Applied Ergonomics 114 (2024) 104123

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Review article

A systematic review of the physiological and biomechanical differences between males and females in response to load carriage during walking activities

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ARTICLE INFO

Keywords:
Load carriage
Sex differences
Walking gait

ABSTRACT

The purpose of this review was to systematically assess literature on differences between males and females in the physiological and biomechanical responses to load carriage during walking. PubMed, CINAHL, Scopus, Web of Science and the Cochrane library were searched. A total of 4637 records were identified and screened. Thirty-three papers were included in the review. Participant characteristics, load carriage conditions, study protocol, outcome measures and main findings were extracted and qualitatively synthesised. Absolute oxygen uptake and minute ventilation were consistently greater in males but there were limited sex-specific differences when these were expressed relative to physical characteristics. There is limited evidence of sex-specific differences in spatio-temporal variables, ground reaction forces (normalised to body mass) or sagittal plane joint angles with load. However, differences have been found in hip and pelvic motions in the frontal and horizontal planes, which might partly explain an economical advantage for females proposed by some authors.

1. Introduction

Load carriage is often associated with recreational pursuits, such as hiking, and is an occupational requirement for military and emergency service personnel (i.e., firefighters and law enforcement). In military occupations, the mass of an external load is often determined by operational or training task requirements, regardless of sex or physical characteristics Nindl et al. (2016). This often leads to males and females carrying the same absolute load despite clear differences in physical characteristics. A North Atlantic Treaty Organisation (NATO) report showed that soldiers from NATO countries carry loads ranging from 55% to 83% body mass (Armstrong, 2017), which exceeds the recommended upper limit of 45% body mass suggested by an earlier NATO report (van Dijk, 2009). Carrying heavy external loads places large amounts of stress on the musculoskeletal system of the trunk and lower body, with ground reaction forces (GRF) (Birrell et al., 2007; Kinoshita, 1985), peak forces on the lumbosacral spine (Goh et al., 1998), and estimated joint moments at the knee and ankle (Krupenevich et al., 2015) increasing as the mass of the external load increases. It is, therefore, unsurprising that load carriage has been frequently cited as a causative factor for musculoskeletal injury in the military (e.g. Davidson et al., 2008; Fox et al., 2020; Knapik et al., 2004; Roy et al., 2012; Schuh-Renner et al., 2017). Furthermore, female soldiers appear to be two to three times more susceptible to musculoskeletal injury during military training activities than their male counterparts (Bell et al., 2000; Blacker et al., 2008; Fallowfield et al., 2020; O'Leary et al., 2018). This might be explained by an increased relative intensity of training for females (Bell et al., 2000; Fallowfield et al., 2020; O'Leary et al., 2018), and related to lower body mass and shorter stature, which have been identified as risk factors for lower limb injury in British army recruits (Blacker et al., 2008).

Gill et al. (2021) used data from Wilson and Usher (2017) to suggested that loaded marching at a fixed-speed and stride length can cause over-striding in shorter individuals. Overstriding has been associated with stress fracture injuries in military populations (Hill et al., 1996; Kelly et al., 2000), which is likely due to increased ground reaction forces (Castro et al., 2015; Seay et al., 2014) and joint moments (Dames and Smith, 2016; Quesada et al., 2000). Gill et al. (2021) suggested that

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https://doi.org/10.1016/j.apergo.2023.104123
Received 5 January 2023; Received in revised form 11 August 2023; Accepted 18 August 2023
Available online 23 August 2023

the evidence is unclear on whether males and females differ in their biomechanical adaptations to marching at a fixed-speed and stride length, or whether these adaptations are associated with stature rather than sex differences. When stride length is not fixed, several studies have suggested that females may not adopt different gait mechanics to males in response to heavy load despite their smaller posture (e.g. Krupenevich et al., 2015; Middleton et al., 2022; Silder et al., 2013; Vickery-Howe et al., 2020), which might be a contributing factor to the increased injury rates reported for female military personnel. However, some authors have reported differing walking gait responses to load carriage between males and females (e.g. Bode et al., 2021; Loverro et al., 2019; Martin and Nelson, 1986) and sex differences have been found for unloaded walking biomechanics, particularly in pelvic, hip and torso motions (Bruening et al., 2015; Kobayashi et al., 2016).

The physiological responses to load carriage have been extensively studied and readers interested in this area should see a recent narrative review by Faghy et al. (2022). Faghy et al. (2022) identified studies reporting sex-based differences in the work of breathing between males and females during torso-based load carriage tasks. These include greater absolute oxygen uptake (VO_2) and minute ventilation (V_E) in males (Bhambhani and Maikala, 2000; Phillips et al., 2019), and increased heart rate in females (Bhambhani and Maikala, 2000; Godhe et al., 2020; Holewijn et al., 1992; O'Leary et al., 2018). These differences are often not present when VO_2 is expressed as a percentage of body mass (Vickery-Howe et al., 2020) or lean body mass (Silder et al., 2013), suggesting that anthropometric differences might explain any differences in the physiological response to load carriage between males and females. However, some authors have suggested that females might have an economical advantage when carrying load (S. Li et al., 2019b; Wall-Scheffler and Myers, 2017). For example, S. Li et al. (2019b) reported that females can carry heavy loads evenly distributed around the torso with less energy expenditure (normalised to the combined external load and body mass) compared to males during 10 min of walking. The authors speculated that this might be caused by differences in gait pattern with load, specifically, shorter step lengths, higher cadence and greater pelvic motions in females leading to reduced vertical movements of the body and load. This seems plausible given that gait adaptations to load carriage have been previously associated with changes in energy expenditure (Lloyd and Cooke, 2011).

Like much of the wider load carriage literature, research comparing males and females has employed a range of load carriage configurations (i.e., type and mass of the carried load), testing protocols (i.e., walking speeds) and participant experience (i.e., military or civilian populations). Organising and appraising this literature will help to elucidate any sex-specific differences in response to load carriage. Understanding the sex-specific responses is essential to help guide employment standards and equipment manufacture, accurately prescribe training, and inform planning for personnel serving in physically demanding occupations that require load carriage. Therefore, the aim of this review was to systematically assess the literature comparing the physiological and biomechanical responses between males and females when walking with load carriage.

2. Method

This systematic review was pre-registered on PROSPERO (Record ID: CRD42021262925) and was conducted and reported in accordance with the Preferred Reporting for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (http://www.prisma-statement.org) (Page et al., 2021).

2.1. Search strategy

Literature searches were conducted in the electronic databases of PubMed, CINAHL, Scopus, Web of Science and the Cochrane library. The search terms (sex OR gender OR (males AND females)) AND (load* OR pack OR equipment) AND (walk* OR gait) NOT children, were used in each database. Searches were conducted by one author (SH) in May 2021 and repeated for records published after this date in June 2022. All articles were saved in Rayyan reference manager software (http://rayyan.qcri.org). Duplicate articles were removed, and the titles and abstracts were screened for relevance by one author (SH). Full texts of the remaining articles were then retrieved and examined separately by two authors (SH & MF) using the eligibility criteria outlined in the section below. Any discrepancies were decided by a third author (MB).

2.2. Eligibility criteria

The inclusion criteria for this review were: 1) original article written in English; 2) abstract available for screening; 3) included relevant load carriage data; 4) compared data between healthy male and female adult participants; 5) reported biomechanical or physiological measurements of walking.

Articles were excluded from the review if they: 1) could be classified as grey literature (such as theses and dissertations - conference proceedings were included if sufficient detail was available); 2) lacked sufficient methodological detail to enable a full quality assessment; 3) took the form of a review article; 4) included no biomechanical or physiological measures of walking gait; 5) used an exoskeleton or energy harvesting device.

