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<http://dx.doi.org/10.1136/bmjmilitary-2020-001645>

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Publication title	BMJ Military Health
Publisher	BMJ Publishing
Type	Article
USIR URL	This version is available at: http://usir.salford.ac.uk/id/eprint/59413/
Published Date	2021

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Role of sex and stature on the biomechanics of normal and loaded walking: implications for injury risk in the military

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Keywords

Marching; Load Carriage; Military; Injury; Walk to Run Transition; Biomechanics.

Contributorship Statement

Niamh Gill produced the manuscript. All authors edited the manuscript for intellectual content. All authors approved the final version of the manuscript.

Funding

This review was funded by the UK Ministry of Defence (Army) through the Analysis Support Construct (Task 0136).

Competing interests

The authors have no competing interests to declare.

Acknowledgement

None.

Abstract

Load carriage and marching 'in-step' are routine military activities associated with lower limb injury risk in service personnel. The fixed pace and stride length of marching typically vary from the *preferred* walking gait and may result in over-striding. Over-striding increases ground reaction forces and muscle forces. Women are more likely to over-stride than men due to their shorter stature. These biomechanical responses to over-striding may be most pronounced when marching close to the *preferred* walk-to-run transition speed. Load carriage also affects walking gait and increases ground reaction forces, joint moments and the demands on the muscles. Few studies have examined the effects of sex and stature on the biomechanics of marching and load carriage; this evidence is required to inform injury prevention strategies, particularly with the full integration of women in some defence forces. This narrative review explores the effects of sex and stature on the biomechanics of unloaded and loaded marching at a fixed pace and evaluates the implications for injury risk. The knowledge gaps in the

literature, and distinct lack of studies on women, are highlighted, and areas that need more research to support evidence-based injury prevention measures, especially for women in arduous military roles, are identified.

Key Points

- Marching 'in-step' at a fixed pace and stride length can result in over-striding in shorter individuals, increasing ground reaction and muscle forces, and injury risk.
- Marching at speeds close to the preferred walk-to-run transition speed may increase these forces and injury risk.
- Load carriage affects movement patterns and increases ground reaction forces, joint moments and the demands on the muscles.
- Few studies have examined the effects of sex and stature on the biomechanics of marching and load carriage.
- It is unknown whether men and women adapt their biomechanics differently when speed and stride length are enforced.

Accepted

Introduction

Military personnel are often required to carry heavy loads for prolonged periods. The load carried can exceed 70 kg in combat roles [1], depending on the operation, which is close to the body mass of some personnel. This heavy load carriage may increase injury risk [2-4], especially as the recommended maximum load that military personnel should carry is 45% of their body mass [5]. The incidence of musculoskeletal injuries ('injuries' herein) during basic training is high in the UK military (1.2 to 16.2% in men and 5.4 to 26.5% in women), and results in lost training days and medical discharge [6]. Women are 1.5 to 3.0 times more likely than men to sustain an injury during basic training [7, 8], increasing their chance of re-injury or sustaining further injury [5]; women are also more susceptible to developing stress fractures, and hip injuries, than men [9]. The smaller stature and lower body mass of women likely contribute to their increased injury risk, particularly when carrying relatively heavier loads than men [10]. Currently, women make up around 10 % of all service personnel in the UK Armed Forces [11], with a recruiting target of 15 %, and all roles are now open to them. Therefore, the biomechanical impact on women of operating in arduous roles needs to be fully understood to optimise training strategies and maximise *through career* opportunities.

Marching is a traditional military activity, performed in a regimented manner at a fixed pace and stride length. Walking with stride lengths longer than *preferred* increases the risk for lower limb and back injuries [12], due to increased joint loading [13, 14], while walking at speeds markedly different to the *preferred* walking speed results in an exponential increase in energy cost [15]. Furthermore, walking at speeds greater than the *preferred* walk-to-run transition speed is associated with greater rates of perceived effort [15]. Both *preferred* walking speed [16] and *preferred* walk-to-run transition speed [17, 18] are positively correlated with stature, in both men and women. However, the strength of the correlation between *preferred* walk-to-run transition speed and stature varies considerably ($r = 0.011$ to 0.690), and only two studies include and present separate data on women. The effect of heavy load carriage on the *preferred* walk-to-run transition is not known [19].

