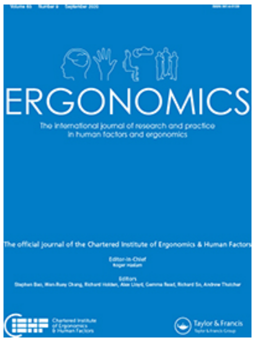

Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: https://www.tandfonline.com/loi/terg20

No physiological or biomechanical sex-by-load interactions during treadmill-based load carriage

Danielle M. Vickery-Howe, Anthea C. Clarke, Jace R. Drain, Ben J. Dascombe & Kane J. Middleton

No physiological or biomechanical sex-by-load interactions during treadmill-based load carriage

Danielle M. Vickery-Howe[a], Anthea C. Clarke[a], Jace R. Drain[b], Ben J. Dascombe[c], Kane J. Middleton[a]

[a]Sport and Exercise Science, School of Allied Health, Human Services and Sport, La Trobe University, Bundoora, Australia

[b]Land Division, Defence Science and Technology Group, Fishermans Bend, Australia

[c]Applied Sport Science and Exercise Testing Laboratory, School of Life and Environmental Sciences, University of Newcastle, Ourimbah, Australia

Corresponding author: Kane Middleton

Address: School of Allied Health, Human Services and Sport, La Trobe University, 1 Kingsbury Drive, Bundoora 3083, Victoria, Australia

Phone: +61 9479 5884

Email: k.middleton@latrobe.edu.au

Word Count: 2,116

Abstract Word Count: 147

Number of tables: 2

Number of figures: 0

Abstract

This study investigated whether physiological demand or gait mechanics differ between sexes during treadmill load carriage. Female (n = 15) and male (n = 15) military recruit-type participants with no load carriage experience completed three 10-minute walking trials at a self-selected speed with increasing relative body-borne loads (0%, 20%, and 40% body weight). A range of cardiorespiratory, perceptual and biomechanical variables were measured. Self-selected walking speed was similar between sexes (4.6-4.8 $km \cdot h^{-1}$, $p > 0.05$) and there were no significant sex-by-load interactions for any variables. Absolute $\dot{V}O_2$ and $\dot{V}CO_2$ were greater in males (difference 175-178 $mL \cdot min^{-1}$, $p < 0.001$), however, when relative to body mass, $\dot{V}O_2$ was similar between sexes ($p > 0.05$). Across all loads, cadence was 7 ± 2 $steps \cdot min^{-1}$ faster ($p = 0.004$) and stance time was 0.06 ± 0.02 s shorter ($p = 0.013$) in females. Increasing load resulted in greater physiological demand, cadence, % stance time, and step length ($p < 0.05$).

Key words: gait; physiological demand; kinematics; spatiotemporal; military ergonomics

Practitioner Summary

Literature comparing physiological and biomechanical variables between sexes during load carriage is scarce. Physiological and biomechanical sex differences were limited to relative measures associated with physical size (height and mass). Future research may pool male and female participants when conducting trials up to ten minutes in length.

Introduction

Understanding the physiological requirements associated with load carriage is essential to guide training, accurately prescribe work-to-rest guidelines, and inform mission planning for personnel serving in the military and other physically demanding occupations (e.g. firefighting). Although load carriage can occur over differing terrain and in extreme environmental conditions, the majority of load carriage research to date has been undertaken in highly controlled laboratory conditions, generally on a motorised treadmill and in male participants[1-3]. Given the recent removal of gender exemptions within many physically demanding occupations, female representation has increased within many organisations. For example, the overall number of females within the Australian Defence Force has increased from 14.4% in 2013[4] to 17.9% in 2018[5]. with the goal to increase workforce diversity within many military and emergency services[6]. Understanding whether there are physiological or biomechanical differences between men and women in this core occupational task is becoming increasingly important given the disparate rates of injury between the sexes [7, 8].