2.3. Methodological quality assessment

The methodological quality of included studies was assessed using the Downs and Black checklist (Downs and Black, 1998). The 27-item checklist was modified to only include items relevant for assessing the methodological quality of non-clinical cross-sectional or observational studies. The modified checklist included 14 items, which were scored as 'Yes' (1), 'No' (0), or 'Unable to determine' (0). The maximum possible score was 14 and a higher score indicates a higher level of quality. The quality assessment was independently conducted by two members of the research team (SH & MF). Any conflicts were resolved by a third reviewer (MB).

2.4. Data extraction

Four authors were involved in data extraction (SH, MF, MD, CL). This involved tabulating the following details for all studies: participant characteristics, load carriage method and mass conditions, walking activity conditions, the outcome measures, (e.g., physiological, biomechanical, and/or perceptual measures), data collection method/instrumentation, and a summary of the main findings. Once tabulated, descriptive frequencies and percentages were calculated for participant characteristics, load carriage methods, mass conditions and outcome measures.

3. Results

3.1. Study identification and selection

A PRISMA flow chart detailing the identification and selection procedures is shown in Fig. 1. The initial search identified 4637 articles. Following the removal of duplicates (n = 925), the titles and abstracts of 3712 articles were screened and 3586 articles were deemed not relevant and excluded. The full texts of the remaining articles were screened, and thirty-three studies were accepted for the review.

3.2. Characteristics of the included studies

A total of 1240 individuals (males, n = 714; females, n = 526) participated in the studies included. Thirteen studies (39% of the reviewed studies) were based on military/emergency service

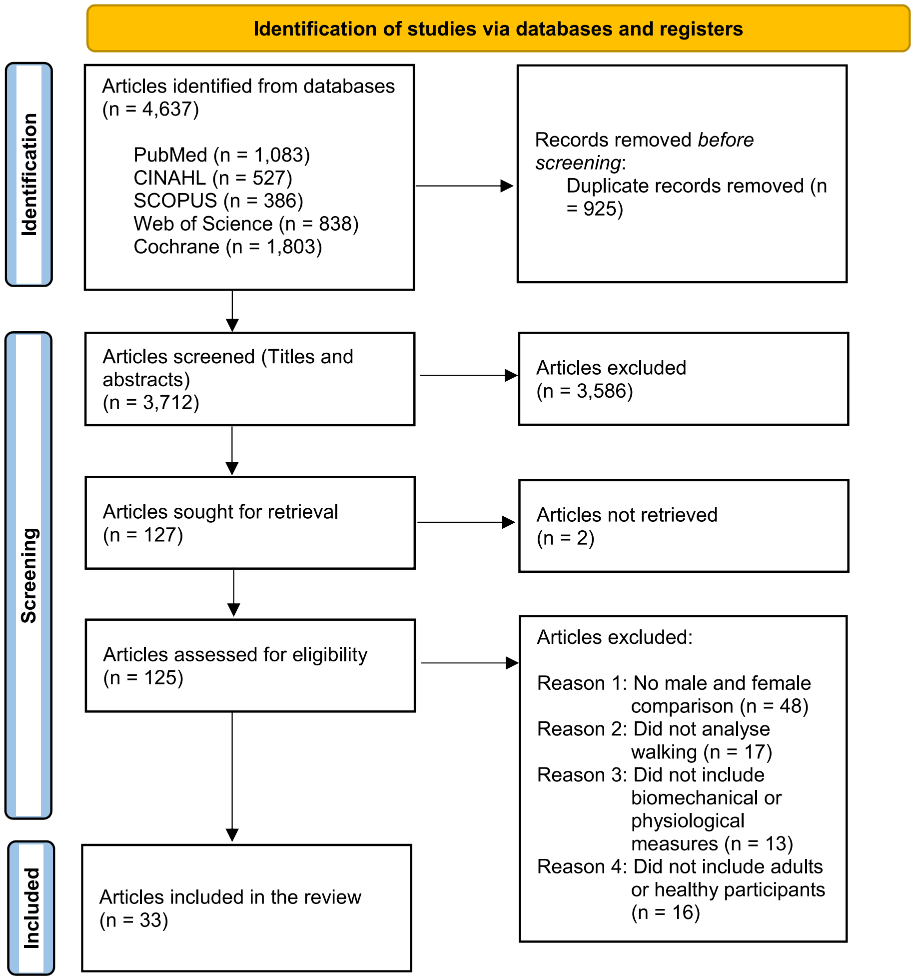

Fig. 1. PRISMA flow diagram of the search and study selection process.

populations, including academy and training corps personnel. Seventeen studies (52% of the reviewed studies) were based on civilian populations. Three studies included participants from both military/emergency service and civilian populations. Twenty-four studies (73% of the total identified studies) used absolute load (range from unloaded to 55 kg weighted vest in Bode et al., 2021), with the remaining studies using some form of relative load (e.g., relative to body mass) ranging from unloaded to 40% of body mass used in Vickery-Howe et al. (2020). The most common load carriage methods were back-loading (e.g., backpacks; n = 16) and combined front and back loading (e.g. weighted vests or body armour; n = 12) (see Table 1).

3.3. Quality of the included studies

The average quality score was 9.8 (±1.3) out of 14 on the modified Downs and Black checklist (Table 4). Quality scores ranged from 43% to 86% (mean = 70.1 ± 9.4%). Most studies (32 out of 33) did not include enough detail to determine whether the individuals asked to participate were representative of the entire population from which they were recruited (question 11), or whether the participants prepared to participate represented the entire population (question 12). Few studies (n = 4) provided sample size calculations to demonstrate sufficient power (question 27). Sixteen studies did not include any method of condition randomisation (question 23) and twelve studies did not report actual probability values when reporting inferential statistics (question 10). The remaining criteria were largely met by the included studies.

3.4. Physiological measures

Twenty-two studies investigated physiological responses (Table 3). They predominantly measured absolute VO_2 (n = 15 studies) and relative VO_2 (n = 12 studies) (or reported derivates of VO_2 such as $\%VO_{2max}$ and carrying cost index (CCI); Prado-Nóvoa et al., 2020). Thereafter, heart rate was the most ubiquitous measure (n = 13 studies), followed by V_E (n = 8 studies), carbon dioxide production (VCO_2; n = 8 studies), respiratory exchange ratio (RER; n = 7 studies) and blood lactate concentration (B_{La}/B_{Lamax}; n = 5 studies). A further twenty-eight physiological measures were reported across studies, but not all provided data or assessed sex-specific differences.

Males tended to have higher absolute VO_2 compared to females when carrying load (Bhambhani and Maikala, 2000; Godhe et al., 2020; Larsson et al., 2022; S. Li et al., 2019b; Phillips et al., 2019; Phillips et al., 2016; Stauffer et al., 1987; Vickery-Howe et al., 2020) with two exceptions (Ricciardi et al., 2007; Wang et al., 2021). Where load mass or VO_2 was calculated relative to body mass, no differences were observed (Santee et al., 2001; Stauffer et al., 1987; Vickery-Howe et al., 2020; Wang et al., 2021). Females tended to have higher relative $\%VO_{2max}$ than males (Bhambhani and Maikala, 2000; Bilzon et al., 2001; Godhe et al., 2020; Holewijn et al., 1992; Turner et al., 2010). One paper reported reduced VO_2 relative to body mass for females compared to males with 30% body mass split between two backpacks simultaneously carried on the front and back of the torso during a 10 min walk at 3.2 km h^{-1}(S. Li et al., 2019a). Where resultant absolute VCO_2 production was reported, VCO_2 was higher in males (Stauffer et al., 1987; Vickery-Howe et al., 2020). There were no sex-specific differences in RER (Bhambhani

Table 1
Characteristics of the studies included in the review.

