfway between the starting position and the front edge of the force plate. Subjects were instructed to stabilize upon landing, to place the hands on the hips once stable and to hold this position for approximately five seconds at which point the tester instructed them to relax.

Subjects performed at least three practice trials for each of the three loading conditions and performed three successful trials as a part of testing. A trial was considered a failure if subjects landed on or touched the ground with their non-dominant limb, did not land with their whole foot on the force plate or hopped or lost balance upon landing. Subjects were given one minute rest between unloaded trials and 90 seconds rest between load condition trials to minimize the risk of fatigue and any potential effects of the previous load.

3.4.5 Loading Conditions

The load carriage conditions involved a load distribution of 0, 20, and 30% of the subject's body mass to correspond to approximate patrol and fighting order load magnitudes.[74] The load was distributed between a rucksack, webbing and weighted vest. A standard load was secured within the rucksack to minimize movement of the load/rucksack that may affect performance during the landing task. The load contained within the rucksack was kept consistent for all participants. Load was adjusted according to participant and condition by altering the load contained within the webbing and weighted vest. This was done to minimize changes in center of mass position between conditions which would occur to a greater extent had load been added to the more posteriorly distributed rucksack. Further, adjusting weight with the webbing and weighted vest allowed for more fine-tuned control of the weight to the within the nearest 0.5lbs. (Combat Rucksack, LBT™, Virginia Beach, VA). Load was added to the webbing and weighted vest centrally to minimize changes in center of mass. Combat boots were worn for all testing procedures in order to provide an ecologically valid means of standardizing footwear.

3.5 DATA REDUCTION

3.5.1 Jump Height

To determine maximum jump height, force plate data was analyzed using principles of the impulse-momentum theorem (Equation 1) where m is mass, Δv is the change in initial and final velocities, F is force and Δt is the change in initial and final time.[62, 102]

$$\text{Momentum=Impulse} \tag{1}$$

$$m\Delta v = F\Delta t$$

The force-time curve is normalized to body mass and the integration of the curve from the moment of initial contact to moment of takeoff is performed to determine takeoff velocity of the center of mass of the subject (Equation 2):

$$\int_{t_i}^{t_o}(F_{GRF} - mg)dt = mv_{to}, \tag{2}$$

where F_{GRF} is the ground reaction force, m body mass and v_{to} velocity at take-off. This value can then be used to calculate the jump height (h) (Equation 3)[62]:

$$h = \frac{v_{to}^2}{2g} \tag{3}$$

where h is maximum jump height, v_{to} velocity at take-off and g the gravitational constant (9.81m/s^2). The force plate data was sampled at 1000Hz using a cutoff frequency of 130Hz.[102] Intra-session reliability for use of the force plate to measure jump height using the impulse-momentum method has been previously established (ICC=0.9856).[5] Criterion validity for the procedure has been established; impulse-momentum jump heights have a strong correlation to jump heights determined using motion analysis (r=0.961).[5]

3.5.2 Dynamic Postural Stability

Force plate data for the single-leg landing task was collected for the first three seconds after initial contact,[113] defined as when vertical ground reaction forces exceeded 5% body mass. Data were collected at 1200Hz and processed using a zero-lag fourth-order Butterworth filter with a cutoff frequency of 20Hz. The DPSI is a composite score of the stability indices in the anterior-posterior (APSI), medial-lateral (MLSI) and vertical (VSI) directions. [113]

$$\mathrm{APSI} = \sqrt{\sum \frac{(0-\mathrm{y})^2}{number\ of\ data\ points}} \div BW$$

$$\mathrm{MLSI} = \sqrt{\sum \frac{(0-\mathrm{x})^2}{number\ of\ data\ points}} \div BW$$

$$\mathrm{VSI} = \sqrt{\sum \frac{(\mathrm{BW}-\mathrm{z})^2}{number\ of\ data\ points}} \div BW$$

$$\text{DPSI} = \sqrt{\frac{\sum(0-y)^2 + \sum(0-x)^2 + \sum(BW-z)^2}{number\ of\ data\ points}} \div BW$$

The DPSI has been found to have high intra-session reliability and to be a precise measure(ICC=0.86, SEM=0.01).[97]

Dependent variables collected included DPSI scores for the successful trials and the number of failed trials for each load condition. Independent variables included anthropometric data, gender and load magnitude as percentage of body mass.

3.6 DATA ANALYSIS

All statistics were performed using SPSS (SPSS Inc. Chicago, IL) with α (0.05) set *a priori*. Descriptive statistics (mean±sd) were calculated for all data. A Shapiro-Wilk test for normality was performed. Sex differences were analyzed using independent *t*-tests for normally distributed data and Mann-Whitney *U* tests for data that was not normally distributed. To address specific aim 1, a one-way repeated measures ANOVA [within subject factor load magnitude with 3 levels] was performed for normally distributed data and the corresponding Freidman's test was performed for non-normally distributed data. To address specific aim 2, a 2-way mixed measures ANOVA [within subject factor of load magnitude with 3 levels, between subject factor of sex with 2 levels] was performed for normally distributed data and the corresponding Freidman's test was performed for non-normally distributed data. To address specific aim 3, the level of association between the change in DPSI from unloaded to each of the two loaded conditions and jumping ability was assessed using Pearson's correlation coefficients for normally distributed data. Bonferroni corrections were completed for any significant findings.

4.0 RESULTS

The purpose of the current study was to investigate the effect of increasing load carriage magnitude, relative to body weight, on dynamic postural stability during a single leg landing and stabilization task assessed using DPSI. Specifically, differences between men and women and differences associated with jumping ability were analyzed.

All variables were found to be normally distributed when analyzed using the Shapiro-Wilk test for normality ($p>0.05$), therefore, parametric tests were used for all data analysis.