Few studies have attempted to quantify the physiological and/or biomechanical differences between men and women during load carriage.[9-12] It has been reported that during walking trials with 15 kg and 20 kg loads, oxygen consumption ($\dot{V}O_2$) relative to body weight (BW) did not differ between men and women, however, when represented as a percentage of their predicted $VO2_{max}$, women were working at higher relative intensities, and above their ventilatory threshold with the 20 kg load.[9] Conversely, when normalised to body mass, the net metabolic cost of walking across various loaded conditions show males have a greater metabolic cost than females, despite similar gait patterns.[12] Inconsistent reports show heart rate is comparable between sexes[10] or higher in female participants compared with males.[11] Unfortunately, due to methodological differences between studies, such as the use of absolute or relative loads, differences in load distribution (carried in arms, backpack, or double pack), and walking speed, a clear understanding of sex differences in response to loaded treadmill walking is not available. Research that accounts for load and walking speed variations is needed to identify any systematic physiological and/or biomechanical differences between sexes during treadmill load carriage. This information will help to inform the requirement for further female-specific research in this area and/or application of existing research.

The aim of the current study was to determine whether there are sex differences in the physiological demand and gait mechanics during treadmill load carriage across a range of relative loads (0%, 20% and 40% BW). It was hypothesised that females would have a greater physiological demand despite similar gait patterns to men, and that the physiological demand and gait mechanics would change similarly between sexes with increasing loads.

Materials and Methods

Fifteen females (age: 25.1 ± 6.1 y, height: 1.65 ± 0.07 m, body mass: 61.5 ± 6.9 kg, predicted VO_{2max}: 44.1 ± 3.8 $ml \cdot kg^{-1} \cdot min^{-1}$; mean ± standard deviation [SD]) and 15 males (22.3 ± 2.3 y, 1.79 ± 0.07 m, 74.2 ± 8.5 kg, 48.7 ± 2.9 $ml \cdot kg^{-1} \cdot min^{-1}$) participated in this study. An a priori sample size calculation indicated that 14 participants would be required to detect an interaction effect size of 0.2 with 80% power at an alpha of 0.05. On average, females were shorter (-0.13 ± 0.03 m, p <0.001, mean difference ± standard error [SE]) and lighter (-12.7 ± 2.8 kg, p <0.001) than males. All participants were injury free for at least six months prior to participating. Ethical procedures were approved by La Trobe University's Science, Health and Engineering College Human Ethics Sub-Committee (Ethics number: HEC18146) and all participants provided written informed consent.

To meet study inclusion criteria, participants were required to meet the Australian Army physical fitness entry standards of 8 (female) or 15 (male) push-ups, 45 sit-ups and a minimum predicted maximal oxygen uptake (VO_{2max}) of 38.1 $ml \cdot kg^{-1} \cdot min^{-1}$ during a submaximal exercise test[13] on a Trackmaster motorised treadmill (TMX58, Newton, Kansas).

Having met the inclusion criteria, participants were familiarised with the testing environment and external loads by walking at a comfortable pace for three minutes with each individual load. This allowed participants' individual self-selected walking speed to also be determined. A self-selected walking speed was chosen to remove it as a potential confounding variable affecting gait mechanics and physiological demand[14].

Participants completed three 10-minute walking trials on the treadmill with different relative torso-borne loads (0% BW, 20% BW, 40% BW). Relative loads were chosen to remove confounding variables such as differences in relative loading, which is consistent with previous research[12, 14]. The control condition (0% BW) was performed first then load incremented (20% BW followed by 40% BW) to allow a linear increase in muscle stiffness to ensure safe completion of the tasks[15]. Ten minutes of passive rest was provided between each trial. Prior to commencing the next trial, heart rate was required to have returned to within 10% of resting prior and additional time was provided if required. The load was added in the form of a weighted vest using 1 kg blocks, added symmetrically with equal distribution anterior-posteriorly and medio-laterally to keep load close to the COM and most comparable to the double backpack.[16]

