| | |
|---|---|
| Title | Using gait parameters to detect fatigue and responses to ice slurry during prolonged load carriage |
| Author(s) | Cheryl S. Tay, Jason K.W. Lee, Ya S. Teo, Phildia Q. Foo, Pearl M.S. Tan and Pui W. Kong |
| Source | *Gait & Posture, 43*, 17–23 |
| Published by | Elsevier |

Citation: Tay, C. S., Lee, J. K. W., Teo, Y. S., Foo, P. Q., Tan, P. M. S., & Kong, P. W. (2016). Using gait parameters to detect fatigue and responses to ice slurry during prolonged load carriage. *Gait & Posture, 43*, 17-23. http://dx.doi.org/10.1016/j.gaitpost.2015.10.010

*Title:* Using Gait Parameters to Detect Fatigue and Responses to Ice Slurry during Prolonged Load Carriage

## Abstract (249 words)

This study examined 1) if changes in gait characteristics could indicate the exertional heat stress experienced during prolonged load carriage, and 2) if gait characteristics were responsive to a heat mitigation strategy. In an environmental chamber replicating tropical climatic conditions (ambient temperature 32°C, 70% relative humidity), 16 males aged 21.8 (1.2) years performed two trials of a work-rest cycle protocol consisting two bouts of 4-km treadmill walks with 30-kg load at 5.3 km/h separated by a 15-min rest period. Ice slurry (ICE) or room temperature water (29°C) as a control (CON) was provided in 200 ml aliquots. The fluids were given 10 minutes before the start, at the 15th and 30th min of each work cycle, and during each rest period. Spatio-temporal gait characteristics were obtained at the start and end of each work-rest cycle using a floor-based photocell system (OptoGait) and a high-speed video camera at 120 Hz. Repeated-measure analysis of variance (trial × time) showed that with time, step width decreased (p = .024) while percent crossover steps increased (p = .008) from the 40th min onwards. Reduced stance time variability (-11.1%, p = .029) step width variability (-8.2%, p = .001), and percent crossover step (-18.5%, p = .010) were observed in ICE compared with CON. No differences in step length and most temporal variables were found. In conclusion, changes in frontal plane gait characteristics may indicate exertional heat stress during prolonged load carriage, and some of these changes may be mitigated with ice slurry ingestion.

## Keywords

Walking; Heat; Fatigue; Step width; Variability; Spatio-temporal

**Word count:** 3829

## Highlights

- Prolonged load carriage leads to unstable gait characteristics in the frontal plane
- Gait instability can be a non-invasive proxy for detecting exertional heat stress
- Ice slurry ingestion can alleviate some undesirable changes in gait patterns

## Introduction

Exertional heat stress is an increase in body core temperature ($T_c$) as a result of exercise and often leads to decrements in performance, especially during prolonged activity.[1] A person experiencing heat stress typically displays an elevated heart rate (HR), higher rating of perceived exertion (RPE), and increased sweat rate.[2] During prolonged activity, oxygen consumption ($VO_2$) increases rapidly in the first 10 minutes, and thereafter remaining relatively stable.[3] While exercise is mostly volitional, there are occupational activities that demand prolonged physical exertion such as military load carriage whereby soldiers carry loads (equipment and supplies) over long-duration marches.[4] Prolonged military load carriage increases the risk of injuries [5-7] and heat stress compared with unloaded walking due to the associated metabolic cost as observed from increased heart rate and $VO_2$.[3,4] Furthermore, heavier loads also led to larger increases in $T_c$.[2] Current assessments of exertional heat stress (e.g. ingestion of temperature sensor, blood draw to measure biochemical stress markers) are invasive [2] and therefore finding an easily observable parameter during such prolonged activities is needed. Measuring gait characteristics can be a potential non-invasive indicator of exertional heat stress during prolonged load carriage since biomechanical analysis presents less risk and discomfort to the participants compared with physiological assessment.

Most biomechanical studies on load carriage have found spatio-temporal adaptations to the walking gait during very short-duration protocols.[8-10] Spatio-temporal variables are step length and step width, while temporal variables include cadence, stance time and double support time (when both feet are in contact with the ground). Compared to kinetic (force) variables, spatio-temporal gait variables are more readily observable. While the literature generally agrees that temporal gait variables such as stance time [5,8-10] and double support time [10] increase with load, it remains inconclusive whether these observable adaptations also occur with increasing duration in prolonged load carriage.[6]

Recent studies have looked at the effects of prolonged load carriage on biomechanical outcomes, with mixed findings. In recreational hikers performing an 8-km free walk with various loads, there were increased stride length and cadence, and decreased stance time with increasing duration.[11] In untrained individuals performing a 120-min treadmill walk with load (~30% of body weight), there was small but significant increase in step length, and no changes in temporal variable (e.g. stance time, double support time and step time).[12] Similarly, spatio-temporal variables remained stable in female participants during a 56-min treadmill walk [13], and male soldiers during a 40-min treadmill walk [3] or a 21-h simulated military mission including a 16-km march.[14] Since absolute gait characteristics appear resistant to the effects of prolonged load carriage, researchers have suggested investigating gait variability as well.[14,15]

Increased gait variability is a way to quantify unstable walking patterns [16], which predisposes a person to trips and falls.[16-19] Unsurprisingly, trips and falls are a major injury concern during prolonged load carriage in the military.[4,6] An increase in step width variability after a fatiguing exercise was observed in 12 male participants with military experience.[20] In the context of military load carriage, the load burden may increase the risk of trips and falls since a destabilising force is created by the heavily-loaded back pack, which is posterior to the body’s centre of gravity.[4] In firefighters who share similar occupational demands with military personnel, prolonged walking while wearing firefighting equipment increased the variability of double-support time during stance.[21] Interestingly, deviations from an individual’s preferred step width (increased gait variability) increased the metabolic cost of walking.[22] This suggests a vicious cycle of increasing gait variability and fatigue. Thus, studies on gait variability in addition to absolute gait variables would be useful in understanding gait changes during prolonged load carriage.