4.1 DESCRIPTIVE DATA

Age, height, weight and the absolute and relative load amounts for each of the load carriage conditions are reported in Table 1.

Table 1: Descriptive data and load carriage magnitudes for men, women and the sample as a whole, mean (standard deviation)

	Men (n=16)	Women (n=16)	Total (n=32)
Age (years)	23.50 (3.80)	22.50 (3.12)	23.00 (3.45)
Height (in)	70.81 (2.74)*	65.39 (2.70)	68.10 (3.84)
Weight (lbs)	179.05 (28.60)*	132.02 (9.45)	155.53 (31.78)
Booted Weight (lbs)	182.50 (28.67)*	135.21 (9.59)	158.85 (31.93)
20% BW Load (lbs)	218.10 (34.69)*	161.50 (11.65)	189.80 (38.40)
20% BW Load Percentage	19.86 (0.62)	19.91 (0.46)	19.88 (0.54)
30% BW Load (lbs)	235.24 (36.76)*	174.30 (12.44)	204.77 (41.08)
30% BW Load Percentage	29.47 (0.81)	29.61 (0.52)	29.54 (0.67)

*significantly different than women ($p < 0.05$)

4.2 EFFECT OF LOAD MAGNITUDE ON DYNAMIC POSTURAL STABILITY

A one-way repeated measures ANOVA [within subject factor of load magnitude with 3 levels] revealed a significant effect of increased load carriage on MLSI (F (2, 62) = 6.295, $p < 0.05$, η^2 = 0.169), APSI (F (1.742, 54.017) = 33.181, $p < 0.05$, η^2 = 0.517), VSI (F (1.387, 42.993) = 121.851, $p < 0.05$, η^2 = 0.797) and DPSI (F (1.387, 43.004) = 100.304, $p < 0.05$, η^2 = 0.764). Subsequent post hoc analysis and analysis of pairwise comparisons revealed significant differences ($p < 0.05$) between the unloaded and 20% BW conditions from MLSI, APSI, VSI and DPSI (Table 2). Significant differences ($p < 0.05$) were also seen between the unloaded and 30% BW conditions for APSI, VSI and DPSI and between the 20% BW and 30% BW conditions for APSI, VSI and

DPSI (Table 2). No significant differences were observed for MLSI between the unloaded and 30% BW conditions (*p* = 0.051) or between the 20% BW and 30% BW conditions (*p* = 1.000) (Table 2). In conditions where significant differences were observed MLSI, VSI and DPSI values increased while APSI values decreased (Table 2). No significant correlations were found between the number of failed trials and postural stability variables for each of the loading conditions (Table 3).

Table 2: Directional stability indices and overall DPSI scores, mean (standard deviation), for men, women and whole sample under each load carriage condition

		Unloaded	20% BW	30% BW
MLSI	Men	0.030 (0.004)	0.024 (0.004)*	0.025 (0.006)
	Women	0.030 (0.008)	0.029 (0.006)	0.029 (0.008)
	Total	0.030 (0.006)	0.027 (0.005)*	0.027 (0.007)
APSI	Men	0.139 (0.013)	0.130 (0.009)*	0.129 (0.011)*, **
	Women	0.138 (0.010)	0.132 (0.007)*	0.128 (0.006)*, **
	Total	0.138 (0.011)	0.131 (0.008)*	0.128 (0.009)*, **
VSI	Men	0.327 (0.051)	0.373 (0.035)*	0.394 (0.033)*, **
	Women	0.331 (0.035)	0.372 (0.036)*	0.403 (0.025)*, **
	Total	0.329 (0.043)	0.373 (0.035)*	0.398 (0.029)*, **
DPSI	Men	0.357 (0.049)	0.396 (0.034)*	0.415 (0.031)*, **
	Women	0.360 (0.032)	0.396 (0.035)*	0.424 (0.024)*, **
	Total	0.359 (0.041)	0.396 (0.034)*	0.420 (0.028)*, **

*significantly different than unloaded condition, *p*<0.05, **significantly different than 20%, *p*<0.05

Table 3: Number of failed single leg landing and stabilization trials for each load condition, mean (standard deviation), and their association with dynamic postural stability performance during each load condition

		Unloaded	20% BW	30% BW
Number of Failed Trials		1.75 (1.814)	1.44 (1.501)	1.75 (1.867)
MLSI	Pearson *r*	0.333	0.161	0.314
	p	0.063	0.378	0.080
APSI	Pearson *r*	0.220	0.020	0.079
	p	0.226	0.911	0.669
VSI	Pearson *r*	0.104	-0.009	0.160
	p	0.570	0.960	0.382
DPSI	Pearson *r*	0.128	-0.006	0.171
	P	0.486	0.972	0.348

4.3 EFFECT OF SEX AND LOAD CARRIAGE MAGNITUDE ON DYNAMIC POSTURAL STABILITY

A two-way mixed measures ANOVA [within subject factor of load carriage magnitude with 3 levels, between subject factor of sex with 2 levels] did not find a significant main effect of sex on MLSI (F (1,30) = 1.736, p = 0.198, η^2 = 0.055), APSI (F (1, 30) = 0.037, p = 0.848, η^2 = 0.001), VSI (F (1, 30) = 0.116, p =0.736, η^2 = 0.004*)* or DPSI (F (1, 30) = 0.131, p = 0.720, η^2 = 0.004). A significant load x sex interaction effect was found for MLSI (F (2, 60) = 3.641, p < 0.05, η^2 = 0.108). Subsequent one-way repeated measures ANOVAs revealed a significant effect of load on the MLSI of the men (F (2, 30) = 10.329, p = 0.001, η^2 = 0.408) but not for women (F (2, 30) = 0.255, p = 0.776, η^2 = 0.017). Analysis of pairwise comparisons revelaed significant differences between the unloaded and 20% conditions for the men (p = 0.001). No significant interaction effect was found for APSI (F (1.744, 52.325) = 1.024, p = 0.357, η^2 = 0.033), VSI (F (1.349, 40.469) = 0.537, p = 0.520, η^2 = 0.018), or DPSI (F (1.360, 40.801) = 0.393, p = 0.598, η^2 = 0.013).