Study	Sample size	Age (years ± SD)	Body mass (kg ± SD)	Stature (m ± SD)	Load carriage Conditions		Participant characterisation
					Method	Mass	
Armstrong (2017)	M: 12 F: 10	M: 23 ± 4 F: 23 ± 4	M: 77.9 ± 8.4 F: 71.4 ± 9.1	M: 1.80 ± 0.10 F: 1.70 ± 0.10	Military equipment (Fighting, patrol and marching)	21, 26, 33, 43 kg	Military
Bhambhani and Maikala (2000)	M: 11 F: 11	M: 25 ± 3 F: 24 ± 3	M: 78.2 ± 10.5 F: 64.1 ± 11.0	M: 1.79 ± 0.06 F: 1.61 ± 0.09	Box carried in hands bilaterally	0, 15, 20 kg	University students
Bilzon et al. (2001)	M: 34 F: 15	M: 26 ± 7 F: 26 ± 6	M: 76.6 ± 10.5 F: 64.6 ± 12.4	M: 1.78 ± 0.07 F: 1.66 ± 0.05	Firefighting equipment & Backpack	11.2 kg–33.3 kg	Navy
Bode et al. (2021)	M: 8 F: 8	M: 20 ± 2 F: 22 ± 1	M: 72.5 ± 5.6 F: 72.0 ± 7.1	M: 1.67 ± 0.06 F: 1.67 ± 0.06	Weighted vest	0, 15, 35, 55 kg	Military
Coakley et al. (2019)	M: 87 F: 48	M: 25 ± 4 F: 26 ± 5	M: 78.7 ± 10.1 F: 66.0 ± 8.2	M: 1.79 ± 0.07 F: 1.66 ± 0.06	Backpack	25 kg	Military
Eckel et al. (2012)	M: 28 F: 25	M: 22 ± 5 F: 24 ± 7	M: 78.1 ± 10.5 F: 59.6 ± 9.7	M: 1.78 ± 0.08 F: 1.63 ± 0.06	Weighted vest	0, 10, 15, 20% BM	Civilian (local community)
Godhe et al. (2020)	M: 19 F: 17	M: 30 ± 6 F: 29 ± 6	M: 82.5 ± 7 F: 66.1 ± 8.9	M: 1.81 ± 0.05 F: 1.68 ± 0.07	Backpack	0, 20, 35, 50 kg	Firefighters, military, police & university students
Herger et al. (2019)	M: 12 F: 12	M: 25 ± 2 F: 26 ± 1	M: 79.1 ± 11.6 F: 62.7 ± 8.4	M: 1.82 ± 0.08 F: 1.67 ± 0.09	Weighted vest	20% BM	Healthy persons
Hindle et al. (2021)	M: 12 F: 7	M: 30 ± 7 F: 33 ± 7	M: 111.5 ± 26.8 F: 81.1 ± 14.5	M: 1.82 ± 0.09 F: 1.65 ± 0.04	Strongman Yoke	85% of 1RM	Experienced Strongman competitors
Holewijn et al. (1992)	M: 5 F: 5	M: 25 ± 6 F: 21 ± 2	M: 72.4 ± 4.6 F: 61.8 ± 5.9	M: 1.81 ± 0.04 F: 1.69 ± 0.06	Waist pack & Combat boots	0, 12 kg	Physically active
Kasović et al. (2020)	M: 186 F: 89	M: 22 ± 3 F: 22 ± 3	M: 83 ± 11 F: 63 ± 8	M: 1.81 ± 0.06 F: 1.66 ± 0.05	Waist	0, ~3.5 kg	Academy Police Officers
Krupenevich et al. (2015)	M: 11 F: 11	M: 20 ± 2 F: 20 ± 2	M: 79.1 ± 13.3 F: 72.9 ± 15.1	M: 1.79 ± 0.09 F: 1.71 ± 0.08	Backpack (lower and upper back)	0, 22 kg	Healthy adults (77% in Army reserve corps)
Loverro et al. (2019)	M: 15 F: 15	M: 26 ± 5 F: 26 ± 5	M: 79.8 ± 9.1 F: 67.8 ± 9.4	M: 1.78 ± 0.08 F: 1.65 ± 0.08	Weighted vest	0, 15, 26 kg	Civilians, military cadets, active military
Larsson et al. (2022)	M: 9 F: 9	M: 23 ± 2 F: 26 ± 5	M: 78.3 ± 8.9 F: 66.5 ± 8.6	M: 1.81 ± 0.05 F: 1.67 ± 0.06	Military equipment + body armour	0, ~16 kg	Military
Leyk et al. (2007)	M: 17 F: 15	M: 27 ± 9 F: 30 ± 7	M: 81.1 ± 10.6 F: 65.7 ± 12.1	M: 1.79 ± 0.06 F: 1.67 ± 0.07	Stretcher carried in hands	35 kg (10 kg uniform + 25 kg stretcher)	Military
Li et al. (2019b)	M: 15 F: 15	M: 23 ± 3 F: 22 ± 2	M: 64.4 ± 8.1 F: 56.3 ± 7.9	M: 1.74 ± 0.04 F: 1.63 ± 0.06	Backpack, Doublepack	30% BM	University students
Li et al. (2019b)	M: 6 F: 6	M: 22 ± 1 F: 23 ± 1	M: 63.4 ± 5.0 F: 53.8 ± 3.6	M: 1.73 ± 0.03 F: 1.66 ± 0.06	Hands	6, 9, 12 kg	University students
Martin and Nelson (1986)	M: 11 F: 11	M: 21 ± 2 F: 21 ± 2	M: 71.0 ± 7.2 F: 60.8 ± 10.9	M: 1.77 ± 0.06 F: 1.66 ± 0.05	Backpack	0, 9, 17, 29, 36 kg	University students in Army reserve
Middleton et al. (2022)	M: 15 F: 15	M: 22 ± 2 F: 25 ± 6	M: 74.2 ± 8.5 F: 61.5 ± 6.9	M: 1.79 ± 0.07 F: 1.65 ± 0.07	Weighted vest	0, 20, 40% BM	Healthy persons
O'Leary et al. (2018)	M: 23 F: 19	M: 21 ± 3 F: 22 ± 4	M: 77.0 ± 11.8 F: 64.0 ± 7.2	M: 1.77 ± 0.09 F: 1.65 ± 0.03	Military backpack + rifle in hands	~15 kg	Military
Phillips et al. (2016)	M: 7 F: 7	M: 25 ± 3 F: 24 ± 5	M: 69.9 ± 4.8 F: 69.7 ± 5.8	M: 1.77 ± 0.04 F: 1.77 ± 0.05	Backpack	0, 25 kg	University students
Phillips et al. (2019)	M: 14 F: 14	M: 26 ± 7 F: 30 ± 6	M: 79.4 ± 8.7 F: 72.7 ± 11.2	M: 1.77 ± 0.04 F: 1.76 ± 0.06	Backpack	0, 20.4 kg	University students

(continued on next page)

Table 1 (*continued*)