In warm environments (> 26°C), heat mitigation strategies can be used to reduce $T_c$ and also the exercise performance detriments caused by exertional heat stress.[23] In a review, Wegmann and colleagues found that cold drink ingestion (water at 4°C or crushed ice) was a promising method for reducing $T_c$.[23] Siegel and colleagues rationalised that a phase change from solid to liquid requires a large amount of energy (enthalpy of fusion).[24] Compared to drinking water, the energy required to change ice slurry (a mixture of crushed ice and melted ice water) to fluid would lower heat strain. Recent studies have also demonstrated the efficacy of ice slurry ingestion as a heat mitigation strategy to attenuate increases in $T_c$ during exercise.[25-27] It is not known whether a heat mitigation strategy such as ice slurry ingestion would alleviate the expected detrimental changes in gait during prolonged load carriage.

Thus, the primary aim of the study was to examine if changes in gait characteristics could indicate the exertional-heat stress experienced during prolonged load carriage. The secondary aim was to investigate if gait characteristics were responsive to an ice slurry heat mitigation strategy. We hypothesised that 1) exertional heat stress incurred during prolonged load carriage would lead to more unstable gait as characterised by narrowing step width and increasing variability in spatio-temporal parameters, and 2) these undesirable gait changes (of narrowing step width and increasing variability in spatio-temporal parameters) could be reduced by a heat mitigation strategy.

## Methods

Sixteen male volunteers participated in this study [mean (SD), age 21.8 (1.2) y, height 173 (4) cm, body mass 69.4 (12.1) kg, estimated maximum oxygen consumption, 52.1 (3.3) ml/kg/min]. Estimated maximum oxygen consumption ($VO_2$ max) for each participant was calculated from his most recent 2.4 km run timing using the equation: $VO_2$ max = 483/(2.4 km timing in minutes) + 3.5.[30] All participants were certified medically fit. The medical clearance criterion was Physical Employment Status (PES) A or B. PES A personnel are medically fit for all combat vocations, while PES B personnel are medically fit for most combat vocations. The PES is a 150-min medical examination that includes a chest x-ray and an electrocardiogram. Other exclusion criteria included: a history of heat illness; asthma; current musculoskeletal injury hindering ability to perform prolonged load carriage; and digestive tract surgery.

Prior to data collection, all participants had the nature, benefits and risks of the study explained to them, and gave their informed consent in writing. Parental consent was required for minors below the age of 21 years, in addition to their own assent. Before each trial, participants were also asked to complete a health declaration form stating they were in good health to proceed with the experiment. All procedures involved in the study were approved by the Institutional Review Boards of DSO National Laboratories and Nanyang Technological University.