4.4 INFLUENCE OF JUMPING ABILITY ON THE EFFECTS OF SEX AND LOAD ON DYNAMIC POSTURAL STABILITY

An independent *t*-test revealed significant differences (t = 5.045, $p < 0.05$) between the maximum jump height of men (9.57 ± 1.98in) and women (6.51 ± 1.40in). Jump height was not significantly correlated with change in DPSI score from unloaded to 20% BW (r = -0.101, p = 0.583), unloaded to 30% body weight (r = -0.017, p = 0.928) or 20% BW to 30% BW (r = 0.168, p = 0.357).

5.0 DISCUSSION

The current study investigated the relationship between dynamic postural stability and load carriage using a single leg landing and stabilization task and load carriage magnitudes that were relative to study participants' body weight. Individually, dynamic postural stability and load carriage each impact Warfighter locomotive ability and risk of injury which in turn affect the survivability of the Warfighter.

The purpose of the study was to investigate the relationship between military related load carriage and dynamic postural stability during a single-leg landing task using load magnitudes normalized to subject BW. A total of 32 recreationally active individuals (16 M, 16 W) completed the study. Testing included assessments of jumping ability and dynamic postural stability. Jumping ability was defined as the participants' maximum jump height and was assessed using countermovement jumps. Dynamic postural stability was assessed using a single leg landing and stabilization task and was tested under three loading conditions: unloaded, 20% BW and 30% BW. Dynamic postural stability was analyzed using DPSI and its directional components. A one-way repeated measures ANOVA was completed to analyze the effect of load carriage magnitude on dynamic postural stability. A two-way repeated measures ANOVA was used to analyze the effect of sex and load carriage magnitude on dynamic postural stability. A two-way repeated measures ANOVA with covariate was completed to analyze how dynamic postural stability under load carriage varied based on an individual's jumping ability. Pearson's correlation coefficients were also used to analyze the relationship between jumping ability and change in dynamic postural stability under increasing load carriage conditions.

Three specific aims were addressed through testing and data analysis. The first specific aim was to investigate the effect of load carriage conditions of 0, 20 and 30% BW on dynamic postural stability. We hypothesized that statistically significant decrements in dynamic postural stability would be observed as load carriage magnitude increased. This hypothesis was partially supported by the results. The second specific aim was to investigate sex differences associated with the effects of load carriage conditions of 0, 20 and 30% BW on dynamic postural stability. We hypothesized that statistically significant differences in dynamic postural stability would be observed between men and women as load magnitude increased. This hypothesis was not supported by the results. The third and final specific aim was to investigate differences in the effects of load carriage conditions of 0, 20 and 30% BW on dynamic postural stability associated with individual differences in jumping ability. We hypothesized that differences in dynamic postural stability under load carriage conditions would be associated with individual differences in jumping ability. This hypothesis was not supported by the results. The effects of load carriage, sex and load carriage and jumping ability on dynamic postural stability, limitations of the current study and areas of future research will be discussed in the following sections.

5.1 EFFECTS OF LOAD CARRIAGE ON DYNAMIC POSTURAL STABILITY

As load carriage magnitude increased, the overall DPSI and VSI scores increased reflecting decreased dynamic postural stability; this supported our hypothesis. However, MLSI scores decreased from the unloaded to the 20% BW load carriage condition and did not significantly differ from the unloaded or 20% BW conditions during the 30% BW load carriage condition. Further, APSI was significantly affected by the changes in load carriage magnitude but decreased with each load increase. These results did not support the hypothesis. While overall DPSI scores increased as the load carriage magnitude increased, each directional stability index responded differently to the load.

Due to differences in subject characteristics and study protocols (postural stability assessments and load carriage configurations) between the current study and previous research making direct comparisons is difficult but some similarities exist. Dynamic postural stability assessments used in different investigations include the single leg landing and stabilization test used in the present study,[98] stabilizing after stepping[83] or dropping[75, 76] off a box, stepping over an obstacle[13] among others. Many of these studies used tests of dynamic postural stability but measured variability in movement patterns rather than directly measuring dynamic postural stability.[13, 75, 76, 83] Sell and colleagues used DPSI to assess dynamic postural stability during the same single leg landing and stabilization task used in the current investigation.[98] Subjects completed the task with and without their personal IBA.[98] DPSI and VSI results from the current investigation are in agreement with those from Sell and colleagues; however, conflicting results exist for MLSI and APSI.

The study by Sell and colleagues found significant decrements in MLSI of Soldiers of the 101st Airborne Division under the loaded conditions.[98] This was not replicated in the current study. MLSI scores decreased between the unloaded and 20% BW conditions and did not differ between the unloaded and 30% BW conditions or the 20% and 30% BW conditions. The decrease in MLSI scores reflects decreased fluctuations along the medial-lateral axis, interpreted as increased stability. The Sell study and the current study, both used loads that were symmetrical about the medial-lateral axis however the load magnitudes used in the current study were greater than those used in the Sell study which may have contributed to the conflicting results.[98] Further, Increased load carriage magnitude of 20% BW did not affect medial-lateral GRFs during gait[53, 55] which supports the results of the current study. The MLSI scores observed in the current study can largely be explained by the increased inertia of the system and reduced postural affordances available under the load carriage conditions.[60, 83] During unloaded conditions, the reduced inertia of the system makes it easier to make compensatory movements to maintain stability when the position of the COM deviates along the medial-lateral or anterior-posterior axes. The increased inertia of the system under the 20% and 30% BW load carriage conditions increases the muscular work that would be required to make such compensatory movements.[60] For this reason, the increased inertia of the system and the increased demands associated with load carriage decrease the postural affordances available to the subjects restricting the movement patterns used to complete the task.[75, 76, 83] The limits of the base of support are tightened under increased load carriage magnitude which was reflected in the reduction and stabilization of MLSI scores under increasing load carriage magnitude in the present study.