Study	Sample size	Age (years ± SD)	Body mass (kg ± SD)	Stature (m ± SD)	Load carriage Conditions		Participant characterisation
					Method	Mass	
Prado-Nóvoa et al. (2020)	M: 27 F: 21	M: 33 ± 7 F: 29 ± 6	M: 80.6 ± 3.4 F: 58.5 ± 8.9	M: 1.78 ± 0.07 F: 1.64 ± 0.07	Backpack	0, 5, 10, 15 kg	University students
Ricciardi et al. (2007)	M: 17 F: 17	M: 32 ± 4 F: 30 ± 5	M: 78.5 ± 14.9 F: 62.1 ± 9.4	M: 1.74 ± 0.05 F: 1.64 ± 0.05	Body armour	Mass not reported	Military
Santee et al. (2001)	M: 10 F: 6	Pooled data: 23 ± 5	Pooled data: 76 ± 15	Pooled data: 1.77 ± 0.07	Backpack	0, 9.1, 18.1 kg	Military
Silder et al. (2013)	M: 17 F: 12	M: 31 ± 7 F: 36 ± 8	M: 75 ± 7 F: 63 ± 7	M: 1.79 ± 0.07 F: 1.69 ± 0.08	Weighted vest	0, 10, 20, 30% BM	Healthy persons
Stauffer et al. (1987)	M: 12 F: 12	Not reported	M: 72.9 F: 58.5 SD not reported	M: 1.78 F: 1.67 SD not reported	Military equipment + Backpack	5, 12, 20 kg	Military
Thakurta et al. (2015)	M: 6 F: 6	M: 29 ± 6 F: 28 ± 3	M: 73.4 ± 14.6 F: 47.2 ± 7.8	M: 1.70 ± 0.04 F: 1.50 ± 0.05	Head, Single shoulder, Hand, Backpack	0, 20% BM	Construction workers (local to Mumbai, India)
Turner et al. (2010)	M: 25 F: 25	M: 31 ± 6 F: 32 ± 6	M: 93.4 ± 14.1 F: 72.8 ± 10.7	M: 1.78 ± 0.04 F: 1.66 ± 0.05	Backpack, helmet, boots	10.5 kg (backpack) + ~2.5–4.0 kg (boots)	Firefighters
Vickery-Howe et al. (2020)	M: 15 F: 15	M: 22 ± 2 F: 25 ± 6	M: 74 ± 9 F: 62 ± 7	M: 1.79 ± 0.07 F: 1.65 ± 0.07	Weighted vest	0, 20, 40% BM	Participants met Australian army test entry standard
Wall-Scheffler et al. (2017)	M: 6 F: 6	Cohort range 21–45	M: 88.6 ± 6.8 F: 57.7 ± 5.1	Not reported	Hip mounted load (toddler manikin)	11 kg	Healthy persons
Wang et al. (2021)	M: 9 F: 10	M: 20 ± 1 F: 20 ± 1	M: 65.0 ± 7.8 F: 56.4 ± 5.5	M: 1.72 ± 0.06 F: 1.65 ± 0.02	Backpack	0, 5, 10, 15, 20% BM	Recreationally active
Wills et al. (2021)	M: 13 F: 12	M: 22 ± 2 F: 21 ± 2	M: 83.9 ± 6.5 F: 64.8 ± 7.5	M: 1.82 ± 0.06 F: 1.67 ± 0.08	Weighted vest	23 kg	Healthy civilians

BM = Body mass; M = Male; F = Female.

and Maikala, 2000; Larsson et al., 2022; S. Li et al., 2019a; Stauffer et al., 1987; Turner et al., 2010; Vickery-Howe et al., 2020).

B_{La} was not linked to the metabolic data with one study finding greater B_{La} in females using a protocol with heavy absolute loads (20–50 kg) (Godhe et al., 2020), which was not replicated in a second study with a non-disclosed body armour weight at fixed intensities (Ricciardi et al., 2007) or in an absolute shared load (i.e., 50 kg stretcher carrying) protocol to exhaustion (Leyk et al., 2007). In tests to exhaustion using relative load (Larsson et al., 2022), or studies using relative load at increments in separate conditions (Wang et al., 2021), there were no differences in B_{La}. Heart rate outcomes tended to be higher in females compared to males in protocols at absolute loads at a fixed or self-selected pace (Bhambhani and Maikala, 2000; Bilzon et al., 2001; Godhe et al., 2020; Holewijn et al., 1992; Wills et al., 2021). This was not entirely consistent across similar protocols where no difference in heart rate was also reported (Leyk et al., 2007; Ricciardi et al., 2007; Santee et al., 2001; Turner et al., 2010). Where relative intensity and self-paced (Thakurta et al., 2015) or test to exhaustion (Wang et al., 2021) protocols were combined there were no heart rate differences reported between sexes whilst carrying load.

3.5. Physical performance

Five studies included measures of physical performance with walking-based protocols (Coakley et al., 2019; Leyk et al., 2007; Li et al., 2019a; O'Leary et al., 2018; Wang et al., 2021). Four of the five studies used absolute loads (Coakley et al., 2019; Leyk et al., 2007; S. Li et al., 2019a; O'Leary et al., 2018), with load positioned on the back (Coakley et al., 2019; O'Leary et al., 2018) or in the hands (Leyk et al., 2007; Li et al., 2019a). The remaining study employed relative load using a backpack (Wang et al., 2021). All studies reported greater performance for males when carrying load compared to females. Males performed better in a loaded march time-trial (Coakley et al., 2019), time to exhaustion tests (Li et al., 2019a; Wang et al., 2021), and hand grip strength tests (Leyk et al., 2007). O'Leary et al. (2018) found a greater loss in maximal voluntary contraction force in males compared to females but similar vertical jump impairments, following a prolonged loaded march (9.7 km in 90 min).

3.6. Biomechanical measures

Twelve studies included biomechanical measures. Table 3 shows these, except for Wills et al. (2021) who collected ground reaction force (GRF) data via a force plate for males and instrumented treadmill for females so no comparative statistical analysis on the sex-specific differences was performed.

3.6.1. Spatio-temporal gait measures

Seven studies compared spatio-temporal responses. The majority (n = 5) reported no sex-specific differences in stride length/rate (Bode et al., 2021; Eckel et al., 2012; Hindle et al., 2021; Krupenevich et al., 2015; Vickery-Howe et al., 2020). Vickery-Howe et al. (2020) found a 7 ± 2 steps·min^{-1} faster cadence in females across all load conditions (loaded and unloaded trials), but the stride rate response to load carriage from unloaded walking was not different between sexes. In the two studies that reported different stride length/rate responses, Martin and Nelson (1986) found an increase in stride rate and concomitant decrease in stride length in females, whilst Wills et al. (2021) reported an increase in stride length over the course of a 5 km loaded march in females but not males. No sex-specific differences in other spatio-temporal variables were reported, apart from a longer double support time in males (Eckel et al., 2012) and a reduced swing time in females (Martin and Nelson,

Table 2
Studies that compared the physiological differences between males and females in response to load carriage during walking activities.

