Military load carriage effects on the gait of military personnel: a systematic review.

Gregory S. Walsh[1] and Daniel C. Low[2]

[1]Department of Sport, Health Sciences and Social Work, Oxford Brookes University, Oxford, UK, OX3 0BP.
[2]Centre for Human Performance, Exercise and Rehabilitation, Brunel University London, London, UK.

Corresponding author: Gregory S. Walsh
Contact: gwalsh@brookes.ac.uk

Cite as: Walsh GS, Low DC. (2021). Military load carriage effects on the gait of military personnel: A systematic review. *Applied Ergonomics*, 93, 103376. https://doi.org/10.1016/j.apergo.2021.103376

Abstract

Carrying heavy loads results in biomechanical changes to gait and to an increased risk of injury in soldiers. The aim of this review is to examine the effects of military specific load carriage on the gait of soldiers. The Web of Science, PubMed and CINAHL databases were searched, a total of 1239 records were screened and 20 papers were included in the review. Participant, load and task characteristics and a summary of key findings were extracted. Due to heterogeneity in the reviewed studies, analysis was restricted to qualitative synthesis. There were limited effects on spatio-temporal variables but consistently reported increased trunk, hip and knee flexion and increased hip and knee extension moments. Muscle activation of lower limb and trunk muscles were also increased with loads. However, there were some conflicting findings for most parameters reviewed and apart from spatio-temporal parameters the findings of this review were in line with previous reviews of combined military and civilian populations.

Keywords
Gait; Military; Load Carriage; Walking;

1. Introduction

Load carriage is a fundamental task for military personnel (Knapik et al., 2004). The load used however, often exceeds the maximum of 45% body mass, recommended for long distances (Andersen et al., 2016; Orr et al., 2015b). Carrying loads can impact the biomechanics of human gait (Liew et al., 2016), and influence the efficiency (Boffey et al., 2019) and safety of movement, increasing the risk of musculoskeletal injury (Orr et al., 2014). In military personnel, stress fractures, overuse soft tissue injury, thoracic and low back pain, foot blisters and neuropathies are common (Andersen et al., 2016; Cohen et al., 2012; Knapik et al., 2004; Orr et al., 2017, 2014) for which load carriage is one risk factor. In fact, it has been reported that 8% of injuries in the Australian army are the result of heavy load carriage (Orr et al., 2015a). The added external mass due to the load will contribute to injury progression, since it requires gait alterations to minimise potential decrements to efficiency and performance (Baggaley et al., 2020; Liew et al., 2016; Orr et al., 2015a; Willy et al., 2019). However these alterations result in greater exposure to forces and joint loadings (Lenton et al., 2018), providing stresses to the legs and trunk that result in the increased risk of injury. It is important to understand the biomechanical responses to load carriage in soldiers in order to understand the injury aetiology and develop interventions and strategies to prevent these injuries occurring in the future.

Recent reviews (Boffey et al., 2019; Liew et al., 2016) have summarised the effects of load carriage on gait biomechanics, demonstrating that changes in joint kinetics and kinematics, spatio-temporal variables and muscle activity occur when carrying a load. These changes included increased trunk flexion, vertical ground reaction force and cadence and reduced stride length (Liew et al., 2016). Changes in gait biomechanics due to load carriage can be associated with injury risk, where for example, increased activity of locomotor and anti-gravity muscle activity results in greater energy expenditure, increasing fatigue, which in turn leads to atypical gait and loads experienced that can increase the risk of injury (Andersen et al., 2016). Trunk flexion also increases the strain on connective tissue and spinal curvature causing low back pain and injury (Orr et al., 2014). Furthermore, greater ground reaction forces and loading rates in loaded conditions (Lobb et al., 2019; Sessoms et al., 2020) increase joint contact forces causing fatigue and damage to articular structures (Lenton et al., 2018). When combined with increased rearfoot eversion, higher loading rates caused by load carriage increases the risk of tibial stress fractures (Baggaley et al., 2020). However, changes in spatio-temporal gait patterns, such as reducing stride length and increasing cadence can partially modulate the resulting increased peak and cumulative stress caused by load carriage (Willy et al., 2019, 2016).

There appears to be significant variability between studies in regards to the gait changes reported, which is likely the result of heterogenous load carriage systems, load carriage experience and inclusion of both military and civilian populations (Knapik et al., 1996; Liew et al., 2016). Load carriage exercise conditioning results in both physiological and biomechanical adaptions, such as greater maximal oxygen uptake, upper body endurance, lower body strength and a distal shift in power generation during gait (Wills et al., 2020, 2019a, 2019b). In addition, active service soldiers have better self-reported and physical health than civilian populations (Hoerster et al., 2012). Therefore, the addition of load may impact the gait changes required to cope with the increased demands differently in military and civilian populations.

Despite these differences, previous reviews on the effects of load carriage on gait (Boffey et al., 2019; Knapik et al., 1996; Liew et al., 2016) have used both civilian and military personnel and with non-military specific load carriage systems. Due to the nature of military experience, training and work requirements with heavy load carriage, and the specific design of military load carriage systems, the findings of previous reviews may therefore not be directly relevant to military personnel. Therefore, the purpose of this study was to review the available literature examining the effects of military specific load carriage on the gait biomechanics and muscle activations of military personnel.

2. Methods

2.1. Search strategy

The systematic review was conducted in accordance with the PRISMA guidelines. The electronic databases of Web of Science, PubMed and CINAHL were searched. In each database the search terms (military OR army OR soldier*) AND (load* OR equipment OR pack) AND (walk* OR gait OR run*) were used. The initial search was conducted on May 6th 2020 and was repeated for records published after this date on July 29th 2020. No limits were placed on the age of the article, however articles were limited to those written in English. Duplicate articles were removed and all remaining article titles and abstracts were screened against the eligibility criteria. Following screening of titles and abstracts, full text papers were retrieved and were screened against the inclusion criteria. A hand search of each of the reference lists of included studies was also performed. Each screening stage was completed independently by each reviewer, any discrepancies were discussed to reach a consensus between the reviewers.

2.2. Eligibility criteria

The criteria for inclusion were studies that: 1) tested military personnel, 2) used military specific load carriage systems (e.g. backpack, webbing, firearms, body armour and vests), 3) reported kinematic, kinetic or electromyography (EMG) measurement of walking or running gait, 4) studied participants aged 18-60 years, who 5) were free from musculoskeletal injury and neurodegenerative disease when the data were collected, 6) included a control condition of either unloaded walking or walking with a rifle, 7) were an original research article, and 8) were written in English. In this systematic review, it was decided that studies performing walking tasks whilst holding a rifle would be included, despite the impact this may have on gait measurements, as this represents an ecologically valid military load task.

The exclusion criteria included studies that: 1) tested a population that included civilians, 2) load carriage systems not rationalised by military criteria, 3) included no biomechanical or EMG measurement of gait, 4) used exoskeletons or energy harvesting packs, 5) were case reports, literature reviews or conference presentations, and 6) that were not written in English.

2.3. Risk of bias assessment

The risk of bias of all included studies was assessed using the Joanna Briggs Institute (JBI) critical appraisal checklist for analytical cross-sectional studies (Moola et al., 2017). The JBI critical appraisal checklist is comprised of 8 elements. Studies that meet every element of the checklist were deemed to have a low risk of bias, studies that missed 1 element of the checklist were deemed to have a moderate risk of bias and studies that missed 2 or more elements were deemed to have a high risk of bias. Studies demonstrating high risk of bias due to issues with reporting or statistical treatment rather than issues with study design were included.

2.4. Data extraction

For all included studies, participant details, load carriage system and mass conditions, walking or running test conditions, biomechanical and/or EMG measurements and summary of key outcomes summary were extracted. Due to the heterogeneity of measurements, protocols, load carriage systems and reported variables it was decided to restrict analysis to a qualitative synthesis.

3. Results

3.1. Search results

The electronic search returned a total of 1615 results including 376 duplicates. Following the screening of all articles a total of 20 studies were included in the review. The flow of studies through the review can be seen in Figure 1.

[Insert figure 1 about here]

3.2. Characteristics of included studies

All studies included in this review had a cross-sectional, repeated measures design. Table 1 provides an overview of the study characteristics and key outcomes. All studies included male participants and 1 study also included female participants. The average age of participants ranged from 20-31 years. Of the included studies, 9 performed gait measurements during overground walking, 9 during treadmill walking, 1 study reported both overground and treadmill walking and 1 study reported overground walk-run transition and running. In addition, 2 studies performed gait measurements pre and post extended simulated marches. Two studies reported gait measurements during running and 1 study reported gait measurements during the walk-run transition, all other studies reported gait measurements during walking.