Expired air samples were collected breath-by-breath using a valid [17, 18] portable metabolic system (Jaeger Oxycon Mobile; Carefusion, Germany) attached to the trunk in a vest, which was connected to a Hans-Rudolf face mask, fitted as per manufacturer guidelines. The device was calibrated before each testing session using gases of a known composition with flow rate calibrated automatically. Ventilation ($\dot{V}E$, $L \cdot min^{-1}$), absolute volume of oxygen consumption ($\dot{V}O_2$, $mL \cdot min^{-1}$), relative $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$), and carbon dioxide production ($\dot{V}CO_2$, $mL \cdot min^{-1}$) were measured throughout the trial. Data over the final three minutes of each trial were averaged and used for analysis. Heart rate was monitored throughout each trial and recorded in the final minute, as steady state was reached. Individuals' maximum heart rate (HR_{max}) was predicted from a validated model[19] and used to calculate percentage HR_{max} (%HR_{max}) for each trial. A rating of perceived exertion (RPE) using the 6-20 Borg scale was obtained at the end of each trial.[20]

For the biomechanical analysis, a total of 36 retroreflective markers were attached to each participant's pelvis and lower limbs. Markers were attached bilaterally on the following anatomical landmarks: anterior and posterior superior iliac spines, iliac crest, medial and lateral femoral epicondyles, medial and lateral malleoli, calcaneus, first metatarsal head, and the second metatarsal head. Additional markers were affixed to a custom molded thermoplastic plate and attached laterally on the thigh and leg to measure segment motion during each trial. Marker trajectories were captured with a 10-camera Vicon V16 opto-reflective motion capture system (Vicon Motion Systems Ltd, Oxford, UK; 100 Hz). Raw trajectory data were filtered using a dual-pass second order low-pass Butterworth filter (f_c = 6 Hz) as determined by a residual analysis and visual inspection. A seven-segment lower limb and pelvis direct kinematic model based on that reported by Besier et al.[21] was used to calculate required joint centres. Hip joint centres were calculated using the regression equation of Harrington[22], while the knee and ankle joint centres were determined by taking the midpoint between the femoral epicondyles and ankle malleoli, respectively. Segment-embedded anatomical coordinate systems were defined following the International Society of Biomechanics recommendations, while non-orthogonal joint coordinate systems were used to calculate sagittal plane hip, knee and ankle flexion-extension joint angles[23, 24]. Data was captured over the 6th minute of each trial with three right strides from each load per participant used for analyses.

Data were screened for normality and sphericity prior to any analysis being conducted. Independent t-tests were used to compare absolute load carried and walking speed between sexes. Split-plot analysis of variance were performed to investigate the interaction and main effects of sex (female, male) and load magnitude (0% BW, 20% BW, 40% BW). An alpha level of 0.05 was used for significance testing. Where significant interactions or main effects were found, effect sizes were reported as partial eta squared (η^2_p) and Tukey's Honest Significant Difference post-hoc tests were performed to determine the location of differences. Data are presented as mean ± SD unless stated otherwise.

Results

Females carried significantly less absolute external load in both the 20% BW (Female 12.2 ± 1.3 kg, Male 14.9 ± 1.8 kg; p <0.001, mean ± SD) and 40% BW conditions (24.5 ± 2.7 kg, 29.9 ± 3.6 kg; p <0.001). Females and males did not differ in self-selected walking speed during any condition (0% BW: 4.8 ± 0.5 km·h^{-1}, 4.7 ± 0.5 km·h^{-1}; 20% BW: 4.8 ± 0.5 km·h^{-1}, 4.7 ± 0.5 km·h^{-1}; 40% BW: 4.6 ± 0.5 km·h^{-1}, 4.6 ± 0.5 km·h^{-1}; Females, Males; p >0.05).

There were no significant sex-by-load interactions for any physiological variables (Table 1). A main effect for sex was found for absolute $\dot{V}O_2$ (p = 0.005, η^2_p = 0.246), $\dot{V}CO_2$ (p = 0.007, η^2_p = 0.230), and %$\dot{V}O_{2max}$ (p = 0.014, η^2_p = 0.198). The mean difference in $\dot{V}O_2$ (± SE) between sexes was -175 ± 58 mL·min^{-1} and for VCO_2 was -178 ± 62 mL·min^{-1}. As a percentage of predicted $\dot{V}O_2$ maximum, females on average worked 5 ± 2% harder than males. A main effect for load was found for all physiological variables (p <0.001; see Table 1).