Study	Load carriage conditions	Test protocol	Measurements	Sex differences
Armstrong (2017)	1)Protective equipment (~21 kg) 2)Fighting equipment (~26 kg) 3)Patrol equipment (~33 kg) 4)Marching equipment (~43 kg)	3-h loaded march (4.9 km h^{-1} at 0% gradient).	Absolute and relative VO_2.	Increased VO_2 per kg lean body mass in females compared to males. Males marched at 31%–41% of VO_{2max} and females 36%–55% of VO_{2max}.
Bhambhani and Maikala (2000)	1)Unloaded 1 2) 15 kg box carried in the hands bilaterally 3) Unloaded 2 4) 20 kg box carried in the hands bilaterally	4 min at self-selected speed (actual speed not reported).	Absolute and relative VO_2; VCO_2; RER; Ventilation rate; Ventilatory equivalent; CO; HR (absolute and %max); SV; BP; total peripheral resistance; rate pressure product; arterio-venous oxygen difference.	Absolute VO_2 higher in males compared to females. Higher relative VO_2 in females in 4). Higher HR for females in 2). Sex differences in 2) and 4) for maximal VO_2, VCO_2, ventilatory equivalent, CO, % of HR_{max}, SV, total peripheral resistance, rate pressure product (refer to paper for data). No difference in RER, ventilation rate, BP, arterio-venous oxygen difference.
Bilzon et al. (2001)	Fire fighter kit (12.3 kg) + 11 kg backpack: 1) 10 kg hose in right hand 2) 7.1 kg hose reel in both hands 3) 10 kg hose under one arm Action Work Dress (mass not stated): 4) 11.2 kg fire extinguisher carry 5) 30 kg drum carry	Simulated fire-fighting tasks. 4 min per task, 60 min recovery between tasks.	Absolute and relative VO_2; $\%VO_{2max}$; HR	Higher relative VO_2 in males in 3) and 5) males. Higher percentage of VO_{2max} in females in 2) and 4) males. HR and $\%HR_{max}$ lower in males in final minute of 1), 2), 3), 4) but not 5).
Godhe et al. (2020)	1) Unloaded 2) 20 kg backpack 3) 35 kg backpack 4) 50 kg backpack	5 min (3 and 5 km h^{-1})	Absolute and relative VO_2; VO_{2max}; B_{La}; HR; Extra Load index (ELI)	Higher absolute VO_2 at 3 km h^{-1} in males in 3) and at 5 km h^{-1} in males in 3). Higher percentage of VO_{2max} in females at 3 km·h^{-1}in 4) and in 3) and 4) at 5 km h^{-1}. HR lower with all loads at both speeds in males. B_{La} higher in females at 5 km h^{-1} in 4).
Herger et al. (2019)	1) Unloaded 2) Reduced BM (−20%) 3) 20% BM in weighted vest	30 min at self-selected speed (4.68 ± 0.36 km h^{-1})	Serum cartilage oligomeric matrix protein (sCOMP)	Higher sCOMP in males. Difference remained when adjusting for BMI
Holewijn et al. (1992)	1) Unloaded (barefoot) 2) Combat boots 3) 12 kg waist pack 4) Combat boots + 12 kg waist pack	6 min (4, 5.25, and 6.5 km h^{-1}) at 0% gradient.	$\%VO_{2max}$; HR	Lower % VO_{2max} in 2) and 3) and 4) at all walking speeds in males. Lower HR in males 2) and 3) and 4) at all walking speeds.
Larsson et al. (2022)	1) Unloaded 2) Combat gear with body armour (M = 15.7 ± 2.0 kg; F = 16.3 ± 2.5 kg)	Graded exercise test to exhaustion - adapted from the Bruce graded protocol	VO_{2peak}; V_{Epeak}; HR_{max}; BF peak; TV peak; RER at exhaustion; B_{La}	Greater VO_{2peak} in males in 2)
Leyk et al. (2007)	1) Approx. 10 kg standard military ambulance uniform +50 kg stretcher manikin (25 kg load measured at front handles).	4.5 km h^{-1} until exhaustion.	HR; B_{La}	No difference in HR or B_{La} between sexes
Li et al. (2019b)	1) Backpack with 30% BM 2) Font + back loading (backpack on front and back) with 30% BM	10 min at 3.2 km h^{-1}	Relative VO_2; RER	Reduced VO_2 standardised to total mass in females in 2). No sex differences in RER.
O'Leary et al. (2018)	1) Load dependent on military trade (16 ± 2 kg for males and 15 ± 1 kg for females). British Army Backpack with rifle in hands.	9.7 km loaded march within 90 min. Neuromuscular fatigue tests pre and post march	HR	HR was higher in females than males
Phillips et al. (2016)	1) Unloaded 2) 25 kg backpack	Test 1: 5.6 km·h^{-1} starting at 0% gradient. Gradient increase 2% every 2 min until exhaustion Test 2: 5.6 km h^{-1} for 45 min (gradient varied based on test 1)	Absolute VO_2; V_E; HR	Higher absolute VO_2 and V_E in males at exhaustion in 1) and 2).
Phillips et al. (2019)	1) Unloaded 2) 20.4 kg backpack	5.6 km h^{-1} and 0% gradient. Gradient increase 2% every 2 min until exhaustion	Absolute VO_2; end tidal CO_2; HR; Spirometry (FVC; FEV_1; PEFR) including lung volumes.	Higher VO_2 in males at 70% of peak VO_2 in 2) and in V_E in males in 2). Lower V_E during submaximal exercise in males in 2). Higher absolute FVC at rest in males in 2), in FEV_1 in 2), and in PEFR in 2)
Prado-Novoa et al. (2020)	1) Unloaded 2) 5 kg backpack 3) 10 kg backpack 4) 15 kg backpack	10 min at 4 km h^{-1}	Relative metabolic cost (carrying cost index (CCI); gross metabolic cost of load expressed as percentage of load carried (RMA))	Lower CCI in males in 4) and RMA in males in 2)

(*continued on next page*)

Table 2 (*continued*)

Study	Load carriage conditions	Test protocol	Measurements	Sex differences
Ricciardi et al. (2007)	1) Unloaded 2) Body armour (mass not specified)	10 min slow walk (F: 3.7 km h^{-1}, M: 3.9 km h^{-1}) at 5% gradient followed by 10 min moderate walk (F: 5.8 km h^{-1}, M: 6.1 km h^{-1}) at 10% gradient	Relative VO_2; HR; RER; Respiratory frequency; B_{La}	No sex differences in VO_2, heart rate, RER, respiratory frequency, B_{La}.
Santee et al. (2001)	1) Unloaded 2) 9.1 kg backpack 3) 18.1 kg backpack	4.8 km·h^{-1}at −12, −10, −8, −4, −2, 0, 4, 8 or 12% gradient.	VO_2; HR	No difference in VO_2 values standardised to body mass between males and females
Silder et al. (2013)	1) Unloaded 2) 10% BM in weighted vest 3) 20% BM in weighted vest 4) 30% BM in weighted vest	5 min at self-selected speed (M: 4.6 ± 0.3 km h^{-1}; F: 4.7 ± 0.4 km h^{-1}).	Metabolic cost (Brockway equation) normalised to body mass and fat-free mass, Muscle activation	Higher net metabolic cost of load in 1), 2), 3) and 4)
Stauffer et al. (1987)	1) Battle dress uniform (5 kg) 2) Items from 1, plus additional military equipment (e.g., rifle, ammunition) (12 kg) 3) Items from 2, plus backpack (20 kg)	3 min at 3, 3.5, 4, 4.5, 5, 5.5 and 6 km h^{-1}.	Absolute and relative VO_2; VCO_2; VE; RER	Males had higher absolute VO_2 values in all three load carriage conditions. No difference in VO_2 between males and females when expressed relative to the combined mass of the body and external load.
Thakurta et al. (2015)	1) Unloaded 2) 20% BM on head 3) 20% BM on one shoulder 4) 20% BM in one hand 5) 20% BM in backpack	15 min at self-selected speed	HR	No sex differences in HR
Turner et al. (2010)	Constant load of 10.5 kg backpack, gloves, helmet. Boot type and mass manipulated: 1) M: ~2.6 kg; F: ~2.4 kg 2) M: ~2.9 kg; F: ~2.5 kg 3) M: ~3.3 kg; F: ~3.0 kg 4) M: ~3.9 kg; F: ~3.4 kg	6 min at 4.8 km h^{-1} and 0% gradient carrying 9.5 kg hose.	Absolute and relative VO_2; VCO_2; V_E; RER; HR; PIF; PEF	Lower relative VO_2 in males during treadmill walking in 1), 2), 3) and 4) No other sex differences.
Vickery-Howe et al. (2020)	1) Unloaded 2) 20% BM in weighted vest 3) 40% BM in weighted vest	10 min at self-selected speed.	Absolute and relative VO_2; V_E; VCO_2; HR	Lower $\%VO_{2max}$ in males in 2) and 3) Higher VO_2 in males in 2) and 3) Higher VCO_2 in males in 3) and 3) No sex differences in VO_2 standardised to body mass
Wall-Scheffler et al. (2017)	1) Overground walking in a gym carrying an 11 kg toddler manikin at the hip	Four self-selected walking speeds (Slow walk; Walk all-day; Brisk walk; Fast walk)	VO_2, VCO_2 to calculate cost of locomotion (CoL); cost per distance (CoD); cost per stride (CoS)	Males were 20%–35% less economical across the walking (CoL). Males were 29%–63% less efficient per unit distance (CoD). Males were 32%–58% less efficient per stride (CoS)
Wang et al. (2021)	1) Unloaded 2) 5% BM in a backpack 3) 10% BM in a backpack 4) 15% BM in a backpack 5) 20% BM in a backpack	Modified Bruce protocol: • 2.7 km h^{-1} at 0% incline • 2.7 km h^{-1} at 5% incline • Start Stage 1 Bruce protocol increase in speed & grade at 3 min intervals until volitional exhaustion	VO_{2max}; V_E; HR; B_{La}	No sex differences in HR, VO_{2max}, V_E, B_{La}.