A backpack was used in 16 studies, 10 studies reported use of body armour or vest, 8 studies reported the use of webbing or a haversack and 3 studies reported the use heavy weaponry for the load conditions. A rifle was included in all conditions, including the control condition in 5 studies, and in 1 or more of the loaded conditions in 7 studies; 15 studies reported an unloaded control condition with no rifle.

Joint or segment angles or range of motion were reported in 11 studies and joint kinetics were reported in 5 studies, 8 studies reported spatio-temporal variables and 5 studies reported ground reaction forces and derived kinetic variables or plantar pressure measurements and 4 studies reported EMG activity.

[Insert table 1 about here]

3.3. Risk of bias

Of the included studies 55% were deemed to have low risk of bias, 30% were deemed to have a moderate risk of bias and 15% were deemed to have a high risk of bias. In the majority of cases studies with a moderate or high risk of bias was the result of issues in reporting as opposed to study design and 1 study reported unclear statistical treatment. The full risk of bias assessment can be found in Table 2.

[Insert table 2 about here]

3.4. Load carriage effects on spatio-temporal gait variables

Key findings and all load conditions for each study are shown in Table 1. Of the 8 studies reporting results for spatio-temporal variables 5 studies reported no effect.

Specifically, walking speed (Majumdar et al., 2010; Park et al., 2013), step or stride length (Coombes and Kingswell, 2005; Majumdar et al., 2010; Park et al., 2013; Schulze et al., 2014; Sessoms et al., 2020), cadence (Coombes and Kingswell, 2005; Majumdar et al., 2010), step width (Park et al., 2013; Sessoms et al., 2020), and double and single support time (Majumdar et al., 2010). Studies reporting no effect employed backpack or combined backpack and armour loads of 10.7-34.7 kg (Majumdar et al., 2010; Schulze et al., 2014; Sessoms et al., 2020), 8 kg webbing (Coombes and Kingswell, 2005), vest or body armour loads of 8-27 kg (Coombes and Kingswell, 2005; Park et al., 2013) and when also carrying a rifle (Majumdar et al., 2010; Schulze et al., 2014; Sessoms et al., 2020).

Studies that reported spatio-temporal variables in conditions of carrying a rifle and no other load also demonstrated no effect on spatio-temporal variables (Majumdar et al., 2010; Schulze et al., 2014).

An increase in stance phase and double support time were found with vest loads up to 27 kg (Park et al., 2013) and during uphill and downhill walking cadence and double support time increased and stride length decreased (Fellin et al., 2016). Attwells et al. (2006) found differences between control (carrying rifle) and the lightest load condition, but not heavier load conditions for stride length, speed and cadence, although speed was not controlled between conditions. Minimum foot clearance was also greater when loaded than control (i.e. unloaded conditions and low obstacle conditions) (Brown et al., 2016).

3.5. Load carriage effects on joint kinematics

Key findings for load carriage effects on joint kinematics, and all load conditions for each study are shown in Table 1. During the loaded conditions, there was evidence of an increase in hip (Majumdar et al., 2010; Schulze et al., 2014) and knee (Majumdar et al., 2010; Quesada et al., 2000; Rice et al., 2017; Schulze et al., 2014) flexion and an increase in ankle dorsiflexion (Majumdar et al., 2010) compared to unloaded conditions. However, studies also reported no effect on hip (Quesada et al., 2000), knee (Lindner et al., 2012; Tilbury-Davis and Hooper, 1999) and ankle (Quesada et al., 2000; Schulze et al., 2014; Tilbury-Davis and Hooper, 1999) joint angles or variability of joint angles (Morrison et al., 2019). Hip and knee flexion decreased during the walk-run transition (Brown et al., 2014) and sample entropy of hip but not knee sagittal plane motion was also decreased in loaded overground walking (Morrison et al., 2019). Trunk sway has been reported to decrease (Sessoms et al., 2020) with an increase in trunk (Attwells et al., 2006; Brown et al., 2014; Majumdar et al., 2010) and neck

(Attwells et al., 2006) flexion and greater sample entropy of transverse and frontal plane trunk motion (Morrison et al., 2019) during loaded treadmill (Sessoms et al., 2020) and overground (Attwells et al., 2006; Majumdar et al., 2010; Morrison et al., 2019) walking and during running and the walk-run transition (Brown et al., 2014). No change in trunk flexion were however reported during treadmill walking with body armour, backpack and rifle load (Sessoms et al., 2020).

Hip (Attwells et al., 2006; Morrison et al., 2019; Seay et al., 2014), knee (Attwells et al., 2006; Morrison et al., 2019; Seay et al., 2014) and ankle (Majumdar et al., 2010; Rice et al., 2017; Seay et al., 2014) range of motion increased when carrying webbing (Attwells et al., 2006; Morrison et al., 2019; Rice et al., 2017), backpack (Attwells et al., 2006; Majumdar et al., 2010; Morrison et al., 2019; Rice et al., 2017), rifle (Attwells et al., 2006; Majumdar et al., 2010; Rice et al., 2017) and vest (Seay et al., 2014) loads during treadmill (Seay et al., 2014) and overground (Attwells et al., 2006; Majumdar et al., 2010; Morrison et al., 2019) walking. Trunk (Morrison et al., 2019) range of motion decreased however, when walking overground with backpack and webbing and knee range of motion decreased during the walk-run transition (Brown et al., 2014); there was also no effect on ankle range of motion during overground walking with backpack, webbing and rifle loads (Attwells et al., 2006).

3.6. Load carriage effects on joint kinetics

As shown in Table 1, peak hip (Quesada et al., 2000; Seay et al., 2014) and knee (Quesada et al., 2000; Rice et al., 2017; Seay et al., 2014) extension moments and ankle plantarflexion (Quesada et al., 2000; Rice et al., 2017; Seay et al., 2014) moments were reported to be greater in loaded conditions compared to unloaded. Trunk, hip and knee extension moments were also greater with loads during the walk-run transition but were not affected during running (Brown et al., 2014). Load carriage also increased tibiofemoral joint contact forces but without altering individual muscle relative contribution to joint contact forces when wearing body armour and backpack loads (Lenton et al., 2018). Total, hip, knee and ankle sagittal power generation was also increased by load carriage with hip and knee contribution to total power also increased (Lenton et al., 2019). However, during the walk-run transition the contribution of hip power to total power was reduced, with no effect on power when running while carrying body armour and backpack loads (Brown et al., 2014).

3.7. Load carriage effects on ground reaction forces and plantar pressure

Key findings from studies reporting ground reaction forces and plantar pressure and all load conditions for each study are shown in Table 1. Average and peak plantar pressure (Goffar et al., 2013; Park et al., 2013) and the plantar area (Park et al., 2013) increase in loaded conditions compared to unloaded, however, distribution of plantar pressure between plantar regions was unchanged (Goffar et al., 2013). Load carriage increased peak anterior-posterior breaking (Majumdar et al., 2013; Sessoms et al., 2020; Tilbury-Davis and Hooper, 1999) and propulsive (Majumdar et al., 2013) ground reaction forces and impulse (Majumdar et al., 2013; Tilbury-Davis and Hooper, 1999), and vertical impact (Goffar et al., 2013; Majumdar et al., 2013; Sessoms et al., 2020) and propulsive (Majumdar et al., 2013) forces and impulse (Goffar et al., 2013; Majumdar et al., 2013; Tilbury-Davis and Hooper, 1999). Medio-lateral ground reaction forces were lower in loaded conditions than unloaded but power and work were increased (Tilbury-Davis and Hooper, 1999), anterior-posterior and vertical power and work were also increased (Tilbury-Davis and Hooper, 1999). Despite increases in force being commonly reported, the relative timing of force peaks was unchanged (Sessoms et al., 2020).

