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Biomechanics of Military Load Carriage and Resulting Musculoskeletal Injury: A Review

Brian D. Fox, Lawrence W. Judge, D. Clark Dickin, Henry Wang*

Biomechanics Laboratory, School of Kinesiology, Ball State University. Muncie, IN, USA

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***Correspondence:**
*Dr. Henry Wang, Biomechanics Laboratory, School of Kinesiology, Ball State University. Muncie, IN, USA; Telephone No: 765.285.5126; Email: hwang2@bsu.edu.

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Abstract

Load carriage is a common activity used in daily tasks for many occupations, so understanding its injury mechanisms, as well as the biomechanical modifications made to gait and posture during load carriage, could reduce injury risk during this activity. The purpose of this review was to compile the most recent literature regarding biomechanical adaptations to load carriage, including its effects on musculoskeletal injury, kinematic, spatiotemporal, and kinetic adaptations, and insights about the future of load carriage research. Researchers found a high degree of injury in personnel who participate in heavy load carriage activities as a part of their job, with lower back and lower extremity injuries being the most common. An observation of several studies that measured kinematic, spatiotemporal, and kinetic adaptations suggest that there may be a threshold in which typical gait kinematics must change to account for the additional load. Not adapting proper mechanisms to deal with increased load carriage forces may lead to lower extremity injury. Future studies should observe how persons untrained in load carriage respond to these loads, and how controlling for variables like speed and cadence affect gait adaptations.

Introduction

Load carriage is a common activity used in daily tasks for many occupations, and can lead to chronic musculoskeletal injury if not performed properly. Military personnel are especially prone to the effects of heavy load carriage, as the loads they are asked to carry can easily exceed 31kg (68.2lbs)[1]. The introduction of these external loads will require the bearer to undergo changes to their gait, posture, or both, in order to compensate. As both postural stability and gait mechanics can be indicators of a person's health, determining how load carriage affects these variables can be essential in preserving a person's wellbeing.

The addition of an external load to a person will result in changes in both gait mechanics and postural stability, as the external load will modify the location of the body's center of mass (CoM). A commonly observed adaptation to posterior load carriage is what is referred to as forward lean[2,3,4]. When a load is applied posteriorly to the trunk, the body must adapt to the change in its CoM position, which is typically achieved by increasing trunk flexion. A number of factors influence the amount of forward lean the bearer undergoes: the magnitude of the load carriage (a heavier load will elicit greater forward lean), its superior/inferior position on the back, or the addition of a hip belt.

An oft-cited study suggests that any type of load carriage should remain at or below 30% of the bearer's body weight for the sake of safety[5]; however, for populations in which load carriage is either a job requirement or an integral aspect of the activity, it may be difficult to adhere to this threshold. This concept as it applies to military personnel was recognized early on by E.T. Renbourn, former Major for the Royal Army Medical Corps, in 1954, who wrote "The load carried by the soldier… will probably always be a compromise between what is physiologically sound and what is operationally essential[6]." As a typical military load can weigh anywhere from 31 – 44kg (68.2 – 96.8lbs), or even greater in emergency situations[1], it becomes important to understand the modifications that are required to bear these heavy loads, so the load carriage can be executed safely, with minimal risk to the bearer.

This review serves to compile the most recent literature regarding biomechanical adaptations to load carriage, including the effects of load carriage on musculoskeletal injury, kinematic, spatiotemporal, and kinetic adaptations, and insights about the future of load carriage research.

Data Acquisition

Articles were found via PubMed and Ball State University Library's OneSearch journal database by searching for "military load carriage," "load carriage AND injury," "military backpack," and "ruck march." Article acquisition began in early 2019; thus, articles that were included in the data analysis had a published date of 2004 or newer (approximately 15 years from the date of article acquisition). Articles were included in the data analysis assuming they dealt exclusively with posteriorly placed loads, rather than symmetrically-placed loads, and measured gait kinetics, kinematics, spatiotemporal parameters, or any combination of those while under load carriage.

Load Carriage and Musculoskeletal Injury

Common Injury Sites

A study performed in 2012 observed musculoskeletal injuries that occurred in Air Force military trainees during Basic Training at Joint Base San Antonio between 2012 and 2014[7]. Of the 67,525 recruits that entered Basic Training over those two years, researchers found that 12.5% (n = 8448) of these recruits sustained at least one musculoskeletal injury during Basic Training. A majority of injuries reported (78.4% of injuries, n = 9147) occurred in the lower extremities, and it was found that the total cost associated with all sustained injuries exceeded $43.7 million over this two year period. The researchers also acknowledged that incoming recruits tended to be undertrained upon their arrival to Basic Training, and that lower levels of aerobic and muscular fitness were associated with increased injury risk[7].