BM = Body mass; M = Male; F = Female; VO_2 = oxygen consumption; VCO_2 = Carbon dioxide production; HR = Heart rate; SV = Stroke volume; BP = Blood pressure; CO = Cardiac output; TV = Tidal volume; RER = Respiratory exchange ratio; B_{La} = Blood lactate; V_E = Minute ventilation; FVC = Forced vital capacity; FEV_1 = Forced expiratory volume in 1-s; PIF = Peak inspiratory flow; PEF = expiratory flow; PEFR = Peak expiratory flow rate.

1986).

3.6.2. Joint kinematics

Ten studies reported joint kinematics. Seven studies found no difference in lower-limb joint kinematics between males and females (Eckel et al., 2012; Herger et al., 2019; Hindle et al., 2021; Krupenevich et al., 2015; Silder et al., 2013; Vickery-Howe et al., 2020). Bode et al. (2021) reported no difference in hip and ankle motions but did find a greater knee range of motion (ROM) in males compared to females with 15, 35, and 55 kg weighted vests. Loverro et al. (2019) found an increase in peak hip adduction in females using weighted vests with absolute loads but reported no difference between sexes for any other lower limb joint angles. Following a 5 km loaded march with a 23 kg weighted vest, Wills et al. (2021) found an increase in hip adduction, hip internal rotation and knee internal rotation in females but not in males. Four studies reported no sex-specific differences in joint angle kinematics using weighted vests with load standardised to body mass (ranging from 10 to 40% body mass) (Eckel et al., 2012; Herger et al., 2019; Silder et al., 2013; Vickery-Howe et al., 2020).

Krupenevich et al. (2015) found that females exhibit greater trunk lean in response to a 22 kg load carried on the back compared to males. Different trunk angles between males and females are not a ubiquitous finding with Martin and Nelson (1986) finding less trunk forward lean for women with 0, 9, and 17 kg, but no sex-specific differences in trunk angle with 29 and 36 kg.

3.6.3. Ground reaction forces

Four studies examined peak vertical ground reaction force (vGRF) in males and females when carrying load. Eckel et al. (2012), Krupenevich et al. (2015), Middleton et al. (2022) and Silder et al. (2013) all found no difference between sexes in terms of peak vGRF.

3.6.4. Joint kinetics

Krupenevich et al. (2015) and Silder et al. (2013) found no sex-specific differences in ankle joint moments when normalised to body mass. However, Eckel et al. (2012) found greater increases in plantarflexion moment normalised to body mass and height in males compared to females. Using continuous data analysis methods, Middleton et al. (2022) found that males had larger plantarflexion moments (normalised to body mass) than females during mid stance. No sex-specific differences have been reported for knee moments with load carriage (Krupenevich et al., 2015; Loverro et al., 2019; Middleton et al., 2022; Silder

Table 3
Studies that compared the biomechanical differences between males and females in response to load carriage during walking activities.

Study	Load carriage position	Absolute or relative load	Walking Speed	Measurements	Biomechanical sex differences			
					Joint angle kinematics	Spatio-temporal	GRF/ Pressure	Joint moment/power/ work
Bode et al. (2021)	Torso (Back + Front)	Absolute	4.8 km h^{-1}	SL, SR, SW, ST, DS; Sagittal hip, knee & ankle angle	Greater sagittal plane knee ROM in males	No differences	–	–
Eckel et al. (2012)	Torso (Back + Front)	Relative	Self-selected	WS, SL, ST, DS, SS; Sagittal & frontal ankle angle; Peak vGRF; Ankle moment	No difference	Greater DS in males	No difference	Greater plantarflexion moment in males
Herger et al. (2019)	Torso (Back + Front)	Relative	Self-selected	Sagittal hip, knee & ankle angle	No differences	–	–	–
Hindle et al. (2021)	Shoulders	Relative	Self-selected	WS, SL, SR; Sagittal hip & knee angle	–	No differences	–	–
Kasović et al. (2020)	Waist	Absolute	Self-selected	Peak foot pressure	–	–	No difference	–
Krupenevich et al. (2015)	Torso (Back)	Absolute	5.4 km h^{-1}	SL; Sagittal trunk position; vGRF, apGRF; Hip, knee & ankle moment & powers	Greater forward lean in females	No difference	No differences	No differences
Loverro et al. (2019)	Torso (Back + Front)	Absolute	4.86 km h^{-1}	Sagittal & frontal hip & knee angle; Hip & ankle moment	Greater hip adduction in females	–	–	Reduced hip abduction moment in females (normalised to total mass)
Martin and Nelson (1986)	Back	Absolute	6.4 km h^{-1}	SL, SR, DS, SS; Sagittal trunk position	Greater forward lean from unloaded in females with heavy load	Shorter SL, greater SR, and reduced SS in females	–	–
Middleton et al. (2022)	Torso (Back + Front)	Relative	Self-selected	SL, SR, SW, ST; Sagittal hip, knee & ankle angle; vGRF; Hip, knee & ankle moment	No difference	Greater SR and ST in females	No difference	Greater plantarflexion moment in males
Silder et al. (2013)	Torso (Back + Front)	Relative	Self-selected	vGRF, apGRF; Sagittal hip, knee & ankle angle; Hip, knee & ankle moment	No difference	–	No difference	No difference
Vickery-Howe et al. (2020)	Torso (Back + Front)	Relative	Self-selected	SL, SR, SW, ST; Sagittal hip, knee & ankle angle	No difference	Greater SR and ST in females	–	–

WS = Walking speed; SL = Stride length; SR = Stride rate; SW = Step width; ST = Stance time; DS = Double leg support time, SS = Single leg support time (also used for studies reporting swing time), vGRF = Vertical ground reaction force, apGRF = Antero-posterior ground reaction force; ROM = Range of motion.

et al., 2013). Krupenevich et al. (2015), Silder et al. (2013), and Middleton et al. (2022) all found no sex-specific differences in hip moments normalised to body mass. Loverro et al. (2019) reported that peak hip abduction moment normalised to total mass did not change in males but decreased in females. Wills et al. (2021) reported that a 10-week resistance and weighted walking training programme increased moments at the hip and knee in females but at the knee and ankle in males.

4. Discussion

The aim of this review was to systematically assess the literature comparing the physiological and biomechanical responses between males and females when walking with load carriage. The qualitative synthesis presents evidence of (1) limited sex-specific differences in VO_2 when expressed relative to body mass; (2) females tend to have an earlier exercise end point during maximal trials due to working at a higher fraction of their aerobic capacity; (3) limited sex-specific differences in spatio-temporal, kinetic (expressed relative to body mass), or sagittal plane joint kinematic responses; (4) potential sex-specific differences in hip and pelvic motions in the frontal and horizontal plane, based on a small sample of studies, that might contribute to the economical advantage for females proposed by some authors in certain load carriage conditions.

