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Effect of fatigue and hypohydration on gait characteristics during treadmill exercise in the heat while wearing firefighter thermal protective clothing

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ABSTRACT

This study compared the gait characteristics of individuals walking in heat while wearing firefighting equipment in fatigued and non-fatigued states. Nineteen subjects performed a 50-min treadmill protocol in a heated room while gait patterns were recorded using a digital video camcorder. Forty gait cycles were analyzed near the beginning (9 min) and at the end (39–49 min) of exercise. Spatio-temporal gait variables including step frequency, step length, swing time, stance time, cycle time and double-support time were determined. Gait variability was quantified by the standard deviation (SD) and coefficient of variation (CV) of each variable. Left–right symmetry was calculated using the symmetry index (SI) and symmetry angle (SA). Paired *t*-tests ($\alpha = 0.05$) were performed to identify difference between the beginning and the end of the protocol for each measured variable. Spatio-temporal gait characteristics did not differ between the beginning and the end of exercise. Gait variability of the double-support time increased at the end as measured by both SD ($P = 0.037$) and CV ($P = 0.030$) but no change was observed for other variables. Left–right symmetry measured using either SI or SA did not differ between sessions. In summary, spatio-temporal gait characteristics and symmetry while wearing firefighting equipment are insensitive to physiological fatigue. Prolonged walking in heat while wearing firefighting equipment may increase gait variability and therefore the likelihood of a fall. Future studies are needed to confirm the potential relationship between fatigue and gait variability and to investigate the possible influence of individual variation.

1. Introduction

Firefighting is a physically demanding occupation that places significant physiological strain on the individual leading to cardiovascular morbidity [1]. Firefighters are also injured by mechanical falls on the fireground that can lead to strains, sprains, temporary disability and even death [2,3]. In order to enhance the safety of firefighters and the public, it is critical to understand the preventable causes of occupational falls during firefighting operations.

Thermal protective clothing (TPC) and self-contained breathing apparatus (SCBA) are employed to protect firefighters from environmental hazards during interior fire suppression. Firefighting TPC typically includes heavy fire-resistant outer garments (pants and coat), safety boots, gloves, a helmet, and a fire-resistant hood. Although wearing TPC and SCBA effectively protects firefighters from environmental hazards, the additional mass and visual obstruction of the SCBA facepiece has been shown to negatively affect balance [4]. This effect of TPC and SCBA on balance may partly explain the higher incidence of fall-related injuries (46.7%) compared to smoke inhalation (14.7%) and burns (38.7%) among firefighters [3].

Furthermore, gait variability, the amount of step-to-step variation during walking is an indicator to predict the risk of falling [5]. Individuals with a falling history often display higher gait variability [6–11] and left–right gait asymmetry [12]. Fatigue can lead to an increased gait variability [13,14] and on the fireground can increase the likelihood of a fall. National Fire Protection Association (NFPA) guidelines recommend that firefighters be provided a formal rest period (rehabilitation) after not more than two SCBA cylinders have been consumed [15]. Depending on the intensity of operation, this means that firefighters may work continuously for 50–60 min before a structured rest period is introduced. While one may expect more falls with increasing fatigue, the timing of fall-related injuries on the fireground is unknown. There is also no information on the gait characteristics while wearing firefighting TPC and SCBA available in the literature.

Thus, there were two main purposes of the present study: (1) to present spatio-temporal gait characteristics during walking in heat

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while wearing firefighting TPC and SCBA; and (2) to investigate the effect of fatigue resulting from cardiovascular strain and thermal stress on gait characteristics, variability and symmetry while wearing firefighting TPC and SCBA. It was hypothesized that fatigue and concomitant hypohydration following treadmill exercise while wearing TPC and SCBA would lead to changes in gait characteristics, increased variability and increased left–right asymmetry.

2. Methods

2.1. Subjects

The University of Pittsburgh Institutional Review Board approved experimental procedures and informed consent was obtained prior to participation. Nineteen subjects (14 males, five females) took part in the study. Subject demographics and morphometrics are shown in Table 1. Three subjects had public safety experience (one career firefighter, one volunteer firefighter, one paramedic) and the remainder were recruited from the university population. A study physician screened subjects including a detailed medical history, physical exam, resting vital signs, 12 lead electrocardiogram (ECG), and exercise stress test. Female subjects were given a urine pregnancy test. Subjects were in good health and free of cardiovascular, neuromuscular, and vestibular disease.