Hauret and colleagues conducted a meta-analysis analyzing injuries sustained by active duty Air Force, Army, Marines, and Navy personnel. By pulling information from scientific databases, field investigations, and medical records, they found almost three-quarters of a million (743,547) injuries had been sustained by this population in the span of a year. They, along with other studies, found that the spine and the lower extremities were the two most popular sites of injury[8,9,10,11], accounting for 40.3% and 39.0% of all injuries, respectively. They noted that inflammation and pain (which they label as "overuse injuries") accounted for 82.3% of all injury types. Breaking this down further, injuries to the lower back (lumbar spine) accounted for 48.5% of all spinal injuries, and injuries to the knee and lower leg accounted for 57.3% of all lower extremity injuries.

However, it is not quite enough to understand the popular sites at which injury is bound to occur. It is also important to know what activity was being performed at the time of the injury. Abt and colleagues asked members of the 3rd Special Forces Group (3SFG) to self-report musculoskeletal injury (MSI) data for the past year. Of the 106 subjects included in the analysis, 26 injuries were reported. Of these injuries, almost half of them (46.2%) occurred during "Command Organized PT," with "running" and "lifting" being the two most popular causes of injury[12]. Knapik and colleagues found that road marching, which was clarified to include load carrying equipment and rucksacks, was the second most popular activity related to new injury encounters, accounting for 15% (n = 625) of injuries, second only to physical training (16%, n = 636)[13]. Schuh-Renner and colleagues (2017) found similar results, with road marching injuries accounting for 23% of injuries (n = 96) between two battalions, second only to running for physical training (27%, n = 113)[14]. Orr and colleagues asked Warfighters to self-report specifically load carriage-related injury throughout their entire career. Of the 338 participants who responded, 116 of them (34%) reported sustaining a load carriage-related injury throughout their military career, and 14% of respondents (n = 49) reported sustaining more than one injury. Of the participants sustaining more than one injury related to load carriage, 21 of them reinjured the same site, 15 sustained an injury in a different location, and 13 went on to reinjure the same site and sustain an injury to a different site. Forty-eight percent of the respondents who reported sustaining an injury also reported at least one injury occurring during initial entry training, and 52% of participants who were injured in initial entry training reported sustaining another injury later in their career[9].

Risk Factors for Load Carriage-Related Injury

Identifying behaviors, musculoskeletal predispositions, or training deficiencies that precede injury during load carriage can allow for better prevention through appropriate training and understanding. The aforementioned study at Joint Base San Antonio acknowledged that low fitness levels among incoming recruits were key factors influencing injury risk[15], and has been further supported by several studies[14,15]. The broadest risk factor for training-related injury was low fitness levels; specifically, low aerobic fitness levels among incoming recruits have been frequently associated with MSI risk. Low anaerobic fitness (muscular endurance) levels were also associated with injury risk, but not as substantially as low aerobic fitness levels[14,15]. Molloy and colleagues also suggest that body mass index (BMI) has a bimodal risk for MSI; rather, those with low and high BMI are both at an increased risk for MSI. Persons with low BMI and low incoming fitness levels may not have the muscle mass needed to carry heavier loads, and persons with high BMI and low incoming fitness levels may be more susceptible to overuse injury. Similarly, participants with higher training volumes are also at higher risk for injury[10,14]. Schuh-Renner and colleagues found that load carriage had an increased relative risk for injury compared to running when observing miles of exposure. This suggests that road marching should be included as a part of an individual's training program, coexisting with other strength, cardiovascular, and endurance exercises[14].

More specifically, certain muscular deficiencies can lead to increased injury risk. Heebner and colleagues found that persons that went on to sustain an MSI had decreased trunk flexion and extension strength compared to those who went uninjured, and those who went on to sustain a lower extremity MSI had decreased trunk flexion strength and decreased knee extension strength compared to uninjured individuals. Individuals who sustained a spinal injury had similar risk factors; these individuals also had decreased trunk flexion and knee extension strength compared to uninjured persons[16].