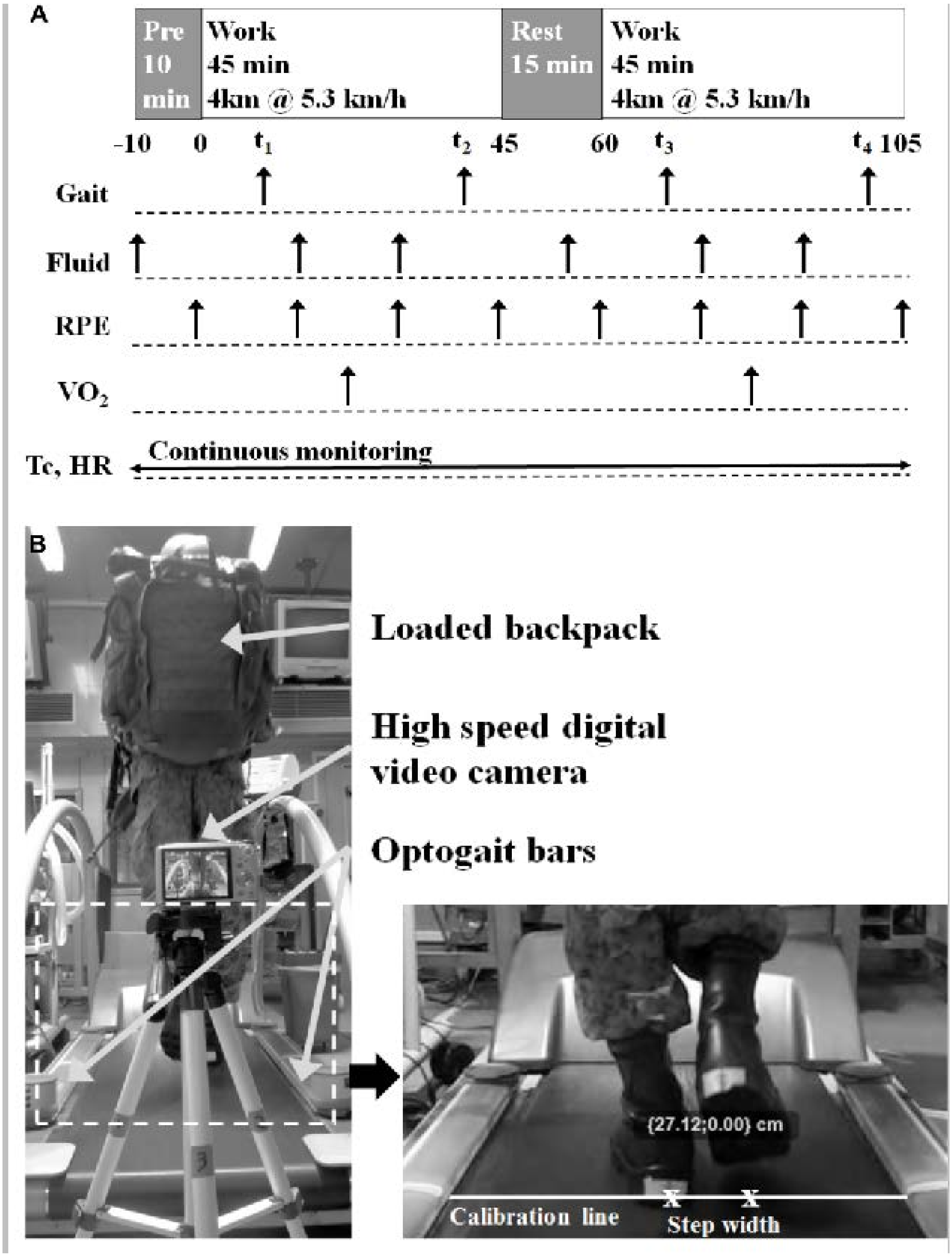
The study comprised three visits to the testing laboratory. The first visit was a familiarisation trial, while the second and third visits were the experimental trials of either the ice slurry (ICE) or control (CON) condition where room temperature water (29°C) was ingested. Plain water was used for the preparation of ice slurry, with each aliquot comprising 80% blended ice (HR2096/01, Philips Electronics Singapore Pte Ltd., Singapore), and 20% cold water. The bottles of ice slurry were stored in a Styrofoam ice box. Trial order was counterbalanced and randomly assigned to participants. To allow adequate recovery and minimise training effects, trials were separated by at least 7 days and at most 14 days. Each participant commenced his trials at the same time (either in the morning or afternoon) to control for circadian variations in $T_c$.[29] The study was conducted in an environmental chamber (VEKZ10, Votsch Industrietechnik, Germany) set at a dry bulb temperature of 32°C and a relative humidity of 70%, with simulated solar radiation of 400 $W/m^2$, to replicate typical tropical climatic conditions.

Participants were asked to maintain a one-day dietary and physical activity record prior to the familiarisation trial, and instructed to follow similar dietary and physical activity patterns one day before each experimental trial. They were also requested to refrain from alcohol, and avoid strenuous physical activities that would affect their performance during the experiment. To decrease the likelihood of commencing trials in a dehydrated state, they also ingested 500 ml of plain water upon waking. Upon arrival at the laboratory, a telemetric check was performed using a core temperature data-recording device to ensure transmission signals from an ingestible temperature-sensing capsule (VitalSense, Mini Mitter Company Inc, USA) swallowed 6 to 10 hours before the trial. Participants wore their standard outfield uniform plus a body armour vest with standard accessories, Kevlar helmet and carried a loaded backpack and dummy rifle. The total load was approximately 30 kg.

For each trial, participants performed 2 work cycles of 4 km each at 5.3 km/h, separated by 15 min of rest, on a treadmill (h/p/cosmos Mercury, h/p/cosmos, Germany). A schematic representation of the gait and physiological measurements is depicted in Figure 1A. Room temperature water (29°C) or ice slurry was provided in 200-ml aliquots 10 min before the start of the protocol, at the 15th and 30th min of each work cycle and during each rest period. A telemetric temperature recording device (VitalSense, Mini Mitter Company Inc, USA) monitored $T_c$ continuously, while HR was logged with a wireless monitor (S810i, Polar Electro Oy, Kempele, Finland) at 15-s intervals. Participants rated RPE from ‘No exertion at all’ to ‘Maximal exertion’ on a 6-20 Borg scale at 15-min intervals. Lastly,

$VO_2$ was measured using indirect calorimetry via a breathing tube, nose clip and metabolic cart (TrueOne 2400®, ParvoMedics, Sandy, UT, USA) midway during each work cycle, i.e. at 23rd min.

Figure 1



Participants were instructed to walk in the middle of the treadmill belt when possible, and not to hold on to the handrails unless they were in danger of falling or tripping. Termination criteria included (1) participant request, (2) $T_c$ reaching the 40°C threshold, and (3) unsteady gait or other reasons that would compromise the participant's safety. All participants completed the entire load carriage protocol.

Spatiotemporal gait variables were obtained using a floor-based photocell system sampling at 1000 Hz (OptoGait, Mircrogate, Bolzano, Italy) and a high-speed digital video camera operating at 120 Hz (Figure 1B). The OptoGait system consists of two parallel bars (100 cm x 8 cm), containing 96 light emitting diodes each, which were mounted on either side of the treadmill. The manufacturer specification of its accuracy is within 1 cm. This system was previously found to be valid for quantitative spatio-temporal gait analysis.[30] A tripod-mounted digital video camcorder (Casio EX-FH 100, Tokyo, Japan) elevated 0.6 m above ground and positioned 0.5 m away from the back end of the treadmill was used to record the posterior view of gait. For step width profiling, reflective tape (4 cm × 1.5 cm) was placed on the heel area of each boot, with the centre line identified by a cross.