3.8. Load carriage effects on electromyography

Key findings and all load conditions for each study are shown in Table 1. Backpack, body armour and webbing load carriage, all while carrying a rifle, increased the activity of the Gastrocnemius (Lindner et al., 2012; Paul et al., 2016; Rice et al., 2017; Sessoms et al., 2020), Erector Spinae (Paul et al., 2016; Sessoms et al., 2020), Vastus Medialis (Paul et al., 2016), Vastus Lateralis (Rice et al., 2017), Soleus (Paul et al., 2016), Trapezius (Sessoms et al., 2020), Quadratus Lumborum (Sessoms et al., 2020), Rectus Femoris (Lindner et al., 2012), Biceps Femoris (Lindner et al., 2012) and Peroneus Longus (Lindner et al., 2012), during overground (Rice et al., 2017) and treadmill (Lindner et al., 2012; Paul et al., 2016; Sessoms et al., 2020) walking and before and after a 12.8 km march (Rice et al., 2017).

4. Discussion

The purpose of this study was to review the available literature examining the effects of military specific load carriage on the gait biomechanics and EMG of military personnel. The qualitative synthesis presented highlighted key effects on the spatio-temporal, kinematic, kinetic and EMG parameters of gait. A summary of the findings of the review are presented in Table 3.

[Insert table 3 about here]

4.1. Risk of bias

In the current review, 45% of included studies were deemed to have moderate or high risk of bias. It should be noted, however, that there is currently no validated risk of bias assessment tool for repeated measures cross-sectional study designs. This may have resulted in studies receiving a higher rating for risk of bias than a tool validated for repeated measures studies. In addition, the studies demonstrating high risk of bias in this review were included as this rating in each case was due to issues with reporting not with study design or data collection procedures. The JBI critical appraisal checklist for analytical cross-sectional studies (Moola et al., 2017) was selected based on previous recommendations for cross-sectional studies (Ma et al., 2020).

4.2. Spatio-temporal

The current review found that of the 8 studies reporting the effects of military load carriage on spatio-temporal variables, 5 found no effect on step or stride length, cadence or step width irrespective of the load type carried (i.e. backpack (Majumdar et al., 2010; Schulze et al., 2014; Sessoms et al., 2020), webbing (Coombes and Kingswell, 2005), vest or body armour (Coombes and Kingswell, 2005; Park et al., 2013; Sessoms et al., 2020) carrying a rifle (Majumdar et al., 2010; Schulze et al., 2014; Sessoms et al., 2020). This suggests that despite mechanical differences between load strategies, e.g. evenly distributed loads such as body armour vs. loads borne on the back, load had little effect on the spatio-temporal gait of soldiers. In comparison to the findings of the current review, a previous review of the effects of backpack loads on gait which included studies of military and civilian populations (Liew et al., 2016) found moderate significant effects on double and single support time. However, their review (Liew et al., 2016) included only 2 studies with military populations and 20 studies with civilian or unknown populations that reported spatio-temporal variables, and a narrative review of military and civilian study populations also reported altered spatio-temporal gait (Boffey et al., 2019). This discrepancy between the current and previous reviews may therefore be indicative of a difference in the response to load carriage between military and civilian populations, suggesting that the gait of military personnel is less affected by loads. However, in agreement with findings of the previous review, Attwells et al. (2006) reported increases in stride length and cadence between the control condition and the lightest load condition (15.95 kg) but no differences to the heavier load conditions (39.95 kg and 50.05 kg). These findings are explained by the participants walking significantly faster in the light load condition than any other condition, with walking speed similar in the heavy load conditions to the control condition (Attwells et al., 2006). It is possible that for military personnel, who are experienced in heavy load carriage, the relatively straightforward task conditions of level uninterrupted walking, the fundamental spatio-temporal structure of walking is too robust to be affected by additional load carried and that changes in spatio-temporal parameters may only be seen with heavier loads (Liew et al., 2016).

In contrast, Park et al. (2013) reported an increase in double support and stance phase time when wearing tactical vests weighing up to 27 kg during overground walking despite finding no change in step length, width or walking speed. Similarly, Majumdar et al. (2010) found an increase in midstance time with no change in step length, cadence and double or single support time with combined backpack, armour and weapon loads of up to 17.5 kg. It is likely that increases in stance times allow for a greater vertical and horizontal ground reaction impulse generation to overcome the added inertia of the carried load, preventing a significant decrease in walking speed. Both of these studies tested walking at self-selected unconstrained speeds (i.e. participants were free to alter their walking speed in each condition), in contrast, studies finding no change in spatio-temporal parameters performed treadmill walking (Schulze et al., 2014; Sessoms et al., 2020) or running (Coombes and Kingswell, 2005) with the walking speed fixed during and between conditions. An alternative interpretation of the conflicting findings on the effect of load carriage on the spatio-temporal gait parameters may therefore be that when soldiers are allowed to self-regulate the walking speed, i.e. unconstrained overground walking, stance phase specific parameters (e.g. double support time, midstance time) are altered to accommodate the load. These effects may be masked by walking on a treadmill as this will constrain the speed of each step and the spatial length and width of each step. A previous meta-analysis on the effects of backpack load carriage on gait reported moderate, significant effects on double and single support time (Liew et al., 2016), however, this review did not separate studies performing treadmill and overground walking.

4.3. Joint kinematics and kinetics

It was commonly reported by the reviewed studies that load carriage increases peak trunk (Attwells et al., 2006; Brown et al., 2014; Majumdar et al., 2010), hip (Majumdar et al., 2010; Schulze et al., 2014) and knee (Majumdar et al., 2010; Quesada et al., 2000; Rice et al., 2017; Schulze et al., 2014) flexion during stance phase. As a result the sagittal plane range of motion is also greater for the hip (Attwells et al., 2006; Morrison et al., 2019; Seay et al., 2014), knee (Attwells et al., 2006; Morrison et al., 2019; Seay et al., 2014) and ankle (Majumdar et al., 2010; Rice et al., 2017; Seay et al., 2014). These findings appear to be in agreement with previous reviews on load carriage effects in military and civilian populations, with effects of load on hip and ankle range of motion (Knapik et al., 2004; Liew et al., 2016), suggesting that the greater load carriage experience does not result in a differing kinematic response between populations. In the present review the findings of increased trunk, hip and knee flexion are not consistently reported with no change found for trunk (Sessoms et al., 2020), hip (Quesada et al., 2000) and knee (Lindner et al., 2012; Tilbury-Davis and Hooper, 1999) flexion, in agreement with a previous meta-analysis reporting no effect of backpack carriage on trunk and knee range of motion (Liew et al., 2016). The reason for this discrepancy in the findings for load effects on kinematics are not immediately clear as similar and conflicting findings have been found for studies performing treadmill and overground walking, a variety of load carriage systems, including rifles, and with load masses ranging from 15-50.05 kg, with no obvious discriminating factor. It is likely that the variety of load carriage systems and masses have influenced the outcome. Backpack loads would result in more forward lean to maintain the anterior-posterior position of the centre of mass, this in turn would be expected to result in changes to hip kinematics (Majumdar et al., 2010; Schulze et al., 2014), whereas, evenly distributed loads would have less impact on centre of mass position. This discrepancy may also be caused by carrying weaponry in the hands in some studies (Lindner et al., 2012; Sessoms et al., 2020) as this will also lead to mass distributed in front of the centre of mass, thus requiring less compensation from the trunk and hip.

Decreases in hip and knee flexion during the walk-run transition (Brown et al., 2014) have also been reported which will likely act to increase joint stiffness to allow for efficient acceleration required during the walk-run transition which is not necessary during steady state walking as has been reported in the other reviewed studies. In addition, no change in the peak ankle angles is also commonly reported when walking (Quesada et al., 2000; Schulze et al., 2014; Tilbury-Davis and Hooper, 1999) with only 1 study reporting an increase in ankle dorsiflexion angle (Majumdar et al., 2010) in loaded conditions. This may be due to the chosen footwear, with participants wearing combat boots which restrict ankle motion (Schulze et al., 2014).

The increased hip and knee flexion and range of motion when carrying loads provides additional shock absorption primarily in the weight acceptance phase in response to the greater impact and breaking ground reaction forces (Goffar et al., 2013; Majumdar et al., 2013; Sessoms et al., 2020; Tilbury-Davis and Hooper, 1999). This occurs concurrently with increased peak hip (Brown et al., 2014; Quesada et al., 2000; Seay et al., 2014) and knee (Brown et al., 2014; Quesada et al., 2000; Rice et al., 2017; Seay et al., 2014) extension moments to resist the additional gravitational force. Ankle peak plantarflexion moment (Quesada et al., 2000; Rice et al., 2017; Seay et al., 2014) also increases with added load to produce the necessary propulsive force to overcome the added inertia. This is reflected in the increase in sagittal plane hip, knee and ankle power generation and the increased contribution of hip and knee power to total power reducing the contribution of the ankle, possibly due to the combat boots worn limiting the range of motion and potential adaptation of power generation (Lenton et al., 2019). A consequence of the increased joint moments in loaded conditions is that knee joint contact forces also increase which leads to a greater risk of acute and chronic musculoskeletal injuries (Lenton et al., 2018).