The results of the current study in the anterior-posterior direction also conflict with those reported by *Sell et al.*[98] *Sell et al* reported increased APSI scores with the addition of load and attributed these increases to load-induced decreases in dynamic postural stability.[98] In the current study, decreased APSI scores were found across all load carriage conditions indicating reduced deviations and fluctuations along the anterior-posterior axis. These differences may have been due to the use of the rucksack in the current study which shifted the distribution of the load posteriorly while the use of IBA by *Sell et al* maintained a more symmetric anterior-posterior load distribution. Still, the results in the current study were unexpected. The increased inertia of the system and altered joint mechanics associated with increased posterior load carriage was expected to negatively affect postural stability;[7, 60] however, this was not the case. The reduced APSI scores were may have been related to load-induced alterations in landing mechanics. Posterior concentrated load increases trunk flexion and knee flexion which reposition the COM over the base of support and aid in shock absorption during the landing.[7, 19, 53, 70, 99] Altered landing mechanics during the completion of the single leg landing and stabilization task may have contributed to the decreased APSI scores. The current study did not investigate joint mechanics at landing which would have helped to elucidate mechanical adaptations to load which may explain our results. Further, as with the MLSI scores, the APSI scores may have decreased due to changes in the available successful movement patterns due to increased system inertia and decreased available postural affordances. The increased inertia of the system during the load carriage conditions increases task demands and restricts the number of successful movement strategies that may be used to complete the task..[75, 76] The concentration of the load posteriorly may further restrict movement anteriorly at landing that was not restricted under the unloaded conditions. Future research should investigate the joint mechanic changes at landing and how they relate to movement pattern variability and measured changes in dynamic postural stability. The VSI scores increased as load carriage increased reflecting increased vertical GRFs; with increased load, the subjects landed with greater force. Similarly Sell and colleagues reported increased VSI scores with the addition of IBA, however, they observed a 4.5% increase in VSI score per 10% increase in load magnitude.[98] The current study observed a 6.7% increase in VSI score per 10% increase in load magnitude. The use of the rucksack in the current study introduced vertical shifting at landing which likely contributed to the observed increases in VSI scores. The load was secured within the rucksack and the rucksack was fitted as tightly as possible for each subject in order to minimize vertical shifting of the load. Still, not all vertical shifting could be eliminated. The effect of the vertical shifting on the VSI scores could not be quantified, but based on agreement with studies investigating the effects of load on GRFs, specifically vertical GRFs, it is apparent that the vertical shifting of the load did not entirely account for the increased VSI scores.[48, 53, 55, 95-97] The increased inertia of the system under load carriage conditions increases the vertical GRFs exerted on the body at initial contact of landing. As the VSI provides a measure of deviations in GRFs during the first three seconds after landing, the increased magnitude of the vertical GRFs are reflected in the VSI scores.

The overall DPSI scores reflect the three directional stability indices.[110] The magnitude of the changes in VSI under increasing load carriage magnitude were greater than the magnitude of changes in MLSI and APSI reflected in the overall increase in DPSI scores even though only one of the directional stability indices showed significant increases. Increased load carriage magnitude decreases dynamic postural stability primarily by impacting stability across the vertical axis rather than the medial-lateral or anterior-posterior axes.

DPSI takes into account one aspect of postural stability, deviations in COM over the base of support; however, postural stability is a complex process involving the coordination of multiple systems and DPSI does not reflect this complexity.[51, 87, 88, 110] Load carriage further complicates the process by perturbing the postural control system; impacting the sensory and motor aspects of the system.[11] The webbing component of the load carriage configuration compromised the subjects' view of the landing which then affected the visual information that contributed to postural control. Further, the combat boots affected subjects' proprioception critical to the maintenance of postural stability.[4, 11] The rigid structure of the boots increases the proprioceptive input to the foot mechanoreceptors; however the rigidity of the boot also compromises the accuracy of this information by impacting the foot-ground interface.[11] The combat boots also restrict the range of motion of the ankle impacting the subjects' ability to make appropriate motor responses.[4, 11] The motor response component of postural control is impacted by the increased demands load places on the body.[10] This is reflected in the restricted movement patterns and increased muscle activation patterns characteristic of load carriage.[74, 75] Future studies should investigate how load carriage impacts different aspects of postural control.

5.2 EFFECTS OF SEX AND LOAD CARRIAGE ON DYNAMIC POSTURAL STABILITY

With increased load carriage the MLSI scores of men decreased while those of women did not change. No sex-related differences in APSI, VSI or DPSI were observed. These results largely did not support our hypothesis of sex differences existing in dynamic postural stability with the addition of external load. Previous research surrounding differences in dynamic postural stability between men and women has reported inconsistent findings.[76, 107] Some of the reported differences in dynamic postural stability between men and women have related to differences in task demands rather than to true differences in dynamic postural stability.[107] Under the normalized load carriage conditions used in the current study, the demands of the task were more equivalent between the sexes, which was reflected in the lack of significant differences in DPSI scores between men and women. Future research should analyze the landing mechanics and muscle activation patterns of men and women at landing to gain insight into the existence of any sex related differences in postural stability strategy.