Non-firefighter subjects participated in a 10-min familiarization walk on the treadmill at 1.3 m s^{-1} wearing full firefighter TPC and SCBA to ensure physiological responses were similar to previous cohorts of firefighters tested in our laboratory and to ensure subject tolerance of the firefighter TPC and SCBA. To continue in the protocol, subjects were required to have a heart rate less than 163 beats per minute (the mean heart rate seen in a previous cohort of firefighters) at the end of the 10-min treadmill walk. To ensure the subject did not suffer mask-induced claustrophobia, the respiratory rate could not exceed 36 breaths per minute at any time during the familiarization procedure.

Subjects completed a treadmill exercise stress test to determine cardiorespiratory capacity and to screen for undiagnosed cardiovascular disease. Subjects were asked to refrain from caffeine, tobacco, and exercise 12 h before the test but were not otherwise controlled for nutrition or hydration. Subjects performed a Bruce treadmill test. In this protocol, the subject begins walking at 0.8 m s^{-1} up a 10% grade. The grade and speed increase every 3 min until the subject reaches volitional fatigue. During testing, an open circuit spirometer (Parvomedics Inc., UT) calculated breath-by-breath analysis of oxygen uptake (VO_2), volume of carbon dioxide produced per minute (VCO_2), and respiratory exchange ratio. The electronic analyzers were calibrated prior to each exercise test using standard reference gases. Heart rate was recorded each minute during exercise and for 5 min following exercise. A 12 lead ECG was obtained every 3 min during exercise and for 10 min following the end of exercise.

2.2. Experimental protocol

Subjects reported to the lab and provided a urine sample. Urine specific gravity was determined and all subjects were euhydrated at the onset of the protocol (USG $\leq$ 1.020). Subjects were weighed nude before donning a standard uniform of cotton/polyester blend long pants and 100% cotton t-shirt. Subjects wore full firefighting TPC ensemble including heavy pants and coat (Lion Apparel, Dayton, OH), polycarbonate helmet (Paul Conway, Dayton, OH), steel-toed rubber boots (Servus, Dayton, OH), heavy gloves, nomex hood, and SCBA (Firehawk, Mine Safety Appliance, Pittsburgh, PA) that weighed approximately 20 kg. All components of the TPC ensemble were provided by the investigators and met the NFPA standard for protective ensembles for structural firefighting [16]. Subjects walked on a treadmill in a room heated between 33 and 35 °C. Instants of touchdown and toe-off were identified on video by placing reflective tape on the heel and toe areas of the safety boots of both feet. A digital video camcorder (Canon ZR 830) was used to record the gait pattern at 60 Hz throughout the protocol.

The 50-min walking protocol was administered as follows. Subjects walked for 20 min at 1.3 m s^{-1} to simulate a work period that would require a firefighter to consume one SCBA cylinder followed by 3 min at 0.7 m s^{-1} to simulate exiting a structure. The subjects then stood for 4 min to simulate an SCBA cylinder change followed by 3 min of walking at 0.7 m s^{-1} and 20 min at 1.3 m s^{-1}. This protocol has been used in previous studies to simulate a common work–rest ratio used in the fire service and typically results in hyperthermia and near maximal heart rates [17,18].

Heart rate was monitored with a wireless heart rate monitor (Polar Electro, NY). Core temperature was monitored by an ingestible thermometer (HQ Inc., Palmetto, FL). Subjects rated perceived exertion during the exercise protocol using the OMNI scale of perceived exertion (0–10) [19]. Termination criteria included (1) subject request, (2) heart rate greater than 10 beats per minute over age predicted maximum (220−age) or (3) unsteady gait making it unsafe to continue treadmill exercise. Subjects took the capsule 8 h prior to the protocol to minimize the effect of oral intake on gastric temperature in the hours leading up to exercise [20].