Shorter stature, lower body mass and female sex are risk factors for lower limb injury in British Army recruits [6]. The independent effects of stature and sex on lower limb biomechanics of marching at a fixed stride length have not been examined. Moreover, the biomechanical effect of carrying relatively heavier loads (>30% of body mass), which better reflect the loads carried by military personnel wearing marching order (59.4 kg), is not fully understood. And, in some cases, military personnel may be required to carry heavier loads over shorter durations. A better understanding of biomechanical responses to changes in walking speed and stride length/frequency, and load carriage, will help inform preventative strategies for injury risk in military personnel. Most studies use male populations, and there is a need for more research to include women to determine if any sex-specific responses exist.

This narrative review aims to provide a broad summary of existing literature and present evidence on biomechanical risk factors for injury, focussing specifically on changes to walking gait and heavy load carriage, typical of military activities.

The role of fixed spatiotemporal parameters on biomechanics and the risk factors for injury during unloaded walking

Spatiotemporal parameters and walking speed

Spatiotemporal parameters are characteristics of gait, which include stride length, stride frequency and speed. The *preferred* stride length for walking is, on average, $42 \pm 3\%$ of an individual's stature [20, 21] and *preferred* walking speed is faster in those with taller stature and longer lower limb length [22]. Marching is performed at a fixed stride length and speed, irrespective of stature or limb length. This may force many individuals to walk with a greater stride length than *preferred*, increasing the risk of lower limb overuse injuries [23-25]. The shorter stature of women (mean (SD) stature for military personnel: men 1.77 (0.07) m and women 1.65 (0.06) m [10]) reduces their *preferred* stride length and results in *over-striding* when marching in a mixed-sex group.

Ground reaction forces

Ground reaction forces (GRFs) are exerted on the body from contact with the ground. GRFs acting at a distance from a joint generates a turning effect, or *torque*, referred to as a joint moment. GRFs reportedly increase with increasing walking speed [26, 27], for example, Sun, Fekete [27] reported a 0.3 bodyweight increase in peak vertical GRF with a 25 % increase in walking speed. Increased GRFs, and the corresponding increases in joint moments, are associated with overuse injuries, including stress fractures and knee joint problems [28]. Interestingly, Zadpoor and Nikooyan [29] showed that studies do not agree on whether there are significant differences in the GRFs and/or loading rates between stress fracture and control groups, during running. However, most studies included in this review compared groups running at a fixed speed and did not consider the effect of how increasing speed increases GRFs. The relationship between stride length and stride frequency on GRFs, normalised by body mass, are similar between sexes: as stride length increases, contact time, anterior-posterior braking and propulsive force, impulse descriptors, and vertical impulse per step systematically increase [30]. Interestingly, vertical peak forces and impulse per meter walked show little variation with changes in stride length [30]. However, it is worth noting that, relatively small (± 5 and ± 10 %) changes in stride length and frequency were investigated, and therefore, the effect of greater changes in stride length on GRFs and lower limb biomechanics in men and women is unknown.

Muscle forces

Increasing stride length alone, to increase speed, results in a greater contribution to the vertical GRFs from the hip and knee muscles than increasing step frequency alone [31]. The (smaller) contribution from limb posture, defined as "*the resistance to the downward pull of gravity provided by the bones and joints of the stance limb*" [31, 32], increases as speed increases [31]; these mechanisms may explain the reduced walking speed and stride lengths that are observed in older adults with weak hip and knee extensors and may reflect an adaptation to alleviate the demand placed on the *gluteus maximus* and *vasti* muscles. This is significant when considering the injury risk of female soldiers marching in a group of men; as *over-striding* may exacerbate weakness in the muscles of the hip and knee that are required for counteracting the joint moments. Overall, lower limb muscle function was affected by changes in stride length more than step frequency [31]. However, participants in this study

were required to walk at a “nominal” stride length (0.73 m) and step frequency (1.92 steps/s), and at $\pm 20\%$ of these values. These “nominal” values were chosen to be representative of the normal for healthy young adults, based on published data, and would not account for differences in *preferred* stride length and step frequency. Therefore, participants may already have had to adjust their *preferred* walking biomechanics and so the effect of enforcing changes from *preferred* stride lengths and frequencies on lower limb muscle forces remains unknown.