5.3 RELATIONSHIP BETWEEN JUMPING ABILITY AND DYNAMIC POSTURAL STABILITY UNDER LOAD CARRIAGE CONDITIONS

Jumping ability did not significantly correlate with change in DPSI score from unloaded to 20% BW, unloaded to 30% BW or 20% BW to 30% BW. These results did not support the hypothesis for the third specific aim that the effect of load carriage on dynamic postural stability would vary based on individual jumping ability. Given that jumping is incorporated in the single leg landing and stabilization task used in the study this finding was unexpected. While the jump distance used in the task is normalized to body height, the jump height used is standardized. The results of the current investigation indicate that the standardized jump height of 12 in. does not challenge the jumping ability of recreationally active individuals. Therefore, the use of a standardized jump height in the current investigation to assess differences in dynamic postural stability is acceptable.

5.4 LIMITATIONS

Some study limitations have been identified throughout the paper. One of the significant limitations of the study was that the mechanisms underlying some of the results could not be explained due to the lack of joint mechanics data. Another limitation of the study was the load carriage magnitudes used. Load carriage magnitudes of 20 and 30% BW do not encapsulate all of the load carriage magnitudes a Warfighter may be asked to carry and maneuver with in the field. Given the population used and time constraints of the study testing additional load magnitudes did not seem practical and may not have been safe. The study participants were recreationally active but they were not experienced with significant load carriage and performing a single leg landing task under load carriage magnitudes exceeding 30% BW may have unnecessarily placed them at an increased risk of musculoskeletal injury. Further, the 30% load carriage condition provided a significant challenge to the participants, given their lack of experience with load carriage and was representative of the loads recruits would be required to carry during the initial portions of training. Furthermore, in regards to the relative nature of the load carriage magnitudes, in military operations where load carriage magnitudes are largely dictated by the demands of the task, there will be many situations when individuals do not carry equivalent relative load carriage magnitudes which limits the applicability of the results from the current study. Future studies should investigate performance differences and postural stability differences between men and women during more functionally relevant tasks and under more ecologically valid and operationally specific load carriage magnitudes and configurations.

5.5 FUTURE RESEARCH

Future research should do a more in-depth investigation into the relationship between sex, load carriage and other dynamic movement patterns. Sex differences in the performance of more military-specific dynamic tasks under load carriage conditions should be investigated to provide a better understanding of any performance differences between men and women Warfighters that may exist. Also investigating joint mechanics during the performance of different dynamic tasks and during the single leg landing and stabilization task would provide greater insight as to the effect of load on the Warfighter.

6.0 CONCLUSION

The purpose of this investigation was to evaluate the effect of increased load carriage magnitude on dynamic postural stability during a single-leg landing and stabilization task using load carriage magnitudes normalized to subject BW. Load carriage had a negative effect on overall dynamic postural stability assessed using a single leg landing and stabilization task; however, the three axes (medial-lateral, anterior-posterior, vertical) responded differently to increased load magnitude. When load carriage magnitudes are defined relative to subject BW, limited differences in dynamic postural stability existed between men and women. The applicability of these results to performance of more operationally relevant tasks needs to be established. Further, the impact of load carriage magnitude on different components of postural control needs to be better understood to understand how to mitigate the effect of load carriage on dynamic postural stability.

Bibliography

1. Are you eligible to join the military? Accessed 2/29/16, 2016.

2. Abt JP, Sell TC, Lovalekar MT, et al. Injury epidemiology of U.S. Army Special Operations forces. *Mil Med.* 2014;179(10):1106-1112.

3. Allison KF, Keenan KA, Sell TC, et al. Musculoskeletal, biomechanical, and physiological gender differences in the US military. *US Army Med Dep J.* 2015:22-32.

4. Andersen KA, Grimshaw PN, Kelso RM, Bentley DJ. Musculoskeletal Lower Limb Injury Risk in Army Populations. *Sports Med Open.* 2016;2(1):22.

5. Aragón-Vargas L. Evaluation of Four Vertical Jump Tests: Methodology, Reliability, Validity, and Accuracy. *Measurement in Physical Education and Exercise Science.* 2000;4(4):215-228.

6. Aramaki Y, Nozaki D, Masani K, Sato T, Nakazawa K, Yano H. Reciprocal angular acceleration of the ankle and hip joints during quiet standing in humans. *Exp Brain Res.* 2001;136(4):463-473.

7. Attwells RL, Birrell SA, Hooper RH, Mansfield NJ. Influence of carrying heavy loads on soldiers' posture, movements and gait. *Ergonomics.* 2006;49(14):1527-1537.

8. Bell NS, Mangione TW, Hemenway D, Amoroso PJ, Jones BH. High injury rates among female army trainees: a function of gender? *Am J Prev Med.* 2000;18(3 Suppl):141-146.

9. Billing DC, Silk AJ, Tofari PJ, Hunt AP. Effects of Military Load Carriage on Susceptibility to Enemy Fire During Tactical Combat Movements. *J Strength Cond Res.* 2015;29 Suppl 11:S134-138.

10. Blacker SD, Fallowfield JL, Bilzon JL, Willems ME. Neuromuscular function following prolonged load carriage on level and downhill gradients. *Aviat Space Environ Med.* 2010;81(8):745-753.

11. Bowser BJ, Rose WC, McGrath R, Salerno J, Wallace J, Davis IS. Effect of Footwear on Dynamic Stability during Single-leg Jump Landings. *Int J Sports Med.* 2017;38(6):481-486.

12. Boyas S, Hajj M, Bilodeau M. Influence of ankle plantarflexor fatigue on postural sway, lower limb articular angles, and postural strategies during unipedal quiet standing. *Gait Posture.* 2013;37(4):547-551.

13. Brown TN, Loverro KL, Schiffman JM. Soldier-relevant body borne load impacts minimum foot clearance during obstacle negotiation. *Appl Ergon.* 2016;55:56-62.

14. Brown TN, O'Donovan M, Hasselquist L, Corner B, Schiffman JM. Soldier-relevant loads impact lower limb biomechanics during anticipated and unanticipated single-leg cutting movements. *J Biomech.* 2014;47(14):3494-3501.

