Invited review

Novel approaches to evaluate characteristics that affect military load carriage

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ABSTRACT

Carrying heavy body-borne loads, an essential component of a service member's duties, is a significant injury risk factor. Physiological and biomechanical data can help illuminate the relationship between load carriage and injuries for service members. This review highlights characteristics that affect load carriage performance and summarises novel approaches to evaluate associated biomechanical changes. Personal characteristics, such as physical fitness and body composition, are good predictors of injury risk and load carriage ability. Effective training programmes can improve load carriage ability by altering fitness and body composition; however, careful planning is needed to integrate training with regular duties to prevent overtraining and, consequently, reduce injury risk in service members. Recent research supports the need for sex-specific training programmes since men and women achieve different training outcomes from similar stimuli. To further minimise injury risk, it is necessary to consider the effects of equipment characteristics (eg, load distribution, form and comfort) on physiological and biomechanical responses. Moreover, novel approaches to evaluate the effects of the various characteristics on load carriage performance are summarised in this review. Markerless motion capture and inertial measurement units have recently been used to evaluate kinematic changes while wearing various combat ensembles. Musculoskeletal modelling can complement kinematic analyses by evaluating internal joint mechanics during dynamic movements. By using frameworks that can leverage modelling approaches in real-time, service members can receive data-driven biofeedback on their load carriage performance and understand the loading experienced by their tissues to ultimately help mitigate their injury risks.

INTRODUCTION

Load carriage (LC) is an essential component of a service member's duties, varying in weight from 20 kg to over 60 kg depending on their Corps, role and task.[1] However, carrying heavy loads is considered a significant musculoskeletal injury risk factor in the military.[1] Nevertheless, the absolute loads that service members carry have increased over time.[2 3] Since increasing fitness levels can help mitigate LC-related injuries, understanding the physiological and biomechanical effects of body-borne load on physical performance supports a holistic approach to investigating injuries.[1] Moreover, investigating physical (eg, marksmanship, mobility, time to exhaustion and completion time)[3 4] and cognitive (eg, accuracy and sensitivity)[5] performance metrics can provide insights into a service member's ability to safely and efficiently complete a mission. These investigations are rapidly improving with advancements in data collection and analytical techniques.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Effective training programmes can improve fitness status and body composition, thereby improving load carriage performance.
⇒ Sex-specific responses to exercise must be considered when designing load carriage training programmes.
⇒ Markerless motion capture and inertial measurement units are valid tools for capturing kinematic changes during load carriage.

WHAT THIS STUDY ADDS

⇒ Carefully considering the personal, equipment and environmental characteristics that affect a service member's physiological and biomechanical responses to load carriage will help military leaders optimise load carriage performance.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Motion capture can be complemented with musculoskeletal modelling to gain insights into internal joint and tissue loading during load carriage.

Understanding the energy cost of LC for service members is essential to optimise task performance and duration.[6] Specifically, energy expenditure (EE) estimations can provide valuable insights into a service member's physiological capability and can be used to plan the LC components of training and missions.[7] Early EE prediction models, using body weight, load, speed, grade and terrain, underestimated values across different speeds due to the non-linear relationship between EE and relative load carried.[4 8] Alternatively, the physiological burden of LC can be expressed as a percentage of maximal aerobic capacity ($\dot{V}O2max$).[6] The Load–Speed Index can be used to estimate task intensity as a percentage of $\dot{V}O2max$ for LC, thereby informing the external load and marching speed required for a given level of exertion.[9] Notably, LC should be performed at or below 47% of one's $\dot{V}O2max$ to limit the use of anaerobic metabolism,[9] which would accelerate fatigue onset, cause postural changes and increase muscle recruitment.[4] When fatigued, muscles generate less force relative to their rested state, and their ability to attenuate ground reaction forces (GRF) on impact is diminished, increasing the risk of overuse injuries.[10]

Researchers have investigated biomechanical movement adaptations observed in response to heavy external loads when marching to gain insights into the factors that increase injury risk. Although conflicting evidence is reported regarding military-specific LC strategies, some key adaptations transpire. Kinematically, during loaded marches, there is an increased trunk, hip and knee flexion with backpack-borne loads, thought to incur in response to the distal shift of the centre of mass.[11] Concurrently, greater hip and knee extension net joint moments are required to counteract the increased gravitational force from the external load, alongside increases in ankle plantar flexion moments to provide propulsive force.[11] The observed kinematic changes are accompanied by increased lower limb and trunk muscle activations to accommodate the additional load.[11] Moreover, LC causes increased anteroposterior and vertical GRF proportional to the increase in load.[1 10 11] When anthropometrically matched, these LC-induced changes are similarly observed in men and women.[12]