An appropriate training protocol, as well as a prior history of sport/physical activity, can both serve to decrease injury risk during load carriage. Sell and colleagues suggest that the implementation of a graduated, nonlinear training protocol is appropriate to reduce risk for MSI. They observed that following the implementation of a five-month training protocol (Eagle Tactical Athlete Program, or ETAP), injury incidence decreased for all injuries and stress fractures, and a trend was observed for a decrease in overuse injuries and lower extremity injuries[17]. Several studies have also observed that a prior history of sport and/or physical activity can decrease risk for MSI. Persons who had a history in a sport requiring multiaxial loading of the lower extremities (such as soccer or basketball) underwent decreased tibial bone strain compared to those who did not participate in these types of activities, indicating that this population was less susceptible to stress fractures[18,19].

Biomechanical Adaptations

Step length is one of the most common kinematic measures when observing gait, and is defined as the anteroposterior distance between two opposite heel strikes. Some researchers choose to observe stride length as well, defined as the anteroposterior distance between two ipsilateral heel strikes, which when combined with step length, allows for asymmetric differences to be observed (favoring one limb over the other, for example). However, the adjustments that occur while under load carriage seem to vary.

Some studies suggest that while under load carriage, the bearer will undergo a decrease in step and/or stride length compared to unloaded walking[3,20,21,22]. This decrease may serve to reduce braking ground reaction forces during gait, serving as a mechanism to reduce or prevent injury in heavy load carriage. It is important to note that the weight of the load carriage in each of the aforementioned studies was at least 20% of the participant's body mass (%BM), with some loads reaching 60%BM[20].

However, it is possible to observe the opposite, that the bearer will increase step length while under the effects of load[23]. Some sources claim that increasing step length is actually an adaptation that serves to increase efficiency. These sources suggest that by increasing the length of their stride, the bearer can preserve the momentum from the propulsive phase of gait initiation, requiring smaller propulsive GRFs as they continue through the gait cycle[24].

It is also possible that neither of these adaptations occur, and that the step length of the bearer remains the same during the load carriage activity [25,26,27,28] when compared to unloaded controls. In all of these studies, the weight of the load carriage was, at most, approximately 30%BM for each participant.

It is possible that the amount of training the participants had in these studies affected their respective gait modifications. In those participants who decreased stride length while under load, all of the participants from Fellin et al.'s study and 77% of participants from Krupenevich et al.'s study had either recently completed Initial Entry Training for the Army[21], or participated in the Reserve Officer's Training Corps (ROTC) at their university[22]. These personnel may have more experience or proper instruction in what adjustments are to be made while under these loads, whereas the participants who underwent increases in stride length were considered untrained personnel (defined as having no experience with prolonged load carriage, as in recreational hiking or military reserves)[23].

Alternatively, the magnitude of the load carriage could be dictating the changes that are undergone by the bearer. In the studies in which stride length decreased while under load, the borne loads were 20%BM or higher, while the magnitude of the loads that did not affect stride length were 30%BM or lower. This could suggest a window or a threshold in which typical gait mechanics must be changed in order to cope with additional load.

Step width is not as often observed during gait, but may serve beneficial when discussing load carriage, an inherently unstable activity. When discussing stability, the center of mass (and/or center of pressure) and base of support are essential in determining how stable a person is. Increasing a person's base of support (by slightly widening their gait pattern, for instance) increases that person's stability. While Birrell and Haslam did not directly measure step width in their study, they suggest that the increased hip abduction they observed served to increase the stability of the person during load carriage[3]. Demura and Demura chose to observe step width in their study, but found no statistically significant differences between four different loads[20]. However, it may be beneficial to discuss clinical significance when dealing with step width, as deviations from the norm may suggest modifications to postural stability.

Joint angles during gait are common kinematic measures, as they can reveal a lot about the kinetics of gait as well. Researchers are typically most concerned with lower extremity joint angles during gait: hip, knee, and ankle angles. However, during a load carriage activity, trunk angles are important when considering gait kinetics as well as postural control. A posteriorly positioned load will shift the body's center of mass backward, requiring the bearer to undergo some degree of forward trunk lean in order to bring their center of mass back within their base of support.

The amount of forward lean is based the magnitude of the load relative to the bearer's body mass. When tasked with carrying increasingly heavy loads, trunk flexion increases significantly compared to unloaded conditions[4,29,30]. When males and females were tasked with carrying the same magnitude of load, females underwent increased trunk flexion compared to males, as the load represented a greater proportion of the body mass of females[22].