15. Bruton MR, O'Dwyer N, Adams R. Sex differences in the kinematics and neuromuscular control of landing: biological, environmental and sociocultural factors. *J Electromyogr Kinesiol.* 2013;23(4):747-758.

16. Buckley TA, Munkasy BA, Tapia-Lovler TG, Wikstrom EA. Altered gait termination strategies following a concussion. *Gait Posture.* 2013;38(3):549-551.

17. Cain SM, McGinnis RS, Davidson SP, Vitali RV, Perkins NC, McLean SG. Quantifying performance and effects of load carriage during a challenging balancing task using an array of wireless inertial sensors. *Gait Posture.* 2016;43:65-69.

18. Caron RR, Lewis CL, Saltzman E, Wagenaar RC, Holt KG. Musculoskeletal stiffness changes linearly in response to increasing load during walking gait. *J Biomech.* 2015;48(6):1165-1171.

19. Caron RR, Wagenaar RC, Lewis CL, Saltzman E, Holt KG. Center of mass trajectory and orientation to ankle and knee in sagittal plane is maintained with forward lean when backpack load changes during treadmill walking. *J Biomech.* 2013;46(1):70-76.

20. Chen B, Lee YJ, Aruin AS. Anticipatory and compensatory postural adjustments in conditions of body asymmetry induced by holding an object. *Exp Brain Res.* 2015;233(11):3087-3096.

21. Cheng KB, Yeh CK. A unified approach for revealing multiple balance recovery strategies. *Hum Mov Sci.* 2015;44:307-316.

22. Chow GC, Fong SS, Chung JW, Chung LM, Ma AW, Macfarlane DJ. Determinants of sport-specific postural control strategy and balance performance of amateur rugby players. *J Sci Med Sport.* 2016.

23. Chu Y, Sell TC, Abt JP, et al. Air assault soldiers demonstrate more dangerous landing biomechanics when visual input is removed. *Mil Med.* 2012;177(1):41-47.

24. Creath R, Kiemel T, Horak F, Jeka JJ. The role of vestibular and somatosensory systems in intersegmental control of upright stance. *J Vestib Res.* 2008;18(1):39-49.

25. Cug M, Wikstrom EA, Golshaei B, Kirazci S. The Effects of Sex, Limb Dominance, and Soccer Participation on Knee Proprioception and Dynamic Postural Control. *J Sport Rehabil.* 2016;25(1):31-39.

26. Dallinga JM, van der Does HT, Benjaminse A, Lemmink KA. Dynamic postural stability differences between male and female players with and without ankle sprain. *Phys Ther Sport.* 2016;17:69-75.

27. Dean C. The Modern Warrior's Combat Load. Dismounted Operations in Afghanistan April-May 2003. *Learned DotACfL (ed).* 2004:119.

28. Dempsey PC, Handcock PJ, Rehrer NJ. Impact of police body armour and equipment on mobility. *Appl Ergon.* 2013;44(6):957-961.

29. 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.

30. Drain J, Billing D, Neesham-Smith D, Aisbett B. Predicting physiological capacity of human load carriage - a review. *Appl Ergon.* 2016;52:85-94.

31. Earhart GM. Dynamic control of posture across locomotor tasks. *Mov Disord.* 2013;28(11):1501-1508.

32. Edwards WT. Effect of joint stiffness on standing stability. *Gait Posture.* 2007;25(3):432-439.

33. Fallowfield JL, Blacker SD, Willems ME, Davey T, Layden J. Neuromuscular and cardiovascular responses of Royal Marine recruits to load carriage in the field. *Appl Ergon.* 2012;43(6):1131-1137.

34. Feldman AG. New insights into action-perception coupling. *Exp Brain Res.* 2009;194(1):39-58.

35. Gibson JJ. The Theory of Affordances. *The Ecological Approach to Visual Perception*; 1979.

36. Haisman MF. Determinants of load carrying ability. *Appl Ergon.* 1988;19(2):111-121.

37. 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.

38. Hollands MA, Marple-Horvat DE. Coordination of eye and leg movements during visually guided stepping. *J Mot Behav.* 2001;33(2):205-216.

39. Holt KG, Wagenaar RC, LaFiandra ME, Kubo M, Obusek JP. Increased musculoskeletal stiffness during load carriage at increasing walking speeds maintains constant vertical excursion of the body center of mass. *J Biomech.* 2003;36(4):465-471.

40. Horak FB, Nashner LM. Central programming of postural movements: adaptation to altered support-surface configurations. *J Neurophysiol.* 1986;55(6):1369-1381.

41. Hrysomallis C. Relationship between balance ability, training and sports injury risk. *Sports Med.* 2007;37(6):547-556.

42. Hrysomallis C, McLaughlin P, Goodman C. Balance and injury in elite Australian footballers. *Int J Sports Med.* 2007;28(10):844-847.

43. Hsu WL, Scholz JP, Schoner G, Jeka JJ, Kiemel T. Control and estimation of posture during quiet stance depends on multijoint coordination. *J Neurophysiol.* 2007;97(4):3024-3035.

44. Hughes G, Watkins J. Lower limb coordination and stiffness during landing from volleyball block jumps. *Res Sports Med.* 2008;16(2):138-154.

45. Hwang S, Agada P, Kiemel T, Jeka JJ. Dynamic reweighting of three modalities for sensor fusion. *PLoS One.* 2014;9(1):e88132.

46. Hwang S, Agada P, Kiemel T, Jeka JJ. Identification of the Unstable Human Postural Control System. *Front Syst Neurosci.* 2016;10:22.

47. Iqbal K. Mechanisms and models of postural stability and control. *Conf Proc IEEE Eng Med Biol Soc.* 2011;2011:7837-7840.