Values recorded from outside the body (external biomechanical measurements; eg, joint angles/moments, muscle activation, GRF) can be used to assess the effects of external forces on body movements and postures.[13] Kinematic data are typically recorded with motion capture technologies, such as marker-based or markerless systems,[14] which can be supplemented with force plates, force gauges and electromyography sensors to measure different aspects of movement generation. Traditionally, external joint biomechanics are used to infer internal biomechanics (ie, the mechanical behaviours of body tissues) using predictive modelling methods since in vivo measurements are difficult to obtain.[13 15] Unfortunately, external biomechanics are considered inadequate estimators of tissue loading, partly due to musculoskeletal redundancies (ie, having more muscles than mechanical df), making them insufficient for understanding injury mechanisms.[13 15] Therefore, modelling methods that can account for various neuromusculoskeletal components (eg, tissue structure, muscle contractions, joint loading, tissue strain) would help explain and predict musculoskeletal tissue and joint loading.[13]

This review outlines some characteristics that can alter LC performance and presents novel approaches conducive to injury and LC research within the military. We define LC performance as the ability to execute slow 'adaptive' and short dynamic 'reactive'[3] tasks while bearing heavy loads. In Section 2, various characteristics are discussed related to their effect on physiological and biomechanical responses in service members. Section 3 discusses the advancements in motion capture technologies and digital modelling techniques that can provide greater insights into the effects of various characteristics on internal biomechanics.

CHARACTERISTICS THAT AFFECT LOAD CARRIAGE PERFORMANCE

A service member's LC performance is multifaceted. An interplay of various characteristics affects one's ability to carry high loads without becoming overly fatigued or injured. These characteristics can be separated into three broad groups: personal, equipment and environmental.[6] Understanding the effects of each characteristic on LC can help identify ways to optimise performance in service members while ensuring their safety.

Modifiable personal characteristics such as physical fitness (ie, aerobic and musculoskeletal) and body composition significantly impact LC performance.[1] Aerobic fitness has the strongest positive correlation to LC performance, followed by upper and lower body relative strength.[16] Body composition, specifically the lean body mass over dead mass (ie, fat mass and external load) ratio, is used to predict the relative metabolic demands of an LC task.[17] High lean body mass percentages indicate that a greater proportion of the total mass can actively participate in countering the negative effects of load. Effective training programmes can positively affect these modifiable personal characteristics, improving LC performance and reducing injury risk.[18]

Various parameters (eg, training frequency, intensity, type and duration) have been explored to identify the most effective programme to improve LC performance.[18] Namely, implementing a combination of resistance and cardiovascular training within LC training programmes is recommended.[1 18] Moreover, improvements in LC performance are mostly facilitated by training intensity, followed by frequency and volume.[19] Accordingly, LC training sessions should be performed approximately every 10 days, progressively increasing the distance travelled and the load carried while also integrating conditioning sessions focusing on functional movement patterns.[19] Considerations must also be given to the physical demands of a service member's regular duties to limit the cumulative loading of musculoskeletal tissues, encompassing the frequency, duration and intensity of physical loading combined as a measure of the total mechanical stress placed on the body, which could increase injury risk.[1] The basis for these recommendations has been established, and progressive load conditioning programmes reduce injury rates by 19% compared with traditional LC training in male US Marine Corps recruits, without reducing training outcomes.[20]

Current military fitness programmes are seldom adapted to individuals. Notably, men and women often face the same training requirements regardless of their physiological differences and potentially differing responses to training stimuli.[18 21] Consequently, others have sought to identify sex-specific responses to a 10-week training programme designed to target the neuromuscular demands of LC tasks.[18 21] Outcomes from this research provide clear evidence of sex-specific differences in physical, neuromuscular and biomechanical adaptations to the same training stimulus.[18 21] Specifically, in women, the same training programme improved upper body strength but not cardiovascular fitness, whereas men experienced the reverse effect.[18] Furthermore, the training programme resulted in sex-related differences in LC strategies, as men shifted power production toward the ankle, whereas women adopted a hip-dominant strategy.[21] Given the recent evidence, if military organisations want to reduce injuries, they must consider the personal characteristics of service members (eg, sex, anthropometrics, age) when preparing them for LC.