There were no sex-by-load interactions on any spatiotemporal variables (p >0.05; Table 2). There was a significant main effect for sex was observed for cadence (p = 0.004, η^2_p = 0.264) and stance time (p = 0.013, η^2_p = 0.200), with females having a 7 ± 2 steps·min^{-1} faster cadence, while males spent 0.06 ± 0.02 s longer in stance compared with females. There was a significant main effect for load for cadence (p = 0.009, η^2_p = 0.154), % stance time (p <0.001, η^2_p = 0.305) and step length (p = 0.034, η^2_p = 0.114). From the 0% BW to 40% BW conditions, cadence decreased 2 ± 1 steps·min^{-1} (p = 0.007) while % stance time increased 0.8 ± 0.2% (p <0.001). From the 20% BW to 40% BW conditions, % stance time increased 0.7 ± 0.2% ($p < 0.001$), and step length decreased by 0.75 ± 0.23% of height ($p = 0.032$). There were no sex-by-load interactions nor main effects for sex for any kinematic variable ($p > 0.05$). There was a significant main effect for load on peak knee flexion ($p = 0.003$, $\eta^2_p = 0.193$, Table 2).

Table 1. Physiological responses in females and males across various loaded treadmill walking trials.

	0% BW		20% BW		40% BW		p-value		
	Females	Males	Females	Males	Females	Males	Sex*Load	Sex	Load
Heart rate (beats·min^{-1})	107 ± 16	102 ± 12	119 ± 13	109 ± 12	127 ± 18	119 ± 14	0.288	0.133	**<0.001**
Heart rate (% max)	56.5 ± 8.3	53.1 ± 6.2	62.8 ± 7.1	56.9 ± 6.3	67.1 ± 9.9	62.2 ± 7.3	0.275	0.084	**<0.001**
$\dot{V}E$ (L·min^{-1})	26.2 ± 3.8	27.9 ± 3.9	31.1 ± 5.1	32.3 ± 4.5	35.2 ± 5.1	37.9 ± 6.8	0.398	0.266	**<0.001**
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})	14.5 ± 2.1	14.1 ± 1.9	17.4 ± 2.5	16.4 ± 2.4	19.4 ± 3.0	19.1 ± 3.4	0.470	0.509	**<0.001**
VO_2 (%VO_{2max})	33.1 ± 0.1	28.9 ± 0.0	39.6 ± 0.1	33.6 ± 0.0	44.2 ± 0.1	39.1 ± 0.1	0.380	**0.014**	**<0.001**
$\dot{V}O_2$ (mL·min^{-1})	886 ± 130	1039 ± 144	1063 ± 159	1212 ± 200	1179 ± 144	1404 ± 223	0.094	**0.005**	**<0.001**
$\dot{V}CO_2$ (mL·min^{-1})	851 ± 146	1013 ± 157	991 ± 180	1143 ± 200	1093 ± 158	1313 ± 218	0.139	**0.007**	**<0.001**
RER (ratio)	0.96 ± 0.07	0.98 ± 0.05	0.93 ± 0.06	0.94 ± 0.05	0.93 ± 0.06	0.94 ± 0.07	0.954	0.523	**<0.001**
RPE (au)	8.8 ± 1.4	8.5 ± 1.6	12.5 ± 0.7	11.5 ± 2.1	15.7 ± 1.4	14.1 ± 2.5	0.172	0.052	**<0.001**

Data presented as mean ± SD. BW, body weight; $\dot{V}E$, ventilation; $\dot{V}O_2$, volume of oxygen consumption; $\dot{V}CO_2$, volume of carbon dioxide produced; RER, respiratory exchange ratio; RPE, rating of perceived exertion.

Table 2. Spatiotemporal and peak joint kinematic measures in females and males across various loaded treadmill walking trials.