Gait data were acquired at four time points ($t_1$ to $t_4$) throughout the protocol, each lasting one min (Figure 1A). In the beginning of each cycle ($t_1$, $t_3$), gait acquisition was performed only after 10 min of walking to allow stabilisation of the participant's gait. Towards the end of each cycle, gait data were collected at the 40th min ($t_2$, $t_4$).

Exercise intensity was estimated from $VO_2$ during exercise divided by estimated $VO_2$ max. Supplementary indicators of exertional heat stress were based on RPE at the end of each cycle, and average HR and $T_c$ data during the last 5 minutes of each cycle.

Gait variables obtained automatically from the OptoGait software were step length (heel-to-heel distance), stance time and double support time. The average values of all the steps measured within each of the four one-min periods were used for subsequent analysis. In addition to mean values, the standard deviations (SD) of the gait variables for each participant were also obtained as a measure of gait variability. Since walking speed was fixed at 5.3 km/h, other gait variables such as cadence were omitted to avoid redundancy.

From the high-speed video recording, spatial variables in the frontal plane were obtained through manual digitisation using open source freeware Kinovea version 0.8.15 (www.kinovea.org). Based on a calibration line of 56.0 cm (distance between Optogait bars) for 273 pixels, the error of the analysis lied within 0.1 cm. Step width was quantified as the medio-lateral distance between the marked crosses identifying sequential heel strikes (Figure 1B). For each one-minute period recorded, mean step width and variability (SD) was calculated for each participant. A crossover step was noted when the step width was zero or negative, indicating that the participant's feet overlapped. The occurrence of crossover steps was expressed as a percentage of the total number of steps analysed within each one-minute period for individual participants.

The dependent variables were the mean and variability of step length, stance time, double support time and step width, as well as the percentage of crossover steps. Raw data were tested for normal distribution using the Shapiro-Wilk *W* test. As normality could not be assumed, log transformations were applied. Repeated-measure analysis of variance (ANOVA) of four time points in two trials (ICE / CON) was conducted to assess the effects of fatigue and ice slurry ingestion on spatiotemporal gait characteristics. To correct for violation of sphericity, significance was assessed from the Greenhouse-Geisser correction for epsilon values $\leq 0.75$, and the Huynh-Feldt correction for epsilon $> 0.75$. Observed power and effect size (partial eta squared, $\eta^2$) were also calculated. For variables displaying significant main effects of time, post hoc pairwise comparisons were conducted between baseline ($t_1$) versus subsequent time points ($t_2$, $t_3$, $t_4$) using Bonferroni's procedures to adjust for multiple comparisons. The time points $t_1$ to $t_4$ corresponded to the 10th, 40th, 70th and 110th min respectively. Due to the technical difficulties of the OptoGait system, data from six participants were not collected accurately. Thus, step length, stance time and double support time data were based on 10 participants.

To quantify exertional heat stress, repeated-measure ANOVA of two time points (start, end) in two trials (ICE / CON) was conducted to assess the effects of fatigue and ice slurry ingestion on $T_{c,}$ HR, RPE and $VO_2$ . For $VO_2$, the time points were the mid-ways of the first and second work cycles (22.5th min of each 45-min cycle). For variables displaying significant interaction effects, post hoc pairwise comparisons were conducted using Bonferroni's procedures to adjust for multiple comparisons. All statistical analyses were performed in IBM™ SPSS™ Statistics (version 23.0, SPSS Inc., Chicago, IL, USA), with significance level set at .05. Data are presented as mean (SD).

## Results

All physiological variables increased with walking duration ($p < .05$, Table 1). There were a reduction in $T_c$ ($p = .025$) and a non-significant reduction in RPE ($p = .056$) in ICE compared with CON. An interaction effect (time × trial) was observed for HR ($p = .016$). While HR increased with time in all trials, post-hoc analyses revealed that HR did not differ between ICE and CON at the start ($p = .724$) but reached a higher value in ICE towards the end of the protocol ($p = .018$). The exercise intensity of the load carriage protocol was estimated to be about 38% $VO_2$ max, or 5.5 metabolic equivalents. The final $T_c$ of 38.0 to 38.2ºC was just under 38.5°C, which is regarded as an indicator of moderate heat strain in heat acclimatisation protocols.[25] Taken together, these physiological changes suggest that participants were close to experiencing a moderate degree of heat stress.