Equipment (eg, load distribution, equipment form, comfort) is the second group of characteristics that affect the physiological and biomechanical responses of service members to LC tasks. Notably, load distribution/location within the LC system, comprised of clothing, protective equipment, combat equipment and sustainment stores, influences a service member's mobility and EE. Energy costs can be minimised by placing heavier loads high on the torso and close to the carrier rather than on the thighs or hands.[2 9] Although placing a load low on the body increases the carrier's stability, a load placed high on the torso helps maintain an upright posture, lowering EE and mitigating fatigue.[9] One design that appears ideal for LC performance due to load placement is the double pack since it minimises load-related postural changes (eg, forward trunk lean); however, this design reduces torso and arm movements, negatively impacting ergonomics relative to a traditional backpack design.[9] Equipment form (ie, the physical shape of the equipment) can alter the location and magnitude of forces felt by the wearer, which impacts mobility, comfort level and EE. Body armour form is especially important as it can mechanically compress the thorax and shoulders.[4] Armour compression increases oxygen consumption more than the load itself; carrying the load on body armour increases oxygen consumption by 12–17%, compared with 5–6% when carrying the same load in a backpack.[9] Moreover, the mechanical pressure applied to the upper body tissues reduces blood flow supply, causes breathing discomfort, alters torso biomechanics and impairs sensory and motor function, which negatively affects energy cost and task performance (eg, marksmanship).[4] Discomfort from ill-fitting equipment (ie, equipment that is either too large or too small) can lead to physical and cognitive declines,[5] an effect disproportionately present in women, as equipment is generally designed using male anthropometric measurements.[22] Notably, body armour form, which is often too long for the female torso and not fitted for breast tissue, restricts breathing and range of motion in female service members, limiting their ability to perform job-related tasks.[22] Equipment stiffness and bulk are thought to impede LC performance; however, further research on their effects independent of added mass is required.[3]

The third group of characteristics that affect LC performance is the environment (ie, temperature extremes). Military clothing and equipment can obstruct the body's cooling mechanisms, causing an insulator effect,[4] particularly when wearing a double pack.[2] Consequently, the LC system can negatively affect thermal responses in service members. The substantial amounts of heat retained during LC increase temperatures locally, increasing the metabolic burden. Specifically, high heat is detrimental to LC performance as it increases sweat rates, thereby increasing the strain on blood volume, which is already being diverted to working skeletal muscles.[9] A lowered central blood volume can lead to a hypotensive response, syncope or heat exhaustion.[9] Moreover, when performing LC in high-heat environments, the burden experienced by service members further increases due to the additional fluid load they must carry.[6] Conversely, cold environments require an increased EE due to the increased load from added clothing and equipment layers.[6 9] Furthermore, maintaining thermal balance in cold environments places an additional metabolic demand on the body, an effect that can be accelerated by shivering as it depletes carbohydrate stores.[6]

MUSCULOSKELETAL AND DIGITAL MODELLING APPROACHES TO EVALUATE LOAD CARRIAGE PERFORMANCE

Marker-based optical motion capture (ie, infrared cameras that capture reflective marker positions in three-dimensional (3D) space) is currently considered the gold standard for human motion analysis.[14] However, marker-based systems are limited by their capture volume, cost, susceptibility to movement artefacts and marker occlusions, and the time needed to obtain, process and analyse the data.[14] In military studies, marker-based motion capture is limited by equipment-related marker occlusions and the operationally relevant movements performed. Consequently, alternative motion capture technologies, namely markerless motion capture and inertial measurement units (IMUs), have garnered the interest of military researchers. Markerless systems can be separated into depth sensor-based systems (eg, Kinect (Microsoft, USA)), which currently lack the accuracy needed for research-grade results,[23] and video-based systems (eg, Theia3D (Theia Markerless, Canada)).[14] Video-based systems collect data from multiple synchronised cameras to recreate 3D poses using computer vision algorithms.[14] Markerless systems can be more affordable than marker-based motion capture systems, quicker to collect and analyse data, and perform reconstructions independent of the operator. In military settings, markerless systems could be integrated into training environments to collect kinematic data on service members, minimising marker placement errors and marker-driven changes to movement patterns from the results.[14] However, LC systems present a unique challenge for markerless systems as the bulkiness of equipment can obstruct landmarks from view. Recent investigations concluded that markerless technology has the potential to reliably track movements while wearing military equipment,[14] but further research on the subject is needed.

IMUs, which measure linear acceleration, angular velocity and variations in the magnetic field, are a wearable motion capture alternative. Compared with traditional camera-based motion capture systems, IMUs are inexpensive, highly transportable and can be placed under clothing, offering the ability to collect movement patterns under natural conditions,[24] such as during training or while in the field. These small wearable devices can be combined into full-body systems or used as individual sensors. Notably, a full-body IMU system has been successfully validated[24] and used for numerous military-relevant tasks.[24 25] Using kinematic data from full-body systems, researchers and military organisations can gain insights into the movement quality of service members. Unfortunately, using full-body systems in training environments is costly and burdens service members. Consequently, easy-to-use, portable options are required. For instance, two IMUs were successfully used to record spatiotemporal and joint angle data from active-duty US Army infantry soldiers during infiltration and exfiltration ruck marches.[26] Moreover, a single IMU has been used to identify movements and quantify task performance.[27] These studies demonstrate the feasibility of using a minimal IMU setup placed underneath military equipment, which can help inform data-driven decisions by military leaders with minimal burden to service members.