	0% BW		20% BW		40% BW		p-value		
	Females	Males	Females	Males	Females	Males	Sex*Load	Sex	Load
Spatiotemporal variables									
Cadence (steps·min^{-1})	116 ± 5	108 ± 6.8	115 ± 6.5	108 ± 6	113 ± 8.2	107 ± 7.1	0.568	**0.004**	**0.009**
Step length (% height)	36 ± 5	36 ± 3	36 ± 5	36 ± 3	36 ± 4	35 ± 3	0.528	0.919	**0.034**
Step width (% height)	7 ± 2	6 ± 1	7 ± 2	6 ± 1	7 ± 2	6 ± 2	0.663	0.126	0.387
Stance time (%)	64 ± 2	64 ± 1	64 ± 1	64 ± 1	65 ± 2	65 ± 1	0.361	0.687	**<0.001**
Stance time (sec)	0.67 ± 0.05	0.71 ± 0.05	0.62 ± 0.18	0.72 ± 0.05	0.69 ± 0.06	0.73 ± 0.07	0.261	**0.013**	0.148
Peak joint kinematics									
Hip flexion (°)	33 ± 7	33 ± 8	34 ± 7	33 ± 7	33 ± 9	34 ± 5	0.569	0.950	0.362
Hip extension (°)	-9 ± 5	-7 ± 6	-10 ± 4	-8 ± 6	-11 ± 7	-8 ± 6	0.536	0.252	0.128
Knee flexion (°)	23 ± 12	21 ± 6	25 ± 12	21 ± 6	29 ± 14	22 ± 6	0.084	0.233	**0.003**
Ankle dorsiflexion (°)	13 ± 5	11 ± 4	14 ± 5	11 ± 3	13 ± 5	11 ± 4	0.872	0.118	0.469
Ankle plantarflexion (°)	-21 ± 6	-22 ± 6	-21 ± 8	-22 ± 5	-22 ± 7	-23 ± 6	0.957	0.647	0.114

Data presented as mean ± SD. BW, bodyweight.

Discussion

This study showed no sex-by-load interactions for any physiological or biomechanical variable during both unloaded and loaded treadmill walking. Sex differences were observed for absolute $\dot{V}O_2$ and $\dot{V}CO_2$, $\%\dot{V}O_{2max}$, cadence, and stance time. No sex or load differences were observed for any peak joint kinematic variables. Increasing loads resulted in significantly greater responses from all physiological variables, as well as some spatiotemporal variables (cadence, step length, and % stance time). Our first hypothesis was partially supported, with females having higher absolute physiological demand, and cadence, as well as a lower absolute stance time. Our second hypothesis was supported with no sex-by-load interaction found for any physiological or biomechanical variable.

As expected, the physiological demands of treadmill walking increase with heavier loads, but no difference between sexes were observed in $\dot{V}O_2$ when accounting for body mass (i.e. relative VO_2). However, females were working at a higher relative intensity (% VO_{2max}) when compared with males across the load conditions. Previous research has similarly observed females working at a greater relative intensity (% VO_{2max})[9]. Bhambhani et al. observed a 9-15% greater relative task demand in females compared with males when carrying 15 and 20 kg in the hands, while walking at self-selected speeds[9]. Holewijn and colleagues implemented equivalent walking speed and absolute load conditions between sexes and similarly observed a greater relative intensity in females[9, 25]. Notwithstanding differences between studies in walking speed (fixed, self-selected), load mass (relative, absolute), load distribution (hands, feet, waist, torso), and training status (VO_{2max}), it is suggested that these results collectively demonstrate that females are typically required to work at a higher relative intensity ($\%VO_{2max}$) when performing load carriage tasks compared with males. Targeted physical conditioning programs could therefore be implemented to increase cardiorespiratory fitness (VO_{2max}) in females, thereby decreasing relative task intensity and increasing the physiological tolerance to load carriage tasks[26].

Small changes in spatiotemporal data were observed between sexes, however, these differences are more likely a result of height or strength differences, rather than a specific sex difference. The faster cadence and shorter stance time of females opposes previous research that shows similar spatiotemporal movements between sexes[12] during self-selected unloaded and loaded (10-30% BW) treadmill walking, but is similar to earlier work by Martin & Nelson at a set walking speed of 6.4 $km \cdot h^{-1}$ (unloaded to 36kg load)[27]. In our study, the self-selected speeds were similar between sexes, whereas small differences in walking speed were reported by Silder et al.[12], and may provide some insight regarding the difference between studies. As there is no difference between sexes when step length is normalized for height in this study, to maintain the same walking speed females were required to have a faster cadence. A meta-analysis by Frimenko, Whitehead and Bruening showed that when matched for height, there is no difference in step length or gait speed between sexes, showing a height-effect rather than a sex-effect[28]. While age can increase the degree of separation between sexes for these spatiotemporal variables[28, 29], it appears that in a healthy population representative of military recruits, spatiotemporal variables of step length, step width, and stance time are similar between sexes when accounting for height. While height is a non-modifiable physical characteristic, previous research has observed the influence of strength within clinical and aging populations and its influence on gait biomechanics[30, 31]. As such, modifiable factors such as muscular strength has the potential to also play a role in the spatiotemporal and kinematic measures of individuals and may also need to be accounted for when comparing sexes.