Finally, the greater trunk flexion would be expected in conditions where the load is borne primarily on the back in order to maintain the centre of mass position, all reviewed studies reporting increased trunk flexion included backpack load conditions (Attwells et al., 2006; Brown et al., 2014; Majumdar et al., 2010). Interestingly, trunk flexion was lower with loads held in the hands or evenly distributed in the absence of a backpack (Majumdar et al., 2010). Furthermore, trunk sway was reduced by body armour and backpack loads (Sessoms et al., 2020) and trunk transverse and frontal plane sample entropy (randomness) was increased by backpack loads (Morrison et al., 2019). Together these findings suggest that the magnitude of trunk motion decreases but less tightly controlled, which may be indicative of the increased demand on the neuromuscular system caused by the load (Morrison et al., 2019). Alternatively, the magnitude of trunk motion may be reduced to conserve angular momentum as loads carried on the trunk will increase the inertia of the torso, thus requiring a smaller transverse range of motion to conserve momentum with respect to the pelvis.

4.4. Ground reaction force and plantar pressure

All studies included in this review reporting ground reaction forces identified an increase in anterior-posterior (Majumdar et al., 2013; Sessoms et al., 2020; Tilbury-Davis and Hooper, 1999) and/or vertical (Goffar et al., 2013; Majumdar et al., 2013; Sessoms et al., 2020; Tilbury-Davis and Hooper, 1999) peak forces or impulse in loaded conditions compared to unloaded, in agreement with previous reviews of military and civilian populations (Andersen et al., 2016; Knapik et al., 2004; Liew et al., 2016). This is unsurprising due to the added mass of the carried load, furthermore, the increases in force were proportional to the increase in load (Tilbury-Davis and Hooper, 1999). No change in medio-lateral ground reaction forces was reported in 2 studies (Majumdar et al., 2013; Sessoms et al., 2020), however, Tilbury-Davis and Hooper (1999) reported a small decrease in force but an increase in power and work in the medio-lateral direction, the inconsistency in load effects on medio-lateral forces is in agreement with a previous review (Liew et al., 2016). This discrepancy may be due to the inclusion of a heavier maximum load, i.e. 40 kg backpack (Tilbury-Davis and Hooper, 1999), in comparison to the maximum loads of 34.7 kg body armour, rifle and backpack (Sessoms et al., 2020) and 17.5 kg backpack and light machine gun (Majumdar et al., 2013), or due to differences and improvements in equipment design over time. It may be expected for effects on ground reaction forces of load to be smaller in the medio-lateral direction since the inertia of the load will require large compensation in anti-gravity and propulsive force production for all trunk borne load conditions.

In addition to changes in ground reaction forces, an increase in plantar pressure (Goffar et al., 2013; Park et al., 2013) and the plantar area (Park et al., 2013) were found when carrying tactical vests up to 27 kg (Park et al., 2013) and body armour and backpacks up to 40 kg (Goffar et al., 2013). However, there was no change in the relative distribution of pressure on the plantar surface (Goffar et al., 2013). The increased plantar pressure is congruent with the increased ground reaction force associated with carrying the additional load (Goffar et al., 2013).

In general, the findings for ground reaction force measures are in agreement with previous reviews which included studies of military and civilian populations (Liew et al., 2016). The greater impact forces associated with carrying loads provide an explanation for the reported incidence of lower limb stress fractures, metatarsalgia, muscle strains and tendonitis associated with load carriage in military personnel (Andersen et al., 2016; Knapik et al., 2004; Orr et al., 2015a). Furthermore, the increased plantar pressure reported when carrying additional loads (Goffar et al., 2013; Park et al., 2013), exacerbated by greater breaking and propulsive forces (Majumdar et al., 2013; Sessoms et al., 2020; Tilbury-Davis and Hooper,

1999) explains the high prevalence of foot blisters in soldiers, with blisters being reported as the most common acute load-carriage related injury (Knapik et al., 2004).

4.5. Electromyography

Load carriage is consistently reported to cause an increase in the activity of lower limb and trunk muscles including the ankle plantarflexors (Lindner et al., 2012; Paul et al., 2016; Rice et al., 2017; Sessoms et al., 2020), trunk (Paul et al., 2016; Sessoms et al., 2020), hip (Lindner et al., 2012) and knee (Paul et al., 2016; Rice et al., 2017) extensors and Trapezius (Sessoms et al., 2020), in agreement with previous reviews of military and civilian populations (Andersen et al., 2016; Liew et al., 2016), suggesting both populations require a similar neuromuscular adaptation to accommodate added loads. The increased activity of muscles responsible for resisting gravity (e.g. Gastrocnemius, Soleus, Vastii, Erector Spinae), propulsion (e.g. Gastrocnemius, Soleus, Vastii) and bracing the spine and shoulder girdle (e.g. Erector Spinae, Trapezius) is in line with the need to support and progress a greater mass in loaded conditions. However, the increased muscle activity required when carrying loads results in in greater fatigue (Paul et al., 2016), which in turn may contribute to the high incidence rate of muscle sprains and tendonitis reported in soldiers following periods of extended load carriage caused by progressive gait alterations to accommodate load and progressive fatigue (Andersen et al., 2016; Knapik et al., 2004; Orr et al., 2015a). The increased activity of trunk and lower limb muscles was reported when carrying backpack and webbing loads of 10.7-35.5 kg (Lindner et al., 2012; Paul et al., 2016; Rice et al., 2017) and body armour and backpack loads of 17.4 and 37.4 kg (Sessoms et al., 2020). This Indicates that additional muscle activity is required even with lighter loads (e.g. <20 kg) than are often operationally required for soldiers (Orr et al., 2015b) and loads with differing mass distribution suggesting that, whilst some strategies of distributing load (more) evenly between front and back attempt to reduce the demand on trunk muscles, greater neuromuscular activity is still required. This may present an increased injury risk, particularly in deconditioned individuals, but also that a potential training stimulus can be achieved with lighter loads.

4.6. Limitations of the review

The scope of this literature was intentionally limited to include only military personnel and military load strategies since the greater exposure, experience and conditioning to load carriage experience by soldiers compared to general civilian populations may lead to different findings between these populations. This approach does necessarily require that a body of work completed on civilian populations be excluded which could be relevant to military populations, however, it was decided that this would provide the greatest specificity to military populations, required to achieve the aims of this review. It was also not possible to complete a meta-analysis due to the large variability in reported measures, measurement techniques, load types and assessment protocols. It was therefore decided that reporting only a qualitative synthesis of the findings was the most reliable approach. This does highlight the need for future research to adopt standardised measurement approaches to study the effects of load carriage in military personnel allowing for the development of effective training and injury prevention strategies and the design and development of load carriage systems specific for consistent military applications.

5. Conclusion

Recent systematic reviews on the effects of load carriage on gait have examined studies reporting data from military and civilian populations. This review sought to examine the effects of military specific load carriage strategies on the gait biomechanics of military personnel. The heterogeneity in the reported load carriage systems, equipment and masses of included studies is indicative of the diverse nature of military load carriage, however this prevented a reliable meta-analysis in this review. Future research in military personnel would benefit from more standardised protocols for the various military load carriage systems. The qualitative findings of this review demonstrate limited, inconsistent, effects on spatio-temporal parameters, in opposition to previous reviews of civilian and military populations. These conflicting findings between reviews potentially indicate that the spatio-temporal gait pattern of military personnel is more robust to the effects of load than civilian populations. However, apart from spatio-temporal parameters the findings of the review were in line with findings of previous reviews including military and civilian populations such as common kinematic and kinetic alterations including increases in hip and knee flexion angles and extension moments, increased vertical and anterior-posterior ground reaction forces and greater plantar pressure, in agreement with previous reviews. In addition, increased activity of muscles responsible for resisting gravity and forward propulsion were consistently reported including with loads lower than is often operationally required in soldiers.

Conflict of interest
None. No funds were received to support this work.