Preferred walking speed and preferred walk-to-run transition speed

Humans have a *preferred* walking speed of approximately $1.4 \text{ m}\cdot\text{s}^{-1}$, on average [33]. Humans adopt a combination of *preferred* stride length and stride frequency to achieve their *preferred* walking speed. Walking at speeds markedly different to the *preferred* walking speed is associated with an exponential increase in energy cost [15] as well as increases in joint moments, particularly at the hip [13, 31, 34], which may increase the risk of lower limb and lower back injuries. Furthermore, as speed increases, there is a spontaneous transition between walking and running, known as the *preferred* walk-to-run transition speed [22]. The *preferred* walk-to-run transition speed is around $2 \text{ m}\cdot\text{s}^{-1}$ for healthy adults [18, 22]. However, this *preferred* speed is dependent on multiple factors (e.g. stature, limb length, and metabolic and mechanical efficiency) [13, 15, 17, 18, 22, 35], and is said to decrease when carrying external load [36], and occurs at a slower speed in women than men [18, 37].

The strength and significance of associations are mixed between the *preferred* walk-to-run transition speed and anthropometry (stature, sitting height, leg length, lower leg length, thigh girth and calf girth) [17, 18, 36, 38]. Greater variability in stride length, frequency and duration is also observed at speeds near the *preferred* walk-to-run transition speed, suggesting a loss of stability in the movement pattern [39], increased rate of perceived effort [15, 40] and increased muscle activity [40, 41]. These findings are relevant and important to a military population marching ‘in-step’. Firstly, Army personnel must complete a 12.8 km load carriage at $\sim 1.8 \text{ m}\cdot\text{s}^{-1}$ [42] as part of their annual physical employment test, which is close to the average *preferred* walk-to-run transition speed for healthy adults [18, 22]. Secondly, a mixed military cohort will have a wide range of statures (mean (SD) statures for military personnel: men 1.77 (0.07) m and women 1.65 (0.06) m [10]), and, consequently, *preferred* walking speeds, walk-to-run transition speeds and stride lengths. To mitigate the biomechanical stress of *over-striding*, shorter personnel are typically placed at the front of a group to ‘control’ speed (when unspecified) and stride length. This formation will not fully prevent some individuals from marching at speeds closer to their *preferred* walk-to-run transition speed than their *preferred* walking speed, which likely results in less efficient marching [15], and increased joint loading [13, 31, 34].

Many studies have investigated the relationship between spatiotemporal parameters and walking biomechanics, and *over-striding* has been shown to increase injury risk [23, 24, 43]. However, the effects of sex and stature on the biomechanical response to enforcing spatiotemporal parameters are unknown. Moreover, whether the effect of stature on the *preferred* walk-to-run transition speed is sex dependent is also unclear.

The effect of load carriage on spatiotemporal parameters, biomechanics and injury risk

A better understanding of the additive effect of load carriage on the biomechanical response to fixed walking speed, stride frequency and stride length will help mitigate injury risk in military personnel. A high number of studies have investigated the effect of load carriage on biomechanical function and metabolic energy expenditure in both civilian [21, 44-51] and military [34, 44, 49, 52-54] populations. However, only a proportion of these studies included women, and only four compared between sexes. This section will describe the effect of load carriage on walking biomechanics and, where data are available, differences between men and women.

Spatiotemporal parameters and walking speed

Studies investigating the effect of load carriage on stride length and frequency report mixed findings. Several studies have reported decreased stride length [44-47, 49-52, 54] and increased stride frequency [47, 50, 52, 54] with the increased load carried at self-selected and fixed (1.5m/s) walking speeds; where the loads carried ranged from approximately 0-65 %body mass. Others reported no effect of the increased load carried on stride length [21, 48] or stride frequency [44, 51, 52]. One study reported decreased walking speed, stride length and stride frequency with increasing load (0-60 %body mass) [47]. In contrast, another reported increased stride length and stride frequency with increased load [53], however, these increases were likely a result of the corresponding increase in walking speed and the relatively small loads considered (0–17 kg).