Peak knee flexion angle was found to increase across loads, with no differences observed in other joint kinematics, regardless of sex or load during treadmill walking. The 3.5° increase in peak knee flexion from 0% BW to 40% BW is similar to the 4° increase found by Silder et al. when they compared 0% BW to 30% BW. Our data supports the conclusions of Silder et al. that the increased knee flexion would be related to increased muscle activation and likely cause an increase in metabolic cost. While doublepacks were used in that study,[12] the use of a self-selected walking speed was based off unloaded trials (females 4.7 ± 0.4 km·h^{-1}; males 4.6 ± 0.3 km·h^{-1}), and so may have resulted in a faster than preferred speed once load was applied, hence altering the kinematics of individuals. Increasing load through the use of backpacks also result in substantial kinematic changes in male soldiers[32, 33]. Whether these changes with increasing load are influenced by previous experience and exposure to load carriage is yet to be observed. Given the participants in this study were representative of a military recruit population[34], but had no previous experience with load carriage, it may be that they were unable to mechanically adapt to increasing load. Alternatively, when using an absolute load of 22 kg, Krupenevich, Rider, Domire, DeVita [35] saw no sex differences for any kinematic or kinetic variable and suggested that females lack effective adaptation to load and do not sufficiently alter their gait despite strength and stature differences to males[35]. More research is required to observe the influence that previous experience in load carriage has on these changes in both males and females, taking into account absolute and relative loads, pack distribution, and the influence of individuals' muscular strength and endurance.

This study has potential limitations and has identified areas of future research. The use of a self-selected walking speed and relative loads does not reflect standard practice within a military setting, i.e. role or mission determines load carriage task requirements. However, it does allow investigation of questions regarding sex differences without relative loading and/or walking speed as a confounder. To improve ecological validity and translation to field settings, occupationally relevant walking speeds, fixed loads, and load distributions (e.g. body armor, webbing, backpack, rifle) need to be investigated. There have been few differences identified in the physiology and biomechanics of acute simulated military load carriage between sexes in the current study, despite the well-documented differences in physical and physiological capacities between males and females[36-38]. In future, grouping participants by stature and body mass may aid in delineating the effects of sex and physical characteristics on responses to load carriage. An increased understanding of the physiological and biomechanical responses to load carriage between sexes, and the influence of physical characteristics (e.g. stature, body mass, lean mass), may facilitate improved load carriage conditioning and task management, and/or reduced injury risk[39].

Females worked at a greater relative intensity, had a faster cadence and a reduced stance time in comparison with males across all treadmill walking conditions. These results suggest the implementation of sex-specific conditioning and recovery may be warranted to bridge the gap in physiological strain between males and females (on average) in the performance of occupational tasks involving load carriage[39, 40]. This is likely to improve acute task performance but also the ability to cope with repeated or chronic occupational exposure and potentially reduce injury risk, given the well-established association between aerobic fitness and musculoskeletal injury risk[41-43]. When accounting for body mass and stature, however, there appears to be minimal difference in physiological and biomechanical responses to loaded treadmill walking at self-selected speeds in a healthy recruit-type population with no load carriage experience. During short duration (≤10 minutes) load carriage tasks, the pooling of male and female data may be acceptable, however the relevance of the current results to prolonged load carriage tasks are less clear. The ability for females to physiologically tolerate load carriage could be improved by the implementation of a conditioning program targeted towards improving aerobic fitness.

Acknowledgements

This work was supported by the La Trobe University Sport, Exercise, and Rehabilitation Research Focus Area Grant Ready scheme under Grant [2000002296]. The authors would like to acknowledge Joel McWilliam for technical support and assistance in data collection.