48. James CR, Atkins LT, Dufek JS, Bates BT. An exploration of load accommodation strategies during walking with extremity-carried weights. *Hum Mov Sci.* 2014;35:17-29.

49. Janssen I, Sheppard JM, Dingley AA, Chapman DW, Spratford W. Lower extremity kinematics and kinetics when landing from unloaded and loaded jumps. *J Appl Biomech.* 2012;28(6):687-693.

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

51. Kiemel T, Zhang Y, Jeka JJ. Identification of neural feedback for upright stance in humans: stabilization rather than sway minimization. *J Neurosci.* 2011;31(42):15144-15153.

52. Kim D, Unger J, Lanovaz JL, Oates AR. The Relationship of Anticipatory Gluteus Medius Activity to Pelvic and Knee Stability in the Transition to Single-Leg Stance. *PM R.* 2016;8(2):138-144.

53. Kinoshita H. Effects of different loads and carrying systems on selected biomechanical parameters describing walking gait. *Ergonomics.* 1985;28(9):1347-1362.

54. Kirby TJ, McBride JM, Haines TL, Dayne AM. Relative net vertical impulse determines jumping performance. *J Appl Biomech.* 2011;27(3):207-214.

55. 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.

56. Knapik JJ, Reynolds KL, Harman E. Soldier load carriage: historical, physiological, biomechanical, and medical aspects. *Mil Med.* 2004;169(1):45-56.

57. Kuszewski M, Gnat R, Sobota G, Mysliwiec A. Influence of passive stiffness of hamstrings on postural stability. *J Hum Kinet.* 2015;45:49-57.

58. LaFiandra M, Holt KG, Wagenaar RC, Obusek JP. Transverse plane kinetics during treadmill walking with and without a load. *Clin Biomech (Bristol, Avon).* 2002;17(2):116-122.

59. LaFiandra MH, K.; Wagenaar, R.; Obusek, J. The effect of backpack moment of inertia on transverse plane kinetics and kinematics and oxygen consumption during walking. *USARIEM Technical Report T03-2.* 2002.

60. Lindner T, Schulze C, Woitge S, Finze S, Mittelmeier W, Bader R. The effect of the weight of equipment on muscle activity of the lower extremity in soldiers. *ScientificWorldJournal.* 2012;2012:976513.

61. Linthorne N. Analysis of standing vertical jumps using a force platform. *American Journal of Physiology.* 2001;69(11):1198-1204.

62. Loverro KL, Brown TN, Coyne ME, Schiffman JM. Use of body armor protection with fighting load impacts soldier performance and kinematics. *Appl Ergon.* 2015;46 Pt A:168-175.

63. Lyle MA, Valero-Cuevas FJ, Gregor RJ, Powers CM. Control of dynamic foot-ground interactions in male and female soccer athletes: females exhibit reduced dexterity and higher limb stiffness during landing. *J Biomech.* 2014;47(2):512-517.

64. Majumdar D, Pal MS, Majumdar D. Effects of military load carriage on kinematics of gait. *Ergonomics.* 2010;53(6):782-791.

65. Mala J, Szivak TK, Flanagan SD, et al. The role of strength and power during performance of high intensity military tasks under heavy load carriage. *US Army Med Dep J.* 2015:3-11.

66. Martin PE, Nelson RC. The effect of carried loads on the walking patterns of men and women. *Ergonomics.* 1986;29(10):1191-1202.

67. McNitt-Gray JL, Hester DM, Mathiyakom W, Munkasy BA. Mechanical demand and multijoint control during landing depend on orientation of the body segments relative to the reaction force. *J Biomech.* 2001;34(11):1471-1482.

68. Mullins AK, Annett LE, Drain JR, Kemp JG, Clark RA, Whyte DG. Lower limb kinematics and physiological responses to prolonged load carriage in untrained individuals. *Ergonomics.* 2015;58(5):770-780.

69. Muslim K, Nussbaum MA. Traditional posterior load carriage: effects of load mass and size on torso kinematics, kinetics, muscle activity and movement stability. *Ergonomics.* 2015:1-13.

70. Myer GD, Ford KR, McLean SG, Hewett TE. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *Am J Sports Med.* 2006;34(3):445-455.

71. Neptune RR, McGowan CP. Muscle contributions to whole-body sagittal plane angular momentum during walking. *J Biomech.* 2011;44(1):6-12.

72. Nindl BC. Physical Training Strategies for Military Women's Performance Optimization in Combat-Centric Occupations. *J Strength Cond Res.* 2015;29 Suppl 11:S101-106.

73. 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.

74. Nordin AD, Dufek JS. Neuromechanical synergies in single-leg landing reveal changes in movement control. *Hum Mov Sci.* 2016;49:66-78.

75. Nordin AD, Dufek JS. Load Accommodation Strategies and Movement Variability in Single-Leg Landing. *J Appl Biomech.* 2017:1-25.

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

77. Orishimo KF, Liederbach M, Kremenic IJ, Hagins M, Pappas E. Comparison of landing biomechanics between male and female dancers and athletes, part 1: Influence of sex on risk of anterior cruciate ligament injury. *Am J Sports Med.* 2014;42(5):1082-1088.

78. Orr R, Pope R, Peterson S, Hinton B, Stierli M. Leg Power As an Indicator of Risk of Injury or Illness in Police Recruits. *Int J Environ Res Public Health.* 2016;13(2):237.

79. Orr RM, Pope R. Gender differences in load carriage injuries of Australian army soldiers. *BMC Musculoskelet Disord.* 2016;17(1):488.

80. Orr RM, Pope R, Johnston V, Coyle J. Soldier occupational load carriage: a narrative review of associated injuries. *Int J Inj Contr Saf Promot.* 2014;21(4):388-396.