Some studies have also chosen to observe craniovertebral angles while under load. Using C7 as the origin, the craniovertebral angle is defined as the angle between the line formed by C7 and the tragus of the ear, and the horizontal line projecting from C7 in the sagittal[31]. Those that measured this angle found with the addition of load equaling approximately 15% or more of body weight, craniovertebral angles decreased, indicating a more forward head posture, which potentially increases cervical spine strain during long bouts[4,31].

Lower extremity joint angles and range of motion (ROM) are important to consider here as well, as they can easily lead into the discussion of kinetics. Seay and colleagues showed that when marching with load at a consistent pace, lower extremity ROM increased as cadence decreased[2]. Regarding hip ROM, no consensus has been reached is terms of adaptations. Some studies report increases in sagittal plane hip ROM with the addition of load[28,32], and others have reported no changes[3,33].

Increased amounts of knee flexion allow for greater force dissipation during activities like running or load carriage by increasing the amount of time the joint has to absorb the impact forces. These adaptations have been seen in other studies[28,32,34], but are not conclusive adaptations. Some research claims the opposite, that increasing loads will actually decrease knee ROM[3,33]. Observing decreased ROM during load carriage may indicate that the bearer is not allowing adequate force dissipation, potentially increasing their risk for injury.

Many studies suggest that the ankle undergoes little to no changes in plantar/dorsiflexion while under load carriage[3,33,35], suggesting that the knee and hip are the primary contributors to modifications in other kinematic and spatiotemporal parameters during gait. Rice and colleagues did observe an increase in dorsiflexion while under load, although they attributed this to an attempt to increase postural stability by lowering the body's center of mass. They also suggest the stiffness of the boot used in their study allowed for increased ROM compared to other studies[34].

Ground reaction forces are likely the most common kinetic measure that can be observed when discussing gait. The ground reaction force (GRF) is defined as a force that is equal in magnitude and opposite in direction to the force applied on the ground by the participant. During load carriage, GRFs in the anteroposterior (AP) direction (braking GRFs during heel strike, and propulsive GRFs during toe-off) and vertical direction are of particular importance, as they can directly influence lower extremity injury. Many studies demonstrate that as load is added, braking GRFs increase[24,26,36,37]. During military marches in particular, unit leaders set both the marching speed and cadence for the group. As step/stride length is inversely related to cadence when walking at a consistent speed, those who increase their step/stride length will typically observe increased braking GRFs as a result[24,36].

Mediolateral (ML) GRFs and GRF impulse are not observed often during gait, but observing changes in these variables may provide more insight into the adaptive mechanisms during load carriage. Several studies have observed that as load carriage weight increases, ML GRFs and ML impulse increase as well[35,36]. Researchers suggest that the increase in ML GRFs/impulse may be related to a decrease in stability, as the participants may have undergone increased ML sway during the load carriage to maintain postural stability.

Limitations

Due to the classification of activities within the military, it can be slightly difficult to pinpoint the activity being performed at the time of the injury; load carriage-related injuries are sometimes combined with running-related or training-related injuries, so the number of injuries that are directly related to load carriage may differ from those sustained during training.

Much of the literature that has studied changes in gait mechanics under military load has done so with participants who are trained military personnel. Thus, extrapolating data from this population to untrained personnel may not be a clear indicator of the adjustments that are made under load. The lack of literature involving untrained personnel makes it difficult to understand the adaptations this population makes while under military load.

It is also difficult to understand how other facets of the load carriage activity (such as time spent under load, distance marched, the frequency of the load carriage activity, and the differing magnitudes of load within military standards) interact and affect the risk for musculoskeletal injury within this population.

Future Directions

Much of the literature that has been compiled to this point discusses how persons trained in load carriage, such as military personnel, respond to load. However, with more epidemiological studies discussing the high incidence of injury as a result of initial entry training, it may be beneficial to observe the biomechanical changes that physically active persons, untrained in load carriage, undergo while under load, in an attempt to replicate incoming military recruits. By understanding the modifications that this population makes while under load, commanding officers and trainers can adjust training protocols to better acclimate this population to the loads they will be experiencing. It also may be beneficial to simulate a standard march with this population by controlling for variables such as marching speed or cadence, to observe how standardizing these variables affect gait mechanics.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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