4.1. *Physiological responses*

Oxygen consumption was the predominant physiological variable reported. The trend for higher absolute VO_2 in males with increasing load mass (Bhambhani and Maikala, 2000; Godhe et al., 2020; Larsson et al., 2022; S. Li et al., 2019a; Phillips et al., 2019; Phillips et al., 2016; Stauffer et al., 1987; Vickery-Howe et al., 2020) is expected because males were heavier, on average, than females in these studies and suggests that males might generally be able to sustain exercise for longer by matching the metabolic demand through aerobic pathways. This is supported by data from research on physical performance, with males performing significantly better in loaded march time-trials with absolute loads (Coakley et al., 2019) and in load carriage endurance tests with absolute (Li et al., 2019a) and normalised (Wang et al., 2021) loads.

Collectively, the study protocol strongly influenced the physiological variables (i.e., absolute or relative load carriage; fixed intensity, self-paced, fixed duration or test to exhaustion). Where the load mass or VO_2 were expressed relative to body mass, no differences were seen between sexes (Table 2). Females did tend to record higher relative percentage of VO_{2max} than males (Bhambhani and Maikala, 2000; Bilzon et al., 2001; Godhe et al., 2020; Holewijn et al., 1992; Turner et al., 2010), suggesting exercise would be terminated earlier at the same absolute load in females due the earlier onset of anaerobic metabolism. This is supported by Wang et al. (2021) who found shorter VO_{2max} test durations in females when carrying 5, 10, 15 and 20% body mass. The lack of sex differences in RER (Bhambhani and Maikala, 2000; Larsson

Table 4
Quality assessment of the included studies.

Reference	Downs and Black (1998) Question														Total	Total (%)
	1	2	3	4	6	7	10	11	12	16	18	20	23	27		
Armstrong (2017)	1	1	1	1	1	0	1	0	0	1	1	1	1	0	**10**	**71**
Bhambhani and Maikala (2000)	1	1	0	1	1	1	0	0	0	1	1	1	1	0	**9**	**64**
Bilzon et al. (2001)	1	1	1	1	1	1	0	0	0	1	1	1	1	0	**10**	**71**
Bode et al. (2021)	1	1	1	1	1	1	0	0	0	1	1	1	1	0	**10**	**71**
Coakley et al. (2019)	1	1	1	1	1	1	1	0	1	1	1	1	0	0	**11**	**79**
Eckel et al. (2012)	1	1	1	1	1	1	1	0	0	1	1	1	1	0	**11**	**79**
Godhe et al. (2020)	1	1	1	1	1	1	1	0	0	1	1	1	1	0	**11**	**79**
Herger et al. (2019)	1	1	1	1	1	1	1	0	0	1	1	1	1	0	**11**	**79**
Hindle et al. (2021)	1	1	1	1	1	1	1	0	0	1	1	1	0	0	**10**	**71**
Holewijn et al. (1992)	1	1	1	1	1	1	0	0	0	1	1	1	1	0	**10**	**71**
Kasović et al. (2020)	1	0	1	1	1	1	1	1	0	1	1	1	0	1	**11**	**79**
Krupenevich et al. (2015)	1	1	0	1	1	1	1	0	0	1	1	1	0	0	**9**	**64**
Larsson et al. (2022)	1	1	1	1	1	1	1	0	0	1	1	1	1	0	**11**	**79**
Leyk et al. (2007)	1	1	1	1	1	1	0	0	0	1	1	1	0	0	**9**	**64**
Li et al. (2019b)	1	1	1	1	1	1	1	0	0	1	1	1	0	0	**10**	**71**
Li et al. (2019b)	1	1	1	1	1	1	1	0	0	1	1	1	1	0	**11**	**79**
Loverro et al. (2019)	1	1	1	1	1	1	1	0	0	1	1	1	1	0	**11**	**79**
Martin and Nelson (1986)	1	1	1	1	0	1	0	0	0	1	1	1	1	0	**9**	**64**
Middleton et al. (2022)	1	1	1	1	1	1	1	0	0	1	1	1	0	0	**10**	**71**
O'Leary et al. (2018)	1	1	1	1	1	1	1	0	0	1	1	1	0	0	**10**	**71**
Phillips et al. (2016)	1	1	0	1	1	1	0	0	0	1	1	1	0	0	**8**	**57**
Phillips et al. (2019)	1	1	1	1	1	1	0	0	0	1	1	1	1	0	**10**	**71**
Prado-Novoa et al. (2020)	1	1	1	1	1	1	1	0	0	1	1	1	0	0	**10**	**71**
Ricciardi et al. (2007)	1	0	0	1	1	1	1	0	0	1	1	1	0	0	**8**	**57**
Santee et al. (2001)	1	1	0	1	1	1	0	0	0	1	1	1	1	0	**9**	**64**
Silder et al. (2013)	1	1	1	1	1	1	1	0	0	1	1	1	1	0	**11**	**79**
Stauffer et al. (1987)	1	1	0	1	0	0	0	0	0	1	1	1	0	0	**6**	**43**
Thakurta et al. (2015)	1	0	1	1	0	1	0	0	0	1	0	1	1	0	**7**	**50**
Turner et al. (2010)	1	1	1	1	1	1	0	0	0	1	1	1	0	1	**10**	**71**
Vickery-Howe et al. (2020)	1	1	1	1	1	1	1	0	0	1	1	1	0	1	**11**	**79**
Wall-Scheffler and Myers (2017)	0	1	0	1	1	1	1	0	0	1	1	1	0	0	**8**	**57**
Wang et al. (2021)	1	1	1	1	1	1	1	0	0	1	1	1	1	1	**12**	**86**
Wills et al. (2021)	1	1	1	1	1	1	1	0	0	1	1	1	0	0	**10**	**71**

et al., 2022; S. Li et al., 2019a; Stauffer et al., 1987; Turner et al., 2010) suggests that the same relative exercise end point would be reached with incremental loads. These observations suggest that many of the physiological differences between males and females might be due to anthropometry rather than inherent biological differences. In occupations were the load carried is dictated by the task, and essential equipment can't be scaled to body mass, physical conditioning to increase strength and lean body mass is likely to be beneficial (Silder et al., 2013; Wills et al., 2020).

S. Li et al. (2019b) are the only authors to report sex-specific differences with VO_2 expressed relative to physical characteristics (standardised to body mass + external load). They found reduced energy expenditure for females during 10 min of walking with 30% body mass carried in a doublepack. The authors speculated that greater pelvic rotations in females could lead to reduced vertical oscillations of the centre of mass, reducing energy expenditure. However, they did not provide data to support this and Gordon et al. (2003), Ortega and Farley (2005), and Wurdeman et al. (2017) have all shown that modifying gait to reduce the vertical displacement of the centre of mass results in an increase in the metabolic cost of unloaded walking. Wall-Scheffler and Myers (2017) also found reduced energy expenditure (calculated as the cost of locomotion) in females compared to males when carrying an 11 kg toddler manakin at the hip. The authors explained their findings by suggesting that the relatively larger medio-lateral pelvis width they also found for a given body mass in females (Wall-Scheffler and Myers, 2017) might provide an economical advantage by enabling greater hip rotation, increasing stride length for a given limb length, and improving gait stability through lowering the height of the centre of mass due to a relatively larger pelvis. Wall-Scheffler and Myers (2017) did not include measures of gait stability, but decreased stability measured via step width and step width variability has been shown to increase the energetic cost of unloaded walking (Abram et al., 2019; Donelan et al., 2004; Shorter et al., 2017). This could be particularly pertinent for load carriage on uneven terrain were increased instability can increase energy expenditure (Voloshina et al., 2013). Bi-trochanteric width has been associated load carriage energy expenditure, although only two studies have reported this to date (Wall-Scheffler et al., 2007; Wall-Scheffler and Myers, 2017).

