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Using gait parameters to detect fatigue and responses to ice slurry during prolonged load carriage

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ABSTRACT

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 min 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.

1. 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 min, 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

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protocols [8–10]. Spatial 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 ice slurry ingestion. 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 ice slurry ingestion.

2. 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 [28]. 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 6–10 h 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