References

Andersen, K.A., Grimshaw, P.N., Kelso, R.M., Bentley, D.J., 2016. Musculoskeletal lower limb injury risk in army populations. Sport. Med. - Open 2. doi:10.1186/s40798-016-0046-z

Attwells, R.L., Birrell, S.A., Hooper, R.H., Mansfield, N.J., 2006. Influence of carrying heavy loads on soldiers' posture, movements and gait. Ergonomics 49, 1527–1537. doi:10.1080/00140130600757237

Baggaley, M., Esposito, M., Xu, C., Unnikrishnan, G., Reifman, J., Edwards, W.B., 2020. Effects of load carriage on biomechanical variables associated with tibial stress fractures in running. Gait Posture 77, 190–194. doi:10.1016/j.gaitpost.2020.01.009

Boffey, D., Harat, I., Gepner, Y., Frosti, C.L., Funk, S., Hoffman, J.R., 2019. The physiology and biomechanics of load carriage performance. Mil. Med. 184, E83–E90. doi:10.1093/milmed/usy218

Brown, T.N., Loverro, K.L., Schiffman, J.M., 2016. Soldier-relevant body borne load impacts minimum foot clearance during obstacle negotiation. Appl. Ergon. 55, 56–62. doi:10.1016/j.apergo.2015.12.009

Brown, T.N., O'Donovan, M., Hasselquist, L., Corner, B.D., Schiffman, J.M., 2014. Body borne loads impact walk-to-run and running biomechanics. Gait Posture 40, 237–242. doi:10.1016/j.gaitpost.2014.04.001

Cohen, S.P., Gallagher, R.M., Davis, S.A., Griffith, S.R., Carragee, E.J., 2012. Spine-area pain in military personnel: A review of epidemiology, etiology, diagnosis, and treatment. Spine J. 12, 833–842. doi:10.1016/j.spinee.2011.10.010

Coombes, J.S., Kingswell, C., 2005. Biomechanical and physiological comparison of conventional webbing and the M83 assault vest. Appl. Ergon. 36, 49–53. doi:10.1016/j.apergo.2004.09.004

Fellin, R.E., Seay, J.F., Gregorczyk, K.N., Hasselquist, L., 2016. Spatiotemporal Parameters are not Substantially Influenced by Load Carriage or Inclination During Treadmill and Overground Walking. J. Hum. Kinet. 50, 27–35. doi:10.1515/hukin-2015-0138

Goffar, S.L., Reber, R.J., Christiansen, B.C., Miller, R.B., Naylor, J. a., Rodriguez, B.M., Walker, M.J., Teyhen, D.S., 2013. Changes in Dynamic Plantar Pressure During Loaded Gait. Phys. Ther. 93, 1175–1184. doi:10.2522/ptj.20120103

Hoerster, K.D., Lehavot, K., Simpson, T., McFall, M., Reiber, G., Nelson, K.M., 2012. Health and health behavior differences: U.S. military, veteran, and civilian men. Am. J. Prev. Med. 43, 483–489. doi:10.1016/j.amepre.2012.07.029

Knapik, J., Harman, E., Reynolds, K., 1996. Load carriage using packs: a review of physiological, biomechanical and medical aspects. Appl. Ergon. 27, 207–216. doi:10.1016/0003-6870(96)00013-0

Knapik, J.J., Reynolds, K.L., Harman, E., 2004. Soldier load carriage: Historical, physiological, biomechanical, and medical aspects. Mil. Med. 169, 45–56. doi:10.7205/MILMED.169.1.45

Lenton, G.K., Bishop, P.J., Saxby, D.J., Doyle, T.L.A., Pizzolato, C., Billing, D., Lloyd, D.G., 2018. Tibiofemoral joint contact forces increase with load magnitude and walking speed but remain almost unchanged with different types of carried load. PLoS One 13. doi:10.1371/journal.pone.0206859

Lenton, G.K., Doyle, T.L.A., Lloyd, D.G., Higgs, J., Billing, D., Saxby, D.J., 2019. Lower-limb joint work and power are modulated during load carriage based on load configuration and walking speed. J. Biomech. 83, 174–180. doi:10.1016/j.jbiomech.2018.11.036

Liew, B., Morris, S., Netto, K., 2016. The Effect of Backpack Carriage on the Biomechanics of Walking: A Systematic Review and Preliminary Meta-Analysis. J. Appl. Biomech. 32, 614–629. doi:10.1123/jab.2015-0339

Lindner, T., Schulze, C., Woitge, S., Finze, S., Mittelmeier, W., Bader, R., 2012. The Effect of the Weight of Equipment on Muscle Activity of the Lower Extremity in Soldiers. Sci. WORLD J. doi:10.1100/2012/976513

Lobb, N.J., Fain, A.L.C., Seymore, K.D., Brown, T.N., 2019. Sex and stride length impact leg stiffness and ground reaction forces when running with body borne load. J. Biomech. 86, 96–101. doi:10.1016/j.jbiomech.2019.01.048

Ma, L.L., Wang, Y.Y., Yang, Z.H., Huang, D., Weng, H., Zeng, X.T., 2020. Methodological quality (risk of bias) assessment tools for primary and secondary medical studies: What are they and which is better? Mil. Med. Res. 7, 1–11. doi:10.1186/s40779-020-00238-8

Majumdar, D.D., Pal, M.S., Majumdar, D.D., 2010. Effects of military load carriage on kinematics of gait. Ergonomics 53, 782–791. doi:10.1080/00140131003672015

Majumdar, Deepti, Pal, M.S., Pramanik, A., Majumdar, Dhurjati, 2013. Kinetic changes in gait during low magnitude military load carriage. Ergonomics 56, 1917–1927. doi:10.1080/00140139.2013.835871

Moola, S., Munn, Z., Tufanaru, C., Aromataris, E., Sears, K., Sfetcu, R., Currie, M., Lisy, K., Qureshi, R., Mattis, P., Mu, P., 2017. Systematic reviews of etiology and risk, in: Aromataris, E., Munn, Z. (Eds.), JBI Reviewer's Manual. JBI. doi:https://doi.org/10.46658/JBIRM-17-06

Morrison, A., Hale, J., Brown, S., 2019. Joint range of motion entropy changes in response to load carriage in military personnel. Hum. Mov. Sci. 66, 249–257. doi:10.1016/j.humov.2019.04.014

Orr, R.M., Coyle, J., Johnston, V., Pope, R., 2017. Self-reported load carriage injuries of military soldiers. Int. J. Inj. Contr. Saf. Promot. 24, 189–197. doi:10.1080/17457300.2015.1132731

Orr, R.M., Johnston, V., Coyle, J., Pope, R., 2015a. Reported load carriage injuries of the Australian army soldier. J. Occup. Rehabil. 25, 316–322. doi:10.1007/s10926-014-9540-7

Orr, R.M., Pope, R., Coyle, J., Johnston, V., 2015b. Occupational loads carried by Australian soldiers on military operations. J. Heal. Saf. Environ. 31, 451–467.

Orr, R.M., Pope, R., Johnston, V., Coyle, J., 2014. Soldier occupational load carriage: a narrative review of associated injuries. Int. J. Inj. Contr. Saf. Promot. 21, 388–396. doi:10.1080/17457300.2013.833944

Park, H., Branson, D., Petrova, A., Peksoz, S., Jacobson, B., Warren, A., Goad, C., Kamenidis, P., 2013. Impact of ballistic body armour and load carriage on walking patterns and perceived comfort. Ergonomics 56, 1167–1179. doi:10.1080/00140139.2013.791377

Paul, S., Bhattacharyya, D., Chatterjee, T., Majumdar, D., 2016. Effect of uphill walking with varying grade and speed during load carriage on muscle activity. Ergonomics 59, 514–525. doi:10.1080/00140139.2015.1073792

Quesada, P., Mengelkoch, L., Hale, R., Simon, S., 2000. Biomechanical and metabolic effects of varying backpack loading on simulated marching. Ergonomics 43, 293–309.