4.2. Biomechanical responses

Studies have generally found no sex-differences for lower-limb joint kinematics when the load is standardised to body mass and carried on the torso (i.e., backpack or weighted vest). There also appear to be no sex-differences for hip and ankle motions when carrying absolute loads, but females do appear to exhibit smaller knee ROM with absolute loads carried using weighted vests (Bode et al., 2021; Loverro et al., 2019). Loverro et al. (2019) did not report knee angles during the swing phase, but they speculated that the smaller knee ROM might be a result of females decreasing their knee extension prior to heel-strike to reduce stress on the knee. This is supported by research showing increased hip and knee flexion in late swing with increased load mass (Middleton et al., 2022; Silder et al., 2013), which is likely to be a preparatory strategy to accommodate heavy load carriage in early stance. Interestingly, Bode et al. (2021) reported similar reductions in knee angle ROM for females when investigating the responses to load carriage in anthropometrically paired males and females (stature and body mass). However, Bode et al. (2021) did not match participants for lean body mass (LBM) (male LBM = 56.6 ± 3.1 kg; female LBM = 46.7 ± 4.9 kg) and an increased lower limb muscle mass in males may have afforded them stronger knee musculature, enabling an increased knee ROM compared to their female counterparts when carrying the same absolute load. As such, it appears that lean body mass and muscular strength might account for differences in load carriage gait mechanics in studies where participants are matched for stature and body mass.

Most load carriage research exploring sex differences have focused on joint kinematics in the sagittal plane (Bode et al., 2021; Eckel et al., 2012; Herger et al., 2019; Krupenevich et al., 2015; Martin and Nelson, 1986; Middleton et al., 2022; Silder et al., 2013; Vickery-Howe et al., 2020), which is likely due to the greatest joint angle excursions occurring in this plane of motion during gait. This could be a major omission from the current body of research as differences between the male and female unloaded walking gait appear to mostly occur in pelvic obliquity, pelvic rotation, hip adduction/abduction, torso rotation (Bruening et al., 2015). In one of the few studies to report frontal plane motions, Loverro et al. (2019) found greater hip adduction in females when unloaded and with 15 kg carried in a weighted vest, although the change from unloaded to loaded walking was not reported, so it is unclear if the response to load carriage differed between males and females.

Much of the load carriage research reporting spatio-temporal variables has found no differences between males and females in response to additional load when walking (Table 3). Several studies have reported a greater stride rate and shorter stance time (Martin and Nelson, 1986; Middleton et al., 2022; Vickery-Howe et al., 2020) for females compared to males across unloaded and loaded conditions, but no sex by load mass interactions were reported. As such, this response might be explained by stature, as males and females walked at similar speeds in these studies and females were generally shorter than the males (Table 1), which would result in a shorter stride length and higher stride rate for a given walking speed.

Few studies included GRF data, and none reported sex differences with force normalised to body mass (Eckel et al., 2012; Krupenevich et al., 2015; Silder et al., 2013; Wills et al., 2021). There were also no sex differences reported for sagittal plane joint moments at the hip and knee with force normalised to body mass (Krupenevich et al., 2015; Silder et al., 2013). There were equivocal findings for ankle plantarflexion moment, with Eckel et al. (2012) and Middleton et al. (2022) reporting greater plantarflexion moments in males with load carried using weighted vests, but Silder et al. (2013) and Krupenevich et al. (2015) reporting no sex differences with load carried in a weighted vest and backpack, respectively. Both Middleton et al. (2022) and Eckel et al. (2012) used relative loads, so it is possible that the greater absolute loads carried by males led to the greater plantarflexion moments, even with the joint moments normalised to body mass (Middleton et al., 2022) or to body mass and height combined (Eckel et al., 2012). In line with these findings, Loverro et al. (2019) observed sex differences in frontal plane hip joint moments (i.e., peak hip abduction) when normalising to total mass (body mass + external load), but not when normalising to body mass only. Future research comparing sex differences might benefit from normalising joint moments to the total mass to gain deeper insights into the effect of additional external load.

Most studies investigated biomechanical responses to load carriage over short walking periods (≤10 min). Wills et al. (2021) is the only study, to date, reporting sex differences in gait in response to load carriage over a prolonged walking period (5 km in 55 min). It appears, based on this single study, that there are sex-specific biomechanical responses to prolonged walking with 22 kg load, with hip adduction, hip internal rotation and knee internal rotation angles increasing after 5 km load carriage for females but not males. This suggests that male and female gait patterns might respond differently to prolonged load carriage. Interestingly, these responses align with some of the sex-specific differences in hip and pelvic motion reported for unloaded walking (Bruening et al., 2015).

4.3. Limitations of this review

The variability in load carriage conditions, walking protocols, and measurement techniques resulted in a heterogenous sample. Therefore, a meta-analysis was not feasible and qualitative synthesis was considered the most reliable approach to analysing the body of research. While systematic reviews provide much needed contributions to the load carriage literature (e.g. Simpkins et al., 2022; Walsh and Low, 2021), not including a meta-analysis reduces the statistical impact of these findings. The scope of this review is limited to walking because it is one of the most prevalent activities for occupational and recreational load carriage, but other loaded activities such as running and jumping might illicit sex-specific differences.

4.4. Future research

Future research might benefit from investigating gait mechanics that have been shown to differ between males and females when walking unloaded. These variables include pelvic obliquity, pelvic rotation, hip adduction/abduction, and torso rotation (Bruening et al., 2015). Loverro et al. (2019) and Wills et al. (2021) are the only studies to report some of these measures and found differences in hip adduction and hip internal rotation between males and females. Furthermore, Wall-Scheffler and Myers (2017) and S. Li et al. (2019b) suggested that an increased pelvic width relative to body mass and larger pelvic rotations might be beneficial for load carriage economy. As such, future research would benefit from modelling joints in 3D rather than planar analysis and include measures of bi-trochanteric breadths. Given the suggested role of pelvic width on improved gait stability (Wall-Scheffler and Myers, 2017) and the link between gait stability and energy expenditure (Voloshina et al., 2013), research on sex-specific response to load carriage over uneven outdoor environments, where most load carriage activities occur, appears warranted. Further research on biomechanical responses to prolonged load carriage would also be beneficial, with Wills et al. (2021) demonstrating increased hip adduction and internal rotation in females after a 5 km loaded walk. This is particularly pertinent given the high incidence of injury reported in female military personnel (Bell et al., 2000; Blacker et al., 2008; Fallowfield et al., 2020; O'Leary et al., 2018).

4.5. Conclusions

This review found limited evidence of sex-specific differences in VO_2 when expressed relative to physical characteristics in sub-maximal exercise protocols. When maximal protocols are used with absolute loads, females tend to have an earlier exercise end point due to working at a higher fraction of their aerobic capacity. We also found limited evidence of sex-specific differences in spatio-temporal variables, ground reaction forces (normalised to body mass) and sagittal plane joint angles when walking with load. Some studies have reported increased stride rates and stance times for females, but these were consistent across unloaded and loaded conditions. Few studies have reported motions in the frontal or horizontal planes, but those that have reported differences in hip motions over short and prolonged periods of load carriage, which aligns with sex-specific differences reported for unloaded walking. Increased pelvic width and rotation angles have been suggested to be an economical advantage for females with hip loading methods, possibly through improved gait stability, although further research is needed to clarify this.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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