*** Table 1 ***

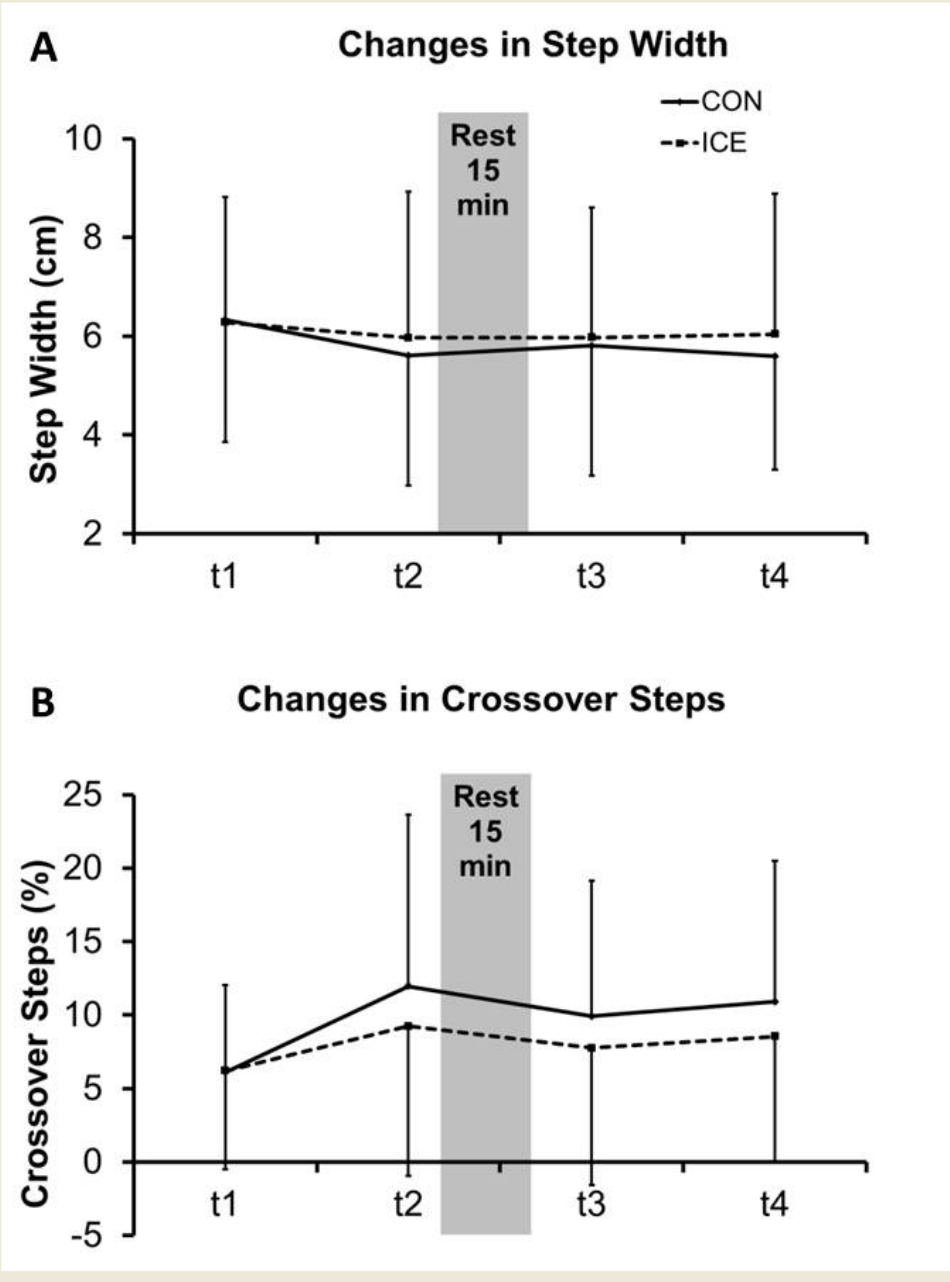
Table 2 reports the repeated measures ANOVA results of the gait variables. Observed power and effect size calculations are presented in Table 3. Among all temporal variables measured, only stance time variability was reduced in ICE compared to CON ($p = .029$). There were no differences in stance time and double support time. For the spatial variables, several main effects were present ($p < .05$). During ICE, participants exhibited reduced step width variability ($p = .001$) and less crossover steps ($p = .010$) compared to CON. A main effect of time was also observed for mean step width ($p = .024$) and percent crossover steps ($p = .008$). As time increased, step width decreased and percent crossover steps increased. No differences were found for step length. No significant interactions were detected for any gait variable. For the non-significant results, the effect sizes ranged from small to large, and power was relatively low at below .80 (Table 3).

*** Table 2 ***

*** Table 3 ***

Figure 2 shows the group responses for step width and crossover steps. It should be noted, however, that there was much between-participant variability in the responses. Supplementary data of individual participants can be found in the Appendix.

Figure 2



## Discussion

This study investigated the association between gait changes and exertional heat stress during prolonged load carriage, as well as how these changes may be affected by ice slurry ingestion. We found that frontal plane spatial variables were sensitive to heat stress during prolonged load carriage, as characterised by narrowing step width and increasing crossover steps. These results support our first hypothesis that exertional heat stress incurred during prolonged load carriage led to more unstable gait. Compared with drinking room temperature water, gait patterns were more stable when participants ingested ice slurry as indicated by reductions in stance time variability, step width variability and crossover steps. These results partially support our second hypothesis that undesirable gait changes could be reduced by ice slurry ingestion. Originally, we had expected the same gait variables to be affected by the effects of time and trial, however, this was the case only for crossover steps (out of the four significant variables).

Temporal and sagittal plane spatial gait variables were largely resistant to exertional heat stress during prolonged load carriage. This is in line with previous studies [3,11-13,20,21]. Thus, future studies intending to use gait characteristics to detect exertional heat stress should extend beyond these variables, as the expected changes are likely to be minimal. In contrast, frontal plane spatial gait variables (i.e. step widths and percent crossover steps) were more sensitive to exertional heat stress from prolonged load carriage. These results support the recommendation to investigate frontal plane gait variables rather than sagittal plane variables. Throughout the protocol, participants experienced more medio-lateral instability in their gait as evident from narrower step widths and increasing percentage of crossover steps at subsequent time points compared to the baseline. Medio-lateral instability has been linked to risk of falls [18-20] and narrower step widths are associated with metabolic inefficiencies.[22] Thus, the gait changes coupled with the slight increase in $VO_2$ with time suggests that prolonged load carriage induces unstable and inefficient gait. Future studies may examine the relationship between step width and metabolic efficiency during prolonged load carriage in greater detail.