Rice, H., Fallowfield, J., Allsopp, A., Dixon, S., 2017. Influence of a 12.8-km military load carriage activity on lower limb gait mechanics and muscle activity. Ergonomics 60, 649–656. doi:10.1080/00140139.2016.1206624

Schulze, C., Lindner, T., Woitge, S., Schulz, K., Finze, S., Mittelmeier, W., Bader, R., 2014. Influence of Footwear and Equipment on Stride Length and Range of Motion of Ankle, Knee and Hip Joint. ACTA Bioeng. Biomech. 16, 45–51. doi:10.5277/ABB-00043-2014-02

Seay, J.F., Fellin, R.E., Sauer, S.G., Frykman, P.N., Bensel, C.K., 2014. Lower Extremity Biomechanical Changes Associated With Symmetrical Torso Loading During Simulated Marching. Mil. Med. 179, 85–91. doi:10.7205/MILMED-D-13-00090

Sessoms, P.H., Gobrecht, M., Niederberger, B.A., Sturdy, J.T., Collins, J.D., Dominguez, J.A., Jaworski, R.L., Kelly, K.R., 2020. Effect of a load distribution system on mobility and performance during simulated and field hiking while under load. Ergonomics 63, 133–144. doi:10.1080/00140139.2019.1690710

Tilbury-Davis, D.C., Hooper, R.H., 1999. The kinetic and kinematic effects of increasing load carriage upon the lower limb. Hum. Mov. Sci. 18, 693–700. doi:10.1016/S0167-9457(99)00026-3

Wills, J.A., Drain, J., Fuller, J.T., Doyle, T.L.A., 2020. Physiological Responses of Female Load Carriage Improves after 10 Weeks of Training. Med. Sci. Sports Exerc. 52, 1763–1769. doi:10.1249/MSS.0000000000002321

Wills, J.A., Saxby, D.J., Glassbrook, D.J., Doyle, T.L.A., 2019a. Load-Carriage Conditioning Elicits Task-Specific Physical and Psychophysical Improvements in Males. J. STRENGTH Cond. Res. 33, 2338–2343. doi:10.1519/JSC.0000000000003243

Wills, J.A., Saxby, D.J., Lenton, G.K., Doyle, T.L.A., 2019b. Ankle and knee moment and power adaptations are elicited through load carriage conditioning in males. J. Biomech. 97. doi:10.1016/j.jbiomech.2019.109341

Willy, R.W., DeVita, P., Meardon, S.A., Baggaley, M., Womble, C.C., Willson, J.D., 2019. Effects of Load Carriage and Step Length Manipulation on Achilles Tendon and Knee Loads. Mil. Med. 184, E479–E486. doi:10.1093/milmed/usz031

Willy, R.W., Wilson, J.D., Clowers, K., Baggaley, M., Murray, N., 2016. The effects of body-borne loads and cadence manipulation on patellofemoral and tibiofemoral joint kinetics during running. J. Biomech. 49, 4028–4033. doi:10.1016/j.jbiomech.2016.10.043

Figure captions

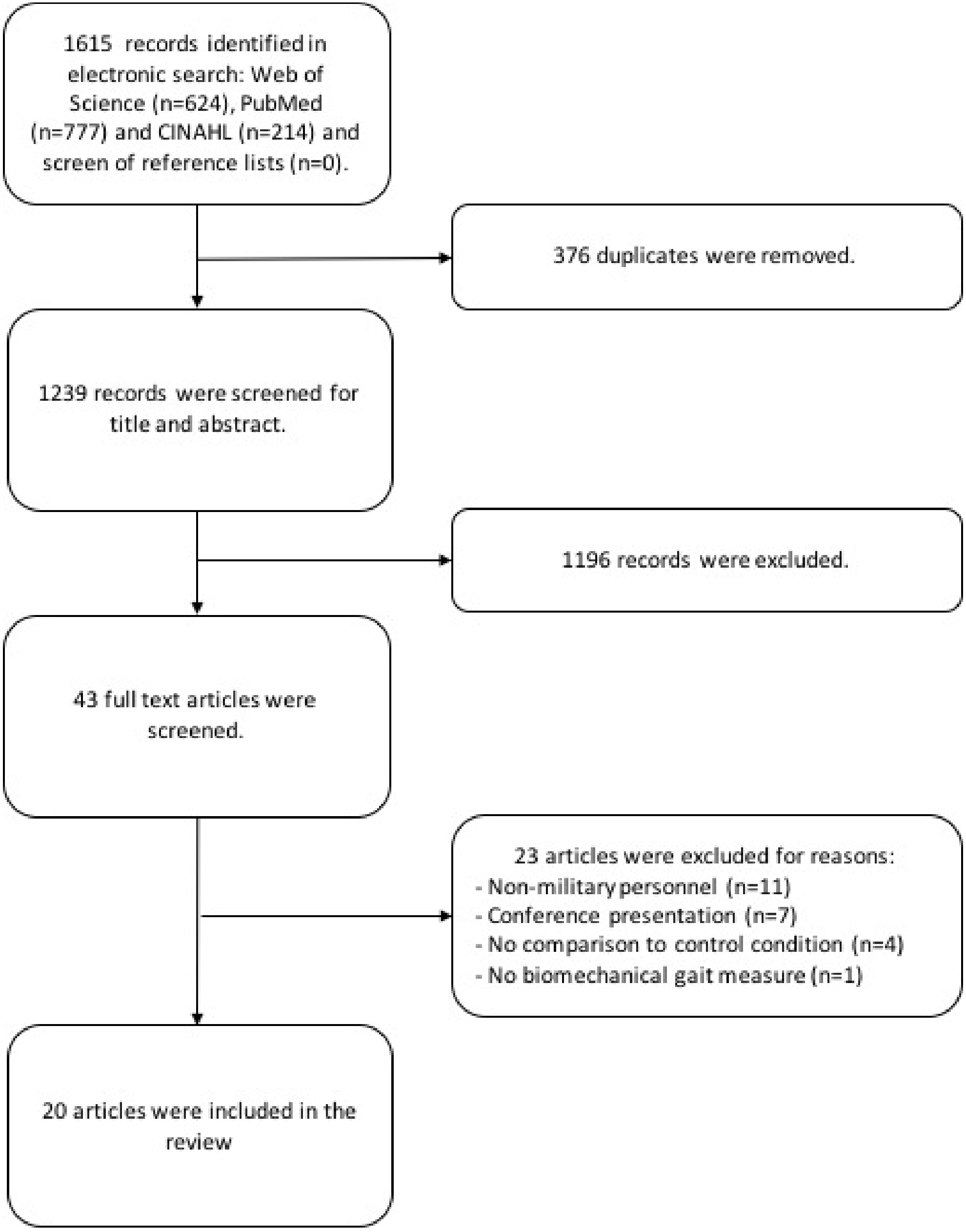

Figure 1. Diagram of the flow of studies through the systematic review.

Tables

Table 1. Study participant, load and task characteristics and a summary of key findings for the 20 included studies.

Reference	Participants	Load conditions	Test conditions	Measurements	Instrumentation	Outcomes
Attwells et al., 2006	20 Males 20±2 years Military personnel	1) Helmet + rifle (7.95 kg) 2) Webbing + rifle (15.95 kg) 3) Webbing + rifle + backpack (39.95 kg) 4) Webbing + rifle + backpack + light anti-tank weapon (50.05 kg)	10 m overground walk (Self-selected speed)	Sagittal plane neck, trunk, hip, knee and ankle ROM. Stride length, cadence, stance time, walking speed.	• OMC	• Stride length was greater in 2) than 1) but lower in 3) and 4) than 2). • Speed, cadence and stride length was greater in 2) than 1), 3) and 4). • No effect on ankle angle. Knee and hip ROM was greater in 3) and 4) compared to 1) and hip ROM was greater in 3) and 4) than 2). Trunk flexion increased in 2-4) compared to 1) and neck flexion increased in 3) and 4) than 1).
Brown et al., 2016	10 Males 21±3 years Active soldiers	1) Helmet + rifle (6 kg) 2) Helmet + rifle + body armour (19.4 kg)	10 m overground walk (1.3 m/s) + low (305 mm) and high (457 mm) obstacle cross	MFC MFC variability Swing phase % at MFC Step length over obstacle	• OMC	• MFC was greater in 2) than 1) for lead foot. • MFC variability was lower in 2) than 1). • No effect on spatio-temporal parameters.
Brown et al., 2014	15 Males 21±3 years Active soldiers	1) Helmet + rifle (6 kg) 2) Helmet + rifle + body armour (20 kg) 3) Helmet + rifle + body armour + backpack (40 kg)	10 m overground walk-to-run (accelerating 1.3 – 3.5 m/s) and run (3.5 m/s)	Sagittal trunk, hip, knee and ankle kinematics (angles) and kinetics (moment, power); stance time	• OMC • FP	• Stance time greater in 3) than 2) and 1) during running but not in walk-run. • In walk-run trunk flexion increased, knee flexion decreased in 3) compared to 1), hip and knee flexion decreased with 2) compared to 1). In run trunk flexion increased in 3) compared to 2) and 1) and in 2) compared to 1). No other kinematic effects. • Trunk, hip, knee extension moment was greater in 3) than 1) and hip extension moment was greater in 2) than 1) in walk-run and run.