Similarly, there is conflicting evidence for sex differences in spatiotemporal measures during load carriage [21, 49]. In two studies, no sex differences were shown in GRFs, stride length or stride frequency while walking with loads at either the *preferred* walking speed [21] or a prescribed speed of 1.50 m·s⁻¹ [49]. In contrast, women walked with higher stride frequencies than men at set speeds of 1.36 m·s⁻¹ [55] and 1.78 m·s⁻¹ [56]. Also, as load increased, women had a greater increase in stride frequency than men [56]. At a fixed speed of 1.36 m·s⁻¹, stride length increased over time, and decreased with heavier loads, in women, but not in men; although, the findings may have been biased by the high number of women who may have had naturally shorter stride lengths [55] and were unable to complete the task.

These different spatiotemporal responses to load may, in part, be due to variability in participant populations (particularly load carriage experience) and the variability in loads carried, and/or reflect a *learned* effect or a non-linear response to load. Load carriage experience affects biomechanical adaptations, and military personnel who are familiar with marching 'in-step' are accustomed to maintaining stride length, even during load carriage [50]. However, *over-striding* is considered a risk factor for overuse injuries [23, 24, 43] and, therefore, shortening stride length is proposedly a mechanism for reducing biomechanical stress while carrying load [2]. The additional load may also reduce the mechanical efficiency of walking and decreases *preferred* walk-to-run transition speeds [36]. The effect of modifying spatiotemporal parameters during load carriage on lower limb biomechanics in men and women may help inform injury prevention measures.

Kinematics

Joint kinematics is the motion between two consecutive segments of the human body. Measurement of joint kinematics may improve our understanding of injury mechanisms, and

the changes observed in energy expenditure, with load carriage [3, 12, 25, 57]. Changes in movement patterns are a likely mechanism to maintain postural control and alignment of the applied GRFs, as well as minimise the energetic cost of load carriage. The postural changes during load carriage may result in measurable changes in kinematic parameters [53], however, study findings are conflicting.

A number of other studies [44, 52, 58-60], and a recent meta-analysis [57], identified an association between load carriage and increased hip sagittal range of motion (RoM) [52, 57], unchanged knee sagittal RoM [57, 58], increased ankle sagittal RoM [45, 53, 57] and unchanged trunk sagittal RoM [52, 57]. However, others have reported decreased knee sagittal RoM [44, 59, 60], increased knee sagittal RoM [2, 52] and increased knee flexion [21, 53, 61] with increased load carriage (0-50 kg). Differences in findings between studies may be explained by variations in load carriage experience, walking speed, hip belt usage and posterior displacement of the load away from the trunk. The biomechanical changes induced by load carriage are also influenced by the phase of walking [45, 53, 57].

Inconsistent findings have also been reported for ankle kinematics. Some studies reported increased ankle dorsiflexion with increasing load [52, 53, 59], however, others observed no change [34, 62]. Furthermore, adding load decreased ankle RoM when barefoot, but increased ankle RoM when shod during treadmill walking [45]. However, these findings were not replicated in a subsequent study investigating overground walking [46]. These conflicting results could be due to different footwear, or walking modalities, influencing ankle kinematics and/or by measurement error with identifying the underlying bony landmarks when wearing footwear.

Increased forward lean of the trunk with increasing (posterior) load is well documented [34, 52, 59, 60]. Forward lean keeps the load centre of mass as close to the base of support as possible. Increased forward lean leads to flexion at the hip [21, 34, 52, 53, 59, 60, 62] that is counteracted by increased muscle activity in pelvic and low back musculature [34, 59, 60]. Load carriage may, therefore, increase the risk of lower back injuries due to the increased stress placed on the local musculature [52].

Krupenevich, Rider [49] observed significant sex by load interaction for average trunk position during walking. Women increased trunk lean to a greater extent than men during load carriage (13% and 11%, respectively); possibly due to their lighter mass and the need to lean further forward to offset the same load. Furthermore, a significant correlation was found between trunk lean and body mass, for the combined dataset of men and women, indicating lighter participants carried the load with greater forward lean [49]. Some epidemiological studies support the role of smaller body size, such as smaller body mass, shorter stature and shorter *preferred* stride length, rather than female sex, as principal risk factors for injury in basic military training [63-65]. Therefore, discerning the independent effects of sex and physical characteristics on biomechanical adaptations to load carriage is important for targeted injury mitigation strategies.