Percent crossover steps is presented here as a new way to quantify gait variability. In studies on elderly populations, increased gait variability during walking is a risk factor for falling.[19] Having a smaller step width reduces the base of support which a person’s centre of gravity must stay within to maintain balance, and therefore increases the chances of falling. In this case where step width is zero or negative, the greatly reduced base of support increases the risks of falling and tripping (over one’s own foot). Percentage of crossover steps may be viewed as a type of “movement error”, a concept introduced by Park and colleagues to quantify occurrences where a participant steps outside a demarcated area (instrumented gait mats placed in the centre of a walkway).[21] While the percentage of crossover steps was originally derived from step width data, the concept of crossing over (or feet overlapping) is much easier to grasp from the layperson’s perspective. Given that crossing over steps are easily observable, this new gait variable could be a useful identifier of exertional heat stress.

Our second hypothesis that ice slurry ingestion would be effective in mitigating undesirable changes in gait was partially supported by the data. Compared to CON, more stable gait patterns were observed in ICE trials as characterised by reduced stance time and step width variability, and less number of crossover steps. As previously suggested, unstable gait patterns are synonymous with injury risk [18-22] and may be viewed as reduced motor performance. It has been suggested that a reduction in physical performance during prolonged exercise in a warm environment is mainly caused by an increase in heat strain.[1] In our study, ice slurry ingestion effectively mitigated the increase in heat strain at the end of the protocol (Table 1) although the exact mechanisms of how it acts to negate performance decrements are still debatable.[24-27] Nevertheless, there appears to be a dual use of ice slurry ingestion for alleviating physiological responses and also reducing the risk of trips and falls. Future studies on fatigue and heat mitigation strategies may consider incorporating medio-lateral gait characteristics (step width and percent crossover steps) in addition to physiological measures to detect exertional heat stress.

Given that considerable inter-individual variations were observed (Appendix), future investigations should incorporate larger sample sizes to confirm the trends presented here, i.e., if some responder/non-responder effect may be identified. In general, the observed power for the non-significant variables was low to moderate (Table 3). The lack of power indicates the need for larger sample sizes to confirm our results. Nonetheless, in instances when both power and effect size are low, it is likely that there were no true differences. For example, when step length was tested for the effect of condition, the low power of .063 and small effect size of .057 suggest a high probability of no meaningful difference between ICE and CON.

While percent crossover steps is a novel way to detect exertional heat stress, it is unclear if such observations from a treadmill protocol would be similarly present in an actual military route march, where soldiers march long distances in formation and possibly at different cadence for different sections of the route march. At present, it is unknown how the constrained interpersonal space may afford changes to medio-lateral gait variables. Future studies could explore whether our findings can be extended to overground marching, and if gait is affected differently when walking in a group. In this study, participants did not experience severe fatigue or heat stress, hence it is unclear how representative the gait changes found would translate in more demanding prolonged load carriage protocols.

## Conclusions

During prolonged load carriage, frontal plane spatial variables are sensitive to exertional heat stress and a heat mitigation strategy of ice slurry ingestion. Specifically, narrowing step width and increasing percent crossover steps accompany increasing fatigue and heat stress. Within all frontal plane gait variables, percent crossover step is the most readily observable. Since crossover gait is inherently unstable and potentially injurious, this new gait variable can be a non-invasive proxy for detecting exertional heat stress during prolonged load carriage. Compared with drinking room temperature water, gait patterns were more stable with ice slurry ingestion as indicated by reductions in stance time variability, step width variability and crossover steps. Thus, ice slurry ingestion can serve a dual purpose of alleviating physiological responses and reducing the risk of trips and falls.

**Conflicts of interest:** None.

**Acknowledgements**

This study was funded by the Ministry of Defence (MINDEF), Singapore. The authors would like to thank the Combat Protection and Performance project team from the Defence Medical and Environmental Research Institute @ DSO National Laboratories (DMERI@DSO) and all participants for the successful completion of the study. The funding source has no involvement in the study design, data collection and analysis, writing of the report and decision to submit for publication.

## References

[1] Gonzalez-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, Nielsen B. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol 1999;86:1032–9.

[2] Lee JKW, Nio AQX, Fun DCY, Teo YS, Chia EV, Lim CL. Effects of heat acclimatisation on work tolerance and thermoregulation in trained tropical natives. J Therm Biol 2012;37(5):366–73.

[3] Quesada PM, Mengelkoch LJ, Hale RC, Simon SR. Biomechanical and metabolic effects of varying backpack loading on simulated marching. Ergonomics 2000;43(3): 293–309.

[4] Beekley MD, Alt J, Buckley CM, Duffey M, Crowder TA. Effects of heavy load carriage during constant-speed, simulated, road marching. Mil Med 2007;172(6):592–5.

[5] Polcyn AF, Bensel CK, Harman EA, Obusek JP, Pandorf C, Frykman P. Effects of weight carried by soldiers: combined analysis of four studies on maximal performance, physiology, and biomechanics. Massachusetts: U.S. Army Research Institute of Environmental Medicine;2002. NATICK/TR-02/010.

[6] Knapik JJ, Reynolds KL, Harman E. Soldier load carriage: historical, physiological, biomechanical, and medical aspects. Mil Med 2004;169(1):45–56.

[7] Reynolds K, Kaszuba J, Mello RP, Patton JF. Prolonged treadmill load carriage: acute injuries and changes in foot anthropometry. Massachusetts: U.S. Army Research Institute of Environmental Medicine;1990. T1–91.

[8] Majumdar D, Pal MS, Majumdar D. Effects of military load carriage on kinematics of gait. Ergonomics 2010;53(6):782–91.