						• Contribution of hip to total power reduced in 3) compared to 2) and 1) in walk -run but no effect in run.
Coombes and Kingswell, 2005	8 Males 21±1 years Active soldiers	1) Unloaded (0 kg) 2) Loaded vest (8 kg) 3) Webbing (8 kg)	Treadmill running incremental max exercise test (4-12 km/h, comparisons made at 12 km/h)	Stride frequency and length	• VMC	• No effect of load on stride frequency or length. • Stride frequency and length were correlated in 1) and 2) but not in 1) and 3).
Fellin et al., 2016	10 Males 21±3 years Active soldiers	1) Helmet +rifle (stated as 0 kg); 2) Helmet + rifle + vest (20 kg) 3) Helmet + rifle + vest + Backpack (40 kg)	Treadmill and overground downhill (-6%), level, uphill (+6%) walking (overground self-selected speed)	Stride length, cadence, double support %	• OMC	• Cadence was greater in 2) and 3) than 1), stride length decreased from 1) to 2) and double support % increased in 2) and 3) compared to 1).
Goffar et al., 2013	97 males, 18 females 31±6 years Active soldiers Grouped based on low, normal and high arch	1) Unloaded 2) Helmet + rifle + body armour (20 kg) 3) Helmet + rifle + body armour + Backpack (40 kg)	30 sec Treadmill walk (4.8 km/h)	In-shoe plantar pressure 9 sector max force and force-time integral	• IPP	• Total max force was greater in 2) and 3) than 1), no effect on max force in central forefoot, lateral midfoot, and medial and lateral hindfoot regions. • Total force time integral was greater in 2) and 3) than 1), no differences for the central forefoot, lateral midfoot, and medial and lateral hindfoot regions.

Lenton et al., 2018	21 males 30±7 years Army reserves	1) Unloaded 2) Body armour (15 kg) 3) 3 different systems body armour with load distribution devices (15 kg) 4) Body armour + backpack (30 kg) 5) 3 different systems body armour with load distribution devices + backpack(30 kg)	10 mins treadmill walk (each at 1.53 m/s and 1.81 m/s)	Tibiofemoral contact forces. Muscle and external joint moments	• OMC • sEMG-W • TFP	• Tibiofemoral contact forces were greater in 2-5) than 1) and greater in 4) and 5) than 2) and 3). • There were no differences in the different body armour systems. • Relative contribution of external and muscle moments to contact forces was not effected by load.
Lenton et al., 2019	20 males 30±7 years Active soldiers	1) Unloaded 2) Body armour (15 kg) 3) 3 different systems body armour with load distribution devices (15 kg) 4) Body armour + backpack (30 kg) 5) 3 different systems body armour with load distribution devices + backpack(30 kg)	10 mins treadmill walk (each at 1.53 m/s and 1.81 m/s)	Total, hip, knee and ankle sagittal plane power in stance and total power in swing phases. Hip, knee and ankle joint sagittal power.	• OMC • TFP	• Total and all joint stance phase positive power were greater in 2-5) than 1). Total and joint power were greater with 4) and 5) than 2) and 3). • Hip and knee power contribution to total power greater with 2-5) than 1) but unchanged for ankle.

Lindner et al., 2012	37 males 29 years Active soldiers	1) Unloaded 2) Helmet (1.5 kg) 3) Helmet + carry strap (2.5 kg) 4) Helmet + carry strap + backpack (17.5 kg) 5) Helmet + carry strap + backpack + rifle (21.1 kg)	Treadmill walk (3.2 km/h) at least 5 gait cycles	Mean, peak and integrated EMG activity of peroneus longus, gastrocnemius lateralis, gastrocnemius medialis, tibialis anterior, rectus femoris, and biceps femoris muscles of the right leg. Knee angle	• sEMG-W • EG	• Activity of all muscles was greater with loads 4) and 5) compared to 1), 2) and 3). • No effect of loads on knee angle.
Majumdar et al., 2013	10 males 23±3 years Active soldiers	1) Unloaded 2) Rifle (4.2 kg) 3) Haversack (4.4 kg) 4) Light machine gun (6.8 kg) 5) Haversack + rifle (8.6 kg) 6) Backpack (10.7 kg) 7) Haversack + light machine gun (11.2 kg) 8) Backpack + rifle (14.9 kg) 9) Backpack + light machine gun (17.5 kg)	Overground walk 10 m (self-selected 0.97-1.11 m/s)	Stance phase impact peak force, max propulsive forces in all directions, AP braking forces and impulses in all directions.	• FP	• Greater AP breaking forces in conditions 5-9) compared to 1) and greater AP propulsive forces in conditions 4-9) compared to 1) for either right or left or both feet. • Greater peak vertical impact force in conditions 3-9) compared to 1) and greater peak vertical propulsion force in conditions 2-9) compared to 1) for either right or left or both feet. • Greater AP and vertical impulse in conditions 6-9) compared to 1) for either right or left or both feet.
Majumdar et al., 2010	10 males 23±3 years Active soldiers	1) Unloaded 2) Rifle (4.2 kg) 3) Haversack (4.4 kg) 4) Light machine gun (6.8 kg) 5) Haversack + rifle (8.6 kg) 6) Backpack (10.7 kg)	Overground walk 10 m (self-selected 0.97-1.11 m/s)	Walking speed, step length, stride length and cadence, total support time, double support time, single support time, midstance time and swing phase time. Sagittal plane, angles for ankle, knee, hip and trunk at foot strike, midstance and toe-off, and ROM	• OMC	• Midstance time increased in 2), 4), 5), 7) and 9) compared to 1). No change in any other spatio-temporal variable. • Ankle angle was smaller at footstrike in 4) and 5) compared to 1) and in midstance in 6) compared to 1).Knee angle was smaller at footstrike in 5) compared to 1). Hip angle was greater at toe-off in 4-9)

		7) Haversack + light machine gun (11.2 kg) 8) Backpack + rifle (14.9 kg) 9) Backpack + light machine gun (17.5 kg)				compared to 1). Trunk angle was greater at foot strike in 2-9) compared to 1) and at midstance 6-9) and was lower at midstance in 2-5) compared to 1). • Ankle ROM was greater in 5), 6), 8) and 9) compared to 1) and hip ROM was greater in 9) compared to 1).
Morrison et al., 2019	11 males 22±2 years Army reserves	1) Unloaded 2) Backpack (15 kg) 3) Backpack (25 kg) 4) Webbing + backpack (15 kg) 5) Webbing + backpack (25 kg)	Overground outdoor terrain walk 800 m (1.8 m/s)	Sagittal plane trunk, hip and knee, frontal plane trunk and hip and transverse plane trunk ROM, ROM variability and sample entropy	• IMU	• Frontal plane trunk ROM was lower in 2-5) compared to 1). Sagittal plane left hip ROM was greater in 2-5) compared to 1), right hip ROM was greater in 3) and 5) compared to 1), and left knee ROM was greater in 2) compared to 1). • Transverse plane trunk sample entropy was greater in 4) compared to 1). Frontal plane trunk sample entropy was greater in 3-5) compared to 1). Sagittal plane left hip sample entropy was lower in 2), 3) and 5) than 1) and right hip sample entropy was lower in 3) than 1). • There were no effects for ROM variability.