Declaration of Interest

No potential conflict of interest was reported by the authors.

References

1. Abe D, Yanagawa K, Niihata S. Effects of load carriage, load position, and walking speed on energy cost of walking. *Applied Ergonomics.* 2004; 35(4):329-335.
2. Lenton G, Saxby D, Lloyd D, Billing D, Doyle T. The effects of load configuration, mass, and movement speed on biomechanical risk factors for musculoskeletal injuries. *Journal of Science and Medicine in Sport.* 2017; 20:174.
3. Mullins AK, Annett LE, Drain JR, Kemp JG, Clark RA, Whyte DG. Lower limb kinematics and physiological responses to prolonged load carriage in untrained individuals. *Ergonomics.* 2015; 58(5):770-780.
4. Australian Government DoD. Defence Annual Report 2012-132013.
5. Australian Government DoD. Women in the ADF Report 2017–182018.
6. Schogol J. Army's new physical fitness test will be gender-neutral, secretary says. 2018.
7. Finestone AS, Milgrom C, Yanovich R, Evans R, Constantini N, Moran DS. Evaluation of the performance of females as light infantry soldiers. *BioMed Research International.* 2014; 2014.
8. Canham-Chervak M, Hauret K, Hoedebecke E, Laurin MJ, Cuthie J. Discharges during U.S. Army Basic Training: Injury Rates and Risk Factors. *Military Medicine.* 2001; 166(7):641-647.
9. Bhambhani Y, Maikala R. Gender differences during treadmill walking with graded loads: biomechanical and physiological comparisons. *European Journal of Applied Physiology.* 2000; 81(1-2):75-83.
10. Ricciardi R, Deuster PA, Talbot LA. Effects of gender and body adiposity on physiological responses to physical work while wearing body armor. *Military Medicine.* 2007; 172(7):743-748.
11. Scott P, Ramabhai L. Comparison of male and female responses to carrying absolute and relative loads while on a three hour military march. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting.* Vol 44: SAGE Publications Sage CA: Los Angeles, CA; 2000:161-164.
12. Silder A, Delp S, Besier T. Men and women adopt similar walking mechanics and muscle activation patterns during load carriage. *Journal of Biomechanics.* 2013; 46(14):2522-2528.

13. Vehrs PR, George JD, Fellingham GW, Plowman SA, Dustman-Allen K. Submaximal treadmill exercise test to predict VO2max in fit adults. *Measurement in Physical Education and Exercise Science.* 2007; 11(2):61-72.
14. Skelly AC, Dettori JR, Brodt ED. Assessing bias: the importance of considering confounding. *Evid Based Spine Care J.* 2012; 3(1):9-12.
15. Caron R, Lewis C, Saltzman E, Wagenaar R, Holt K. Musculoskeletal stiffness changes linearly in response to increasing load during walking gait. *Journal of Biomechanics.* 2015; 48(6):1165-1171.
16. Knapik J, Reynolds K, Santee WR, Friedl KE. *Load carriage in military operations: a review of historical, physiological, biomechanical and medical aspects*, Fort Detrick, Maryland, Office of The Surgeon General; 2012.
17. Huynh H, Roberts C, Taylor M, Sowash J, Souren T, Liang M. Comparison of the Jaeger Oxycon Mobile unit with two standard laboratory metabolic carts: 2628: Board#138 2:00 PM - 3:00 PM. *Medicine and Science in Sports and Exercise.* 2006; 38(5)(Supplement):S500.
18. Rosdahl H, Gullstrand L, Salier-Eriksson J, Johansson P, Schantz P. Evaluation of the Oxycon Mobile metabolic system against the Douglas bag method. *European Journal of Applied Physiology.* 2010; 109(2):159-171.
19. Gellish R, Goslin B, Olson R, McDonald A, Russi G, Moudgil V. Longitudinal modeling of the relationship between age and maximal heart rate. *Medicine and Science in Sports and Exercise.* 2007; 39(5):822-829.
20. Borg G. Perceived exertion as an indicator of somatic stress. *Scandinavian Journal of Rehabilitation Medicine.* 1970; 2:92-98.
21. Besier T, Sturnieks D, Alderson J, Lloyd D. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *Journal of Biomechanics.* 2003; 36(8):1159-1168.
22. Harrington M, Zavatsky A, Lawson S, Yuan Z, Theologis T. Prediction of the hip joint centre in adults, children, and patients with cerebral palsy based on magnetic resonance imaging. *Journal of Biomechanics.* 2007; 40(3):595-602.
23. Wu G, Siegler S, Allard P, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. *Journal of Biomechanics.* 2002; 35(4):543-548.

24. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *Journal of Biomechanical Engineering.* 1983; 105(2):136-144.

25. Holewijn M, Hens R, Wammes LJA. Physiological strain due to load carrying in heavy footwear. *Eur J Appl Physiol.* 1992; 65(2):129-134.

26. Drain J, Billing D, Neesham-Smith D, Aisbett B. Predicting physiological capacity of human load carriage – A review. *Applied Ergonomics.* 2016; 52:85-94.

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

28. Frimenko R, Whitehead C, Bruening D. Do men and women walk differently? a review and meta-analysis of sex difference in non-pathological gait kinematics. Dayton OH: Air Force Research Laboratory; 2014:1-29.

29. DeVita P, Hortobagyi T. Age causes a redistribution of joint torques and powers during gait. *Journal of Applied Physiology.* 2000; 88(5):1804-1811.

30. Persch LN, Ugrinowitsch C, Pereira G, Rodacki ALF. Strength training improves fall-related gait kinematics in the elderly: A randomized controlled trial. *Clinical Biomechanics.* 2009; 24(10):819-825.

31. Gutierrez GM, Chow JW, Tillman MD, McCoy SC, Castellano V, White LJ. Resistance training improves gait kinematics in persons with multiple sclerosis. *Archives of Physical Medicine and Rehabilitation.* 2005; 86(9):1824-1829.

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

33. Attwells R, Birrell S, Hooper R, Mansfield N. Influence of carrying heavy loads on soldiers' posture, movements and gait. *Ergonomics.* 2006; 49(14):1527-1537.

34. Burley SD, Drain JR, Sampson JA, Groeller H. Positive, limited and negative responders: The variability in physical fitness adaptation to basic military training. *Journal of Science and Medicine in Sport.* 2018; 21(11):1168-1172.

35. Krupenevich R, Rider P, Domire Z, DeVita P. Males and females respond similarly to walking with a standardized, heavy load. *Military Medicine.* 2015; 180(9):994-1000.

36. Lewis DA, Kamon E, Hodgson JL. Physiological differences between genders implications for sports conditioning. *Sports Medicine.* 1986; 3(5):357-369.

37. Kraemer WJ, Mazzetti SA, Nindl BC, et al. Effect of resistance training on women's strength/power and occupational performances. *Medicine and Science in Sports and Exercise.* 2001; 33(6):1011-1025.

38. Reilly TJ, Sharp MA, Cao M, Canino MC. A database of predictor test sex bias for development of military physical employment standards. *Work.* 2019; 63:591-601.

39. O'Leary TJ, Saunders SC, McGuire SJ, Izard RM. Sex differences in neuromuscular fatigability in response to load carriage in the field in British Army recruits. *Journal of Science and Medicine in Sport.* 2018; 21(6):591-595.

40. Blacker SD, Wilkinson DM, Rayson MP. Gender differences in the physical demands of British army recruit training. *Military Medicine.* 2009; 174(8):811-816.

41. Rappole C, Grier T, Anderson MK, Hauschild V, Jones BH. Associations of age, aerobic fitness, and body mass index with injury in an operational Army brigade. *Journal of Science and Medicine in Sport.* 2017; 20:S45-S50.

42. Knapik JJ, Sharp MA, Canham-Chervak M, Hauret K, Patton JF, Jones BH. Risk factors for training-related injuries among men and women in basic combat training. *Medicine and Science in Sports and Exercise.* 2001; 33(6):946-954.

43. Fallowfield JL, Leiper RG, Shaw AM, et al. Risk of injury in Royal Air Force training: does sex really matter? *Military Medicine.* 2020; 185(1-2):170-177.