2.3. Data reduction

Forty consecutive footsteps in the beginning (9 min) and at the end (49 min) of the protocol were analyzed using the Pro-Trainer software (Sports Motion, Inc., Atlantic Highlands, NJ). For subjects who could not complete the entire bout, the 40 steps immediately prior to the final minute were analyzed. We did not use the gait data during the initial 8 min to allow extra time for accommodation as previous studies have demonstrated that gait characteristics during treadmill walking stabilize within this time period [21,22]. Spatio-temporal gait variables were calculated based on the timing of touchdown and toe-off [23]. The six gait variables of interest included step frequency, step length, stance time, swing time, cycle time and double-support time. The mean value of the 40 steps for each variable was used to represent general gait characteristics. In addition, the variability and left–right symmetry of five gait variable (step length, stance time, swing time, cycle time and double-support time) were quantified. The variability and symmetry of step frequency were not reported to avoid redundancy to step length variables since the walking speed was held constant by the treadmill. Standard deviation (SD) and coefficient of variation (CV) of the 40 steps were employed to measure variability [24–26]. Symmetry was also computed using two methods: symmetry index (SI) (Eq. (1)) [27] and symmetry angle (SA) (Eqs. (2) and (3)) [28] to indicate the degree of left–right difference:

$$SI = \frac{|x_R - x_L|}{0.5(x_R - x_L)} \times 100\% \quad (1)$$

$$\text{if } \alpha \leq 90^\circ, \quad SA = \frac{|\alpha|}{90^\circ} \times 100\% \quad (2)$$

$$\text{if } \alpha > 90^\circ, \quad SA = \frac{|\alpha - 180^\circ|}{90^\circ} \times 100\% \quad (3)$$

where x_R is the variable of the right leg, x_L is the variable of the left leg, and $\alpha = 45^\circ - \tan^{-1}(x_L/x_R)$. The SA has been proposed as a more robust method than SI and is not prone to problems due to normalization [28]. An SA value of 0% indicates perfect symmetry while 100% indicates that the values of the left and right sides are of equal and opposite magnitude.

2.4. Statistical analysis

All statistical analyses were performed in SPSS version 16.0 (SPSS Inc., Chicago, IL). Descriptive statistics were calculated for each gait variables. Paired *t*-tests were used to identify difference between the beginning and the end of the protocol. Statistical significance was set at 0.05. Data are expressed in mean (SD).

3. Results

The general spatio-temporal gait characteristics did not differ between the beginning and the end of the protocol (Table 2). Gait variability of the double-support time increased at the end as measured by both SD (P = 0.037) and CV (P = 0.030) but no change was observed for other variables (Table 3). Left–right symmetry measured using either SI or SA did not differ between sessions

Table 1
Morphometrics and demographics of the subject pool.

	Male (n = 14)	Female (n = 5)
Age (year)	28.1 (5.3)	25.8 (1.1)
Height (cm)	179.1 (7.1)	164.3 (6.6)
Mass (kg)	79.6 (13.5)	54.8 (3.6)
BMI (kg m^{-2})	24.1 (3.9)	20.2 (0.9)
VO_{2max} (ml min^{-1} kg^{-1})	50.4 (7.1)	46.3 (10.1)

BMI: body mass index and VO_{2max}: maximum oxygen consumption.

Table 2
Spatio-temporal gait characteristics in the beginning and at the end of a 50-min treadmill walk in thermal protective clothing in the heat.

Variable	Beginning	End
Step frequency (Hz)	1.73 (0.10)	1.73 (0.10)
Step length (m)	0.73 (0.04)	0.73 (0.04)
Stance time (ms)	761 (61)	754 (42)
Swing time (ms)	400 (57)	408 (29)
Cycle time (ms)	116 (66)	116 (65)
Double-support time (ms)	180 (49)	173 (15)

Table 3
Gait variability at the beginning and at the end of a 50-min treadmill exercise in thermal protective clothing in the heat.

Variable	Standard deviation (SD)		Coefficient of variation (CV)	
	Beginning	End	Beginning	End
Step length	0.02 (0.01) m	0.02 (0.01) m	2.73 (0.77)%	3.01 (0.72)%
Stance time	14 (3) ms	15 (3) ms	1.88 (0.44)%	2.03 (0.48)%
Swing time	14 (3) ms	16 (5) ms	3.64 (0.94)%	3.91 (1.07)%
Cycle time	18 (5) ms	19 (5) ms	1.56 (0.47)%	1.60 (0.42)%
Double-support time	11 (2) ms	13 (3) ms[a]	6.51 (1.51)%	7.65 (2.07)%[a]

[a] Significant difference between the beginning and the end ($P < 0.05$).