Park et al., 2013	7 males 21±1 years Army reserves	1) Unloaded 2) Tactical vest (9 kg) 3) Tactical vest + evenly distributed front loads (18 kg) 4) Tactical vest + evenly distributed front and back loads (27 kg) 5) Tactical vest +evenly distributed back loads (27 kg) Note: additional conditions of unilateral loading were not included in this review.	Overground walk 8 steps	Average plantar pressure, peak plantar pressure, plantar contact area, stance phase %, double support %, walking speed, step length and step width	• OMC • PPM	• Stance phase was longer in 4-5) than 1) and double support was longer in 3-5) than 1). No effect for step length, width, or velocity. • Peak plantar pressure was greater in 3-5) than 1) and average plantar pressure was greater in 4) than 1) and 2). Plantar contact area was greater in 4-5) than 1) and 2).
Paul et al., 2016	20 males 27±4 years Active soldiers	1) Unloaded 2) Haversack + webbing + rifle (10.7 kg) 3) Backpack + webbing + rifle (17 kg) 4) Backpack + webbing + rifle + haversack (21.4 kg)	Treadmill walk 6 mins (2.5 and 4 km/h each at 0, 5, 10,1 5, 20, 25% gradient)	Average EMG activity of Erector Spinae, Vastus Medialis, Gastrocnemius Medialis and Soleus	• sEMG-W	• Erector Spinae activity increased as load increased with a load x gradient interaction. Vastus Medialis activity increased as load increased with a load x gradient interaction. Gastrocnemius Medialis activity increased as load increased with a load x gradient interaction. Soleus activity increased as load increased with a load x gradient interaction. • Pairwise comparisons of individual loads not reported.

Quesada et al., 2000	12 males 18-26 years Army reserve	1) Unloaded 2) Backpack (15% body mass) 3) Backpack (30% body mass)	Overground 10 m walk (6 km/h) pre and post treadmill loaded walk 40 mins (6 km/h)	Sagittal plane peak joint angles for late stance hip extension and ankle plantarflexion, late swing hip flexion, early stance knee flexion, swing phase knee flexion, mid- stance ankle dorsiflexion. Sagittal plane peak moments for late stance hip extension and ankle plantarflexion and early stance knee extension	• OMC • FP	• Peak early stance knee flexion angle was greater in 2) and 3) than 1) and in 3) than 2). No other kinematic effects of load. • All moments were greater in 2) and 3) than 1) and in 3) than 2).
Rice et al., 2017	32 males 24±4 years Active soldiers	1) Unloaded 2) Backpack + webbing + rifle (35.5 kg)	Overground walking (5.12 km/h) pre and post overground terrain loaded walking 12.8 km (5.12 km/h)	Ankle and knee touchdown angle, peak dorsiflexion and knee flexion angle and ROM. Peak ankle plantarflexor and knee extensor moments. Ground contact time. Peak amplitude and integrated EMG activity of the Vastus Lateralis, Gastrocnemius Lateralis, Peroneus Longus	• OMC • FP • sEMG-W	• Ground contact time, ankle ROM, knee flexion touch down and peak angles, plantarflexor and knee extensor moments were greater in 2) than 1). • Gastrocnemius Lateralis integrated EMG and Vastus Lateralis peak activity were greater in 2) than 1).

Schulze et al., 2014	32 males 20-53 years Active soldiers	1) Unloaded 2) Helmet (1.5 kg) 3) Load carrying strap (1 kg) 4) Backpack (15 kg) 5) Rifle (3.6 kg)	Treadmill walking (3.2 km/h) at least 5 strides	Stride length, hip, knee and ankle joint angles and ROM.	• VMC • EG	• Knee flexion was greater in 4) and 5) than 1) but no change in ROM. • No effect of load on ankle joint angle or ROM. • Hip flexion and ROM were greater in 4) and 5) than 1). • No effect on stride length
Seay et al., 2014	14 males 19±1 years Active soldiers	1) Unloaded 2) Loaded vest (15 kg) 3) Loaded vest (55 kg)	Treadmill walking (1.3 m/s) 5.5 mins	Stance phase hip, knee and ankle sagittal plane ROM, peak early stance and late stance phase sagittal plane hip, knee and ankle moments.	• TFP • OMC	• Hip, knee and ankle ROM was greater in 2) and 3) than 1) and hip and ankle ROM was greater in 3) than 2). • All joint moments were greater in 3) than 2) and 1) and early stance hip, knee and ankle moments were greater in 2) than 1).
Sessoms et al., 2020	10 males 22±4 years Active soldiers Note: This study reported a separate field assessment but this did not report comparisons to a control condition	1) Helmet + rifle (7.3 kg) 2) Body armour + helmet + rifle (17.4 kg) 3) Body armour + helmet + rifle (24.8 kg) 4) Body armour + backpack + helmet + rifle (34 kg) 5) Prototype body armour + helmet + rifle (18.1 kg) 6) Prototype body armour + helmet + rifle (25.4 kg) 7) Prototype body armour + backpack + helmet + rifle (34.7 kg)	Treadmill walking simulated mountain pass 1.61 km (1.3 m/s)	Trunk AP lean, ML sway. Step width and length. Peak vertical, AP and ML GRFs, timing of peak GRFs. Average EMG activity of Trapezius, Quadratus Lumborum, Erector Spinae, Gastrocnemius.	• OMC • TFP • sEMG-W	• No effect of load on step width or length, or trunk lean. Trunk sway decreased with increasing load (pairwise comparisons not reported). • No effect of load on GRF peak timing. Vertical and AP peak GRFs increased with increasing load (pairwise comparisons not reported). • Activity of all muscles was greater in 2)-7) than 1).

Tilbury-Davis and Hooper, 1999	10 males 25±4 years Active soldiers	1) Unloaded 2) Backpack (20 kg) 3) Backpack (40 kg)	Overground walk 10 m (self-selected speed)	Knee and ankle sagittal plane joint angles and velocities. Vertical, AP and ML peak GRF, power and work. Braking and propulsion impulse	• FP • VMC	• No effect of load for any joint angle or velocity. • Peak ML force was lower in 2) and 3) than 1) and lower in 3) than 2), ML power and work were greater in 2) and 3) than 1) and greater in 3) than 2). • Peak breaking AP force power, work and impulse was greater in 2) and 3) than 1) and greater in 3) than 2). • Peak vertical impulse, power, work and propulsion was greater in 2) and 3) than 1) and greater in 3) than 2).

MFC: Minimum foot clearance; ROM: Range of motion; GRF: Ground reaction force; ML: Medio-lateral; AP: Anterior-posterior; OMC: 3D optical motion capture; FP: force plate; VMC: 2D video motion capture; IPP: in-shoe plantar pressure; sEMG-W: wireless surface electromyography; TFP: force plate instrumented treadmill; EG: electrogoniometer; IMU: inertial measurement unit; PPM: plantar pressure mat

Table 2. Risk of bias assessment for the 20 included studies using the Joanna Briggs Institute critical appraisal checklist.

Reference	Were the criteria for inclusion in the sample clearly defined?	Were the study subjects and the setting described in detail?	Was the exposure measured in a valid and reliable way?	Were objective, standard criteria used for measurement of the condition?	Were confounding factors identified?	Were strategies to deal with confounding factors stated?	Were the outcomes measured in a valid and reliable way?	Was appropriate statistical analysis used?	Overall risk of bias
Attwells et al., 2006	No	Yes	Yes	Yes	Yes	No	Yes	Yes	High
Brown et al., 2016	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Brown et al., 2014	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Coombes and Kingswell, 2005	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Moderate
Fellin et al., 2016	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Moderate
Goffar et al., 2013	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Lenton et al., 2018	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Lenton et al., 2019	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Moderate
Lindner et al., 2012	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Majumdar et al., 2013	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Moderate
Majumdar et al., 2010	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Moderate
Morrison et al., 2019	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Park et al., 2013	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Moderate

Paul et al., 2016	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Quesada et al., 2000	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Rice et al., 2017	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Schulze et al., 2014	No	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	High
Seay et al., 2014	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Sessoms et al., 2020	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Tilbury-Davis and Hooper, 1999	Yes	Yes	Yes	Yes	No	No	Yes	Yes	High

Table 3. Summary of the results of the qualitative review of included studies.

Category	Variable	Outcome
Spatio-temporal	Walking speed	=
	Step or stride length*	=
	Cadence	=
	Step width	=
	Double or single support time	=
Kinematic	Hip, knee and ankle peak flexion angles	x
	Trunk flexion	x
	Hip and knee ROM*	+
	Ankle ROM*	x
	Trunk ROM*	-
Kinetic	Propulsive, breaking and vertical GRF*	+
	Medio-lateral GRF*	x
	Plantar pressure and plantar area*	+
	Hip, knee extension moments*	+
	Ankle plantar flexion moments*	+
	Hip, knee and ankle sagittal power generation	+
Electromyography	Activity of anti-gravity and propulsive trunk and leg muscles*	+

+: indicates variable value increases with added load; -: indicates variable value decreases with added load; =: indicates no effect of load; x: indicates effect of added load is inconclusive; * indicates grouped or analogous variables; GRF: ground reaction forces (and variables derived from GRF); ROM: range of motion