Ground reaction forces and kinetics

Overuse injuries result from repeated loading of the skeleton and soft tissue during training and operational tasks, with inadequate recovery [66]. During basic military training, recruits generally experience increased unaccustomed stresses, which may be relatively higher in

women [67], including increased joint loading from running and load carriage [66]. Measurement of joint kinetics — the forces/moments that cause movement at the joint — and GRFs will improve our understanding of the biomechanical risk factors of injury with load carriage.

Load carriage increases the first and second peaks, and the minima between peaks, in the vertical GRF; the braking and propulsive GRF peak; and, the vertical, braking and propulsive impulse [57, 59, 60, 68]. Vertical GRFs increase proportionally with increasing load [2, 21, 46, 48, 69]. Silder, Delp [21] reported increased vertical GRF by approximately 6% for each 10% increase in load; no sex differences were detected for peak vertical GRFs normalised to body mass, although women were typically 12 kg lighter suggesting a lower absolute peak vertical GRF. A similar proportional increase is observed between the braking and propulsive GRFs and increasing load [2, 46, 69].

Peak hip and knee, flexor and extensor moments, and peak ankle plantar flexor moments increase with increasing load [21, 46, 61, 70, 71]. Although the relative increase in joint loading due to load carriage is likely speed dependent, the largest increase in joint moment consistently occurs at the knee joint [46, 70]. This increased knee joint moment may be a mechanism for dissipating energy and reducing joint loading elsewhere [70], however, this has not been experimentally tested. Furthermore, as load carriage will increase GRFs, joint moments will also likely increase and the muscles crossing joints will be required to produce more force to counteract these, which may lead to a greater risk of injury. The lack of sex differences suggests that the forces generated from load carriage are not attributable to the increased injury risk in women [21]; however, the intrinsic ability to cope with these loads could be a differentiating factor.

Changes to stride length and stride frequency affect the GRFs during loaded walking [12, 72]. At a fixed speed, when stride frequency decreases (and stride length increases) the anterior-posterior GRF increases [12]. Whereas at self-selected speeds, all GRF peaks were higher at a high stride frequency (1 Hz) compared with a low stride frequency (0.6 Hz) [72]. Importantly, as stride frequency decreased the knee extensor moment increased, which could have implications for the development of muscle fatigue; however when stride frequency increased there was no change to the knee extensor moment [12]. These findings are important when considering marching 'in-step,' where shorter individuals, who are more likely to be women, must *over-stride* to match stride lengths of taller individuals; shorter individuals will experience greater stress on the knee extensor muscles compared with marching at their *preferred* stride length/frequency [12].

Despite the high number of studies investigating the biomechanics of load carriage, in both military and civilian populations, there are still gaps in our understanding. Specifically, there are very few studies comparing the effects of load carriage between the biomechanics of men and women. Women are typically smaller and have less muscle mass than men [67, 73], and it seems logical that absolute increases in load carriage would generally have a greater impact on the biomechanics of women than men. This is not the case as it has been reported that men and women implement similar biomechanical adaptations to load carriage [21, 49]. It is possible the relatively small sample sizes in these studies may increase the chance of type II error, and sex differences may only occur with the development of greater muscle fatigue. A larger study with adequate statistical power is required to rigorously compare the effect of load carriage on the biomechanics between men and women and to identify if any differences are

specifically related to sex, or a consequence of known sex differences in strength, stature and/or mass. A better understanding of sex differences in biomechanics during load carriage, and the effect of load carriage on the biomechanical changes induced by stride lengths and stride frequencies, is important when designing training protocols, developing strategies to mitigate injury risk, and optimising the performance of women in arduous roles.

Conclusions

This narrative review explores the influence of sex and stature on lower limb biomechanics, when walking at a fixed speed, stride length or stride frequency, and during load carriage. Marching 'in-step' at a fixed pace and stride length can result in *over-striding* in shorter individuals, increasing GRFs, muscle forces, and injury risk, particularly at speeds close to the *preferred* walk-to-run transition speed. Load carriage affects movement patterns and increases ground reaction forces, joint moments and the demands on the muscles. Many of these biomechanical responses are associated with injuries typically seen in military populations. It is unknown whether men and women adapt their biomechanics differently when speed, stride length and frequency are enforced, or whether these biomechanical adaptations are related to stature rather than sex.

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