Although markerless motion capture and IMUs are promising for LC kinematic assessments, collecting kinematic data for every combination of personal (eg, anthropometrics, $\dot{V}$O2max), task (eg, external load) and environmental (eg, temperature) characteristics is not feasible. Consequently, alternative statistical methods are required to incrementally represent the effects of various characteristics on LC. For instance, a framework has been developed to produce morphable movement patterns for military tasks from whole-body IMU data using machine learning and pattern classification.[25] These morphable models enable the evaluation of incremental changes in various characteristics (eg, load, experience, body weight) that affect LC.[25] The kinematic data provided by motion capture technologies and the morphable model framework can provide meaningful insights into how load affects service members' movements. Nonetheless, they do not measure internal mechanics, which are essential for understanding biomechanical response and injury mechanisms from LC.

Directly measuring internal loading is only possible through invasive techniques.[15] However, recent advances in computational neuromusculoskeletal models enable the estimation of in vivo tissue loading.[15] Musculoskeletal modelling and simulation approaches can assess internal joint mechanics under dynamic conditions and identify loading patterns that lead to chronic injuries, which can provide meaningful insights into injury mechanisms.[14 25 28 29] Inverse dynamics are commonly used in musculoskeletal modelling to estimate joint reaction and muscle forces from body kinematics (ie, motion capture data) and external kinetics data (ie, force plates[30] and electromyography[14 28 29]). As force plates limit the capture area, methods of predicting GRF and moments from markerless systems[14] and IMUs[24 25 27 30] have been successfully implemented, allowing internal biomechanical analyses to be performed in real-world settings.

Analysing joint kinetics during LC presents an additional challenge: accounting for the backpack-body interactions (ie, shoulder straps, backpack weight and hip belt). To model the relative motion between the backpack and human, spring and damper elements have recently been introduced into LC musculoskeletal models.[28 29] Adding a backpack load greatly increased the joint contact forces in the lumbar spine, more so than the magnitude of the added load, identifying a mechanism for chronic injury and low back pain. The magnitude of joint contact forces also depends on terrain, with the greatest forces shown during uphill walking.[29] In addition, reductions in spinal loading when wearing a hip belt were only apparent when walking downhill.[29] Additional simulation analysis revealed that backpack-borne loads increase concentric and eccentric musculotendon work at the hip, which is exacerbated by sloped terrain and backpack configuration.[28 29] Notably, the long head of the biceps femoris produced the greatest amount of musculotendon work during uphill walking, revealing a possible injury mechanism of this muscle.[28]

The ability to conduct valid internal mechanical analyses is important for evaluating LC performance and investigating injury mechanisms. However, further work is still required for model personalisation, which is essential to determining individual injury risk and developing guidelines to reduce injury risk. A framework was recently developed to provide users with real-time personalised biofeedback of musculoskeletal tissues, pivoting the focus from external biomechanical measurements to the internal mechanics of the tissues of interest.[15] This framework combines personalised neuromusculoskeletal models, wearable sensors and machine learning techniques to provide near real-time estimates of tissue loading.[15] These recent technological advancements demonstrate the rapidly changing landscape of military research and the exciting opportunities to obtain data-driven biofeedback on LC performance.

CONCLUSION

Modifiable and non-modifiable characteristics affect LC performance. Effective training programmes that include LC sessions and appropriately designed resistance training can help improve fitness levels, LC performance and reduce injury risk. Considerations should be made to individualise the training programmes by considering the sex-specific adaptations to LC and training that have been previously identified. Optimal load placement and equipment design can assist service members performing LC by enhancing mobility, comfort and reducing EE. Integrating information regarding the personal (ie, body composition, physical fitness and sex), load (ie, distribution, compression and comfort) and environmental characteristics that affect LC performance can help optimise performance, reduce injury risk and support service members in their missions. Recent advancements in technologies and techniques enable military organisations to collect and analyse data in real-world settings. Notably, IMUs can be used underneath the LC system to record kinematic data in the field. IMU data can help explain injury mechanisms and internal biomechanics during LC when used with novel digital modelling approaches. Further work is needed to develop systems that integrate the various characteristics that affect LC performance and provide real-time biofeedback to service members that can be used to minimise injury risk.

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