[9] Birrell SA, Hooper RH, Haslam RA. The effect of military load carriage on ground reaction forces. Gait Posture 2007;26:611–4.

[10] Birrell SA, Haslam RA. The effect of military load carriage on 3-D lower limb kinematics and spatiotemporal parameters. Ergonomics;2009:52(10):1298–304.

[11] Simpson KM, Munro BJ, Steele JR. Effects of prolonged load carriage on ground reaction forces, lower limb kinematics and spatio-temporal parameters in female recreational hikers. Ergonomics 2012;55(3):316–26.

[12] 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):770–80.

[13] Ling W, Houston V, Tsai YS, Chui K, Kirk J. Women's load carriage performance using modular lightweight load-carrying equipment. Mil Med 2004;169(11):914–9.

[14] Grenier JG, Millet GY, Peyrot N, Samozino P, Oullion R, Messonnier L et al. Effects of extreme-duration heavy load carriage on neuromuscular function and locomotion: a military-based study. PLoS One 2012;7(8):e43586.

[15] Federolf P, Tecante K, Nigg B. A holistic approach to study the temporal variability in gait. J Biomech 2012;45(7):1127–32.

[16] Heiderscheit BC. Movement variability as a clinical measure for locomotion. J Appl Biomech 2000:16(4):419-27.

[17] Qu X, Yeo JC. Effects of load carriage and fatigue on gait characteristics. J Biomech 2011;44(7):1259–63.

[18] Kong PW, Beauchamp G, Suyama J, Hostler D. Effect of fatigue and hypohydration on gait characteristics during treadmill exercise in the heat while wearing firefighter thermal protective clothing. Gait Posture 2011;31(2):284–88.

[19] Maki B. Gait changes in older adults. J Am Geriatr Soc 1997;45(3):313–20.

[20] Owings TM, Grabiner MD. Step width variability, but not step length variability or step time variability, discriminates gait of healthy young and older adults during treadmill locomotion. J Biomech 2004;37(6):935–38.

[21] Park K, Rosengren KS, Horn GP, Smith DL, Hsiao-Wecksler ET. Assessing gait changes in firefighters due to fatigue and protective clothing. Safety Sci 2011;49(5):719–26.

[22] Donelan JM, Kram R, Kuo AD. Mechanical and metabolic determinants of the preferred step width in human walking. Proc Biol Sci 2001;268(1480):1985–92.

[23] Wegmann M, Faude O, Poppendieck W, Hecksteden A, Fröhlich M, Meyer T. Pre-cooling and sports performance. Sport Med 2012;42(7):545–64.

[24] Siegel R, Mate J, Brearley MB, Watson G, Nosaka K, Laursen PB. Ice slurry ingestion increases core temperature capacity and running time in the heat. Med Sci Sport Exerc 2010;42(4):717–25.

[25] Yeo ZW, Fan PW, Nio A, Byrne C, Lee JK. Ice slurry on outdoor running performance in heat. Int J Sports Med 2012;33(11):859–66.

[26] Siegel R, Maté J, Watson G, Nosaka K, Laursen PB. The influence of ice slurry ingestion on maximal voluntary contraction following exercise-induced hyperthermia. Eur J Appl Physiol 2011;111(10):2517–24.

[27] Siegel R, Maté J, Watson G, Nosaka K, Laursen PB. Pre-cooling with ice slurry ingestion leads to similar run times to exhaustion in the heat as cold water immersion. J Sport Sci 2012;30(2):155–65.

[28] Reilly T, Brooks GA. Exercise and the circadian variation in body temperature measures. Int J Sport Med 1986;7(6):358–62.

[29] Burger SC, Bertram SR, Stewart RI. Assessment of the 2.4 km run as a predictor of aerobic capacity. S Afr Med J 1990;78(6):327–9.

[30] Lienhard K, Schneider D, Maffiuletti NA. Validity of the Optogait photoelectric system for the assessment of spatiotemporal gait parameters. Med Eng Phys 2013;35(4):500–4.

**Table 1** Physiological changes during prolonged load carriage in the heat

| Variable | | Time $^a$ | | ANOVA p-value | | |
|---|---|---|---|---|---|---|
| | | Start of protocol | End of protocol | Time | Trial | Time × Trial |
| Core temperature, $T_c$ (°C) | ICE | 36.9(0.3) | 38.0(0.5) | <.001* | .025* | .091 |
| | CON | 37.0(0.3) | 38.2(0.5) | | | |
| Heart rate (bpm) | ICE | 86(10) | 146(16) | <.001* | .139 | .016* |
| | CON | 85(12) | 152(19) | | | |
| Rating of perceived exertion | ICE | 10(3) | 13(3) | <.001* | .056 | .301 |
| | CON | 10(2) | 14(2) | | | |
| Oxygen consumption, $VO_2$ (ml/kg/min)$^a$ | ICE | 18.9 (2.0) | 19.9 (2.8) | .017* | .624 | .169 |
| | CON | 19.3 (2.8) | 19.7 (3.0) | | | |

Complete data for $T_c$ was obtained for only 14 participants. ANOVA analysis of variance, ICE ice slurry, CON control. $^a VO_2$ was measured in the middle of each work cycle. *p < .05.