81. Palmer CJ, Bigelow C, Van Emmerik RE. Defining soldier equipment trade space: load effects on combat marksmanship and perception-action coupling. *Ergonomics.* 2013;56(11):1708-1721.

82. Palmer CJR, G.E.,; Van Emmerik, R.E.A. Orienting under load: intrinsic dynamics and postural affordances for visual perception. *Ecological Psychology*. 2012;24(2):95-121.

83. 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.

84. Pescatello LS, American College of Sports Medicine. *ACSM's guidelines for exercise testing and prescription*. 9th ed. Philadelphia: Wolters Kluwer/Lippincott Williams & Wilkins Health; 2014.

85. Quesada PM, Mengelkoch LJ, Hale RC, Simon SR. Biomechanical and metabolic effects of varying backpack loading on simulated marching. *Ergonomics.* 2000;43(3):293-309.

86. Rice PE, Goodman CL, Capps CR, Triplett NT, Erickson TM, McBride JM. Force- and power-time curve comparison during jumping between strength-matched male and female basketball players. *Eur J Sport Sci.* 2017;17(3):286-293.

87. Riemann BL, Lephart SM. The sensorimotor system, part I: the physiologic basis of functional joint stability. *J Athl Train.* 2002;37(1):71-79.

88. Riemann BL, Lephart SM. The Sensorimotor System, Part II: The Role of Proprioception in Motor Control and Functional Joint Stability. *J Athl Train.* 2002;37(1):80-84.

89. Rios JL, Gorges AL, dos Santos MJ. Individuals with chronic ankle instability compensate for their ankle deficits using proximal musculature to maintain reduced postural sway while kicking a ball. *Hum Mov Sci.* 2015;43:33-44.

90. Ritzmann R, Freyler K, Weltin E, Krause A, Gollhofer A. Load Dependency of Postural Control--Kinematic and Neuromuscular Changes in Response to over and under Load Conditions. *PLoS One.* 2015;10(6):e0128400.

91. Santello M, McDonagh MJ, Challis JH. Visual and non-visual control of landing movements in humans. *J Physiol.* 2001;537(Pt 1):313-327.

92. 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.

93. 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.

94. Sell TC, Abt JP, Crawford K, et al. Warrior Model for Human Performance and Injury Prevention: Eagle Tactical Athlete Program (ETAP) Part I. *J Spec Oper Med.* 2010;10(4):2-21.

95. Sell TC, Chu Y, Abt JP, et al. Minimal additional weight of combat equipment alters air assault soldiers' landing biomechanics. *Mil Med.* 2010;175(1):41-47.

96. Sell TC, Pederson JJ, Abt JP, et al. The addition of body armor diminishes dynamic postural stability in military soldiers. *Mil Med.* 2013;178(1):76-81.

97. Silder A, Delp SL, Besier T. Men and women adopt similar walking mechanics and muscle activation patterns during load carriage. *J Biomech.* 2013;46(14):2522-2528.

98. Simpson KM, Munro BJ, Steele JR. Does load position affect gait and subjective responses of females during load carriage? *Appl Ergon.* 2012;43(3):479-485.

99. Simpson KM, Munro BJ, Steele JR. Effects of prolonged load carriage on ground reaction forces, lower limb kinematics and spatio-temporal parameters in female recreational hikers. *Ergonomics.* 2012;55(3):316-326.

100. Street GM, S; Board, W; Rasmussen, M; Heneghan, JM. Sources of Error in Determining Countermovement Jump Height With the Impulse Method. *Journal of Applied Biomechanics.* 2001;17:43-548.

101. Treloar AK, Billing DC. Effect of load carriage on performance of an explosive, anaerobic military task. *Mil Med.* 2011;176(9):1027-1031.

102. Valovich-mcLeod TC, Hale TD. Vestibular and balance issues following sport-related concussion. *Brain Injury.* 2015;29(2):175-184.

103. von Lassberg C, Beykirch KA, Mohler BJ, Bulthoff HH. Intersegmental eye-head-body interactions during complex whole body movements. *PLoS One.* 2014;9(4):e95450.

104. Wang H, Frame J, Ozimek E, Leib D, Dugan EL. The effects of load carriage and muscle fatigue on lower-extremity joint mechanics. *Res Q Exerc Sport.* 2013;84(3):305-312.

105. Weinhandl JT, Irmischer BS, Sievert ZA. Sex differences in unilateral landing mechanics from absolute and relative heights. *Knee.* 2015;22(4):298-303.

106. Wikstrom EA, Powers ME, Tillman MD. Dynamic Stabilization Time After Isokinetic and Functional Fatigue. *J Athl Train.* 2004;39(3):247-253.

107. Wikstrom EA, Tillman MD, Kline KJ, Borsa PA. Gender and limb differences in dynamic postural stability during landing. *Clin J Sport Med.* 2006;16(4):311-315.

108. Wikstrom EA, Tillman MD, Schenker S, Borsa PA. Failed jump landing trials: deficits in neuromuscular control. *Scand J Med Sci Sports.* 2008;18(1):55-61.

109. Wikstrom EA, Tillman MD, Schenker SM, Borsa PA. Jump-landing direction influences dynamic postural stability scores. *J Sci Med Sport.* 2008;11(2):106-111.

110. Wikstrom EA, Tillman MD, Smith AN, Borsa PA. A new force-plate technology measure of dynamic postural stability: the dynamic postural stability index. *J Athl Train.* 2005;40(4):305-309.

111. Yiou E, Fourcade P, Artico R, Caderby T. Influence of temporal pressure constraint on the biomechanical organisation of gait initiation made with or without an obstacle to clear. *Comput Methods Biomech Biomed Engin.* 2015;18 Suppl 1:2082-2083.

112. Young W, Cormack S, Crichton M. Which jump variables should be used to assess explosive leg muscle function? *Int J Sports Physiol Perform.* 2011;6(1):51-57.