**Table 2** Gait characteristics and statistical results during prolonged load carriage in the heat

| Variable | | Time | | | | ANOVA p-value | | | Post-hoc |
|---|---|---|---|---|---|---|---|---|---|
| | | $t_1$ | $t_2$ | $t_3$ | $t_4$ | Time | Trial | Time × Trial | |
| Step length (cm) | ICE | 75.8 (2.3) | 76.0 (2.7) | 75.3 (2.2) | 75.3 (2.5) | .321 | .785 | .617 | |
| | CON | 75.3 (3.9) | 76.3 (2.8) | 75.6 (2.3) | 75.5 (3.0) | | | | |
| Step length variability (cm) | ICE | 2.6 (0.5) | 2.7 (0.8) | 2.8 (0.4) | 2.8 (0.4) | .619 | .083 | .626 | |
| | CON | 2.9 (0.6) | 3.1 (0.9) | 2.8 (0.4) | 3.1 (0.9) | | | | |
| Stance time (ms) | ICE | 675 (31) | 680 (30) | 674 (29) | 676 (30) | .300 | .722 | .147 | |
| | CON | 668 (45) | 681 (35) | 676 (31) | 678 (33) | | | | |
| Stance time variability (ms) | ICE | 15 (4) | 15 (5) | 17 (6) | 17 (7) | .152 | .029* | .709 | ICE < CON |
| | CON | 18 (5) | 17 (7) | 18 (4) | 19 (7) | | | | |
| Double support time (ms) | ICE | 322 (32) | 326 (30) | 325 (27) | 326 (32) | .089 | .343 | .158 | |
| | CON | 312 (43) | 324 (35) | 325 (33) | 330 (26) | | | | |
| Double support time variability (ms) | ICE | 18 (6) | 19 (9) | 20 (9) | 22 (12) | .250 | .351 | .161 | |
| | CON | 24 (8) | 17 (7) | 23 (8) | 18 (4) | | | | |
| Step width (cm) | ICE | 6.3 (2.5) | 6.0 (3.0) | 6.0 (2.6) | 6.0 (2.8) | .024* | .478 | .629 | $t_1 > t_2, t_3, t_4$ |
| | CON | 6.3 (2.5) | 5.6 (2.6) | 5.8 (2.6) | 5.6 (2.3) | | | | |
| Step width variability (cm) | ICE | 3.2 (0.5) | 3.4 (0.6) | 3.5 (0.5) | 3.4 (0.5) | .123 | .001* | .791 | ICE < CON |
| | CON | 3.5 (0.7) | 3.8 (0.6) | 3.7 (0.6) | 3.7 (0.7) | | | | |
| Crossover step (%) | ICE | 6.2 (6.7) | 9.2 (10.2) | 7.8 (9.3) | 8.5 (8.6) | .008* | .010* | .351 | $t_1 < t_2, t_3, t_4$ |
| | CON | 6.1 (5.9) | 12.0 (11.7) | 9.9 (9.2) | 10.9 (9.6) | | | | ICE < CON |

ANOVA analysis of variance, ICE ice slurry, CON control. Time points $t_1$ 10th min $t_2$ 40th min $t_3$ 70th min $t_4$ 100th min. Temporal and step length data were obtained from the OptoGait system (*n* = 10); step width data were determined from video analysis (*n* = 16). *p < .05.

**Table 3** Observed power and effect size calculations of gait characteristics

| Variable | Time | | Trial | | Time × Trial | |
|---|---|---|---|---|---|---|
| | Power | $\eta^2$ | Power | $\eta^2$ | Power | $\eta^2$ |
| Step length (cm) | .446 | .303 | .009 | .057 | .139 | .094 |
| Step length variability (cm) | .203 | .121 | .297 | .414 | .209 | .124 |
| Stance time (ms) | .561 | .620 | .063 | .015 | .189 | .318 |
| Stance time variability (ms) | .463 | .564 | . 635* | .426* | . 084 | .113 |
| Double support time (ms) | .260 | .405 | .146 | .100 | .189 | .318 |
| Double support time variability (ms) | .206 | .342 | .143 | .097 | .326 | .467 |
| Step width (cm) | .675* | .465* | .105 | .034 | .265 | .229 |
| Step width variability (cm) | .583 | .417 | .988* | .577* | .090 | .061 |
| Crossover step (%) | .822* | .545* | .788* | .367* | .225 | .198 |

*Significant ANOVA effects at $p < .05$.

## Figure Legends

**Figure 1 A.** Schematic representation of the experiment protocol. RPE rate of perceived exertion, $VO_2$ oxygen consumption, $T_c$ body core temperature, HR heart rate. Time points $t_1$ 10th min, $t_2$ 40th min, $t_3$ 70th min, $t_4$ 100th min. **B.** Experimental setup overview (left) with screenshot of step width analysis (right). Experiment was conducted in an environmental chamber replicating tropical climatic conditions. A participant is shown wearing the loaded backpack. A high-speed video camera is positioned away from the back end of the treadmill. OptoGait bars are mounted either side of the treadmill. Heel reflective tape midpoints are marked 'X' where they meet the calibration line of 56.0 cm. Step width is the distance between two successive steps (between two 'X's).

**Figure 2** Changes in **A.** step width ($n$ = 16) and **B.** crossover steps ($n$ = 16) during work-rest cycles consisting two bouts of 4-km treadmill walks with 30-kg load at 5.3 km/h. Time points $t_1$ 10th min, $t_2$ 40th min, $t_3$ 70th min, $t_4$ 100th min.

## Appendix

Individual responses in step width and crossover steps during work-rest cycles consisting two bouts of 4-km treadmill walks with 30-kg load at 5.3 km/h. Time points $t_1$ 10th min, $t_2$ 40th min, $t_3$ 70th min, $t_4$ 100th min.