Table 4
Gait symmetry in the beginning and at the end of a 50-min treadmill walk in thermal protective clothing in the heat.

Variable	Symmetry index (SI) (%)		Symmetry angle (SA) (%)	
	Beginning	End	Beginning	End
Step length	0.57 (0.47)	0.71 (0.60)	0.72 (0.59)	0.91 (0.76)
Stance time	0.30 (0.23)	0.31 (0.26)	0.39 (0.29)	0.39 (0.33)
Swing time	0.59 (0.42)	0.57 (0.50)	0.75 (0.53)	0.73 (0.64)
Cycle time	0.01 (0.01)	0.01 (0.02)	0.01 (0.01)	0.02 (0.02)
Double-support time	1.01 (0.95)	1.32 (1.16)	1.28 (1.21)	1.67 (1.48)

(Table 4). A post hoc ANOVA conditioned on time (pre vs. post) and sex (male vs. female) was performed. Male subjects displayed longer double-support time when compared to females ($P = 0.039$) while females displayed higher double-support time variability as measured by CV ($P = 0.023$). However, there was no time × sex interaction indicating males and females responded to the onset of fatigue during exercise in TPC and SCBA in the same manner.

Five subjects were unable to complete the entire 50-min protocol due to fatigue resulting in a mean walk time of 48.1 (3.6) min. On closer examination, we failed to identify a consistent pattern or difference between these five and the remainder of the group that completed the entire protocol. In addition, participants were markedly heat stressed and hypohydrated at the termination of the exercise session as evidenced by physiological and subjective measurements. Mean termination heart rate was 167 (19) beats per minute and peak core temperature was 38.9 (0.5) °C. Subjects lost 1.1 (0.4) kg of body water during the treadmill exercise [29]. Subjects rated their perceived exertion increased at 3 (1) after 10 min of exertion to 8 (2) during the final minute of treadmill exercise using the 0–10 OMNI scale.

4. Discussion

The present study compared the spatio-temporal gait characteristics in a fatigue/hypohydrated and non-fatigue/euhydrated state during treadmill walking in heat while wearing firefighting TPC and SCBA. This is the first study to examine the effect of fatigue on the biomechanics of walking while wearing firefighting equipment using an operationally relevant protocol incorporating heat stress and physical exertion. At the end of the 50-min walking protocol, we found increased variability in the double-support time but did not observe any changes in general gait characteristics of left–right symmetry when compared to the beginning of the exercise period. Examination of the five subjects who did not complete the entire 50-min protocol failed to reveal a consistent pattern or difference between these five and the remainder of the group that completed the entire protocol.

4.1. General gait characteristics

At the end of the walking protocol, subjects experienced significant fatigue resulting from hyperthermia, hypohydration, and cardiovascular stress as evidenced by elevated heart rate, core temperature, and perceived rating of exertion. Prior studies of exercise in uncompensable heat stress have defined the exhaustion secondary to heat strain as the inability to continue the exercise protocol. Endpoint criteria typically range from core temperatures of 39.5 to 40.0 °C and heart rates approaching 95% maximal heart rate [17,30]. Data from the present report are consistent with those criteria indicating that the subjects suffered significant hyperthermia and cardiovascular fatigue.

While previous studies have shown that prolonged running on a treadmill often leads to changes in stride length and/or frequency [31,32], fatigue does not seem to influence the spatio-temporal characteristics during walking. We did not detect changes in any spatio-temporal gait characteristics after 50 min of treadmill walking in TPC and SCBA when compared to the beginning of the exercise period. Another study found no difference in step length, step frequency, stance time or double-support time during treadmill walking before and after a 30-min bout of running [33]. Similarly, in a study of school boys walking under a load carrying condition, there was no change in velocity, cadence, step length, stance time, swing time, single- or double-support time after a prolonged overground walk (approximately 2 km) carrying loads up to 20% of body weight [34]. Thus, despite the fatigue and hypohydration induced by prolonged walking in heat while wearing heavy firefighting equipment, these data are consistent with previous studies that spatio-temporal gait variables remain unaffected during walking. Other biomechanical variables such as plantar pressure [33] and joint kinematics [35] may be more sensitive to physiological fatigue.

It is interesting to note that 11 subjects decreased step length by 0.015 (0.008) m while eight subjects increased step length by 0.022 (0.021) m in response to fatigue resulting in a negligible change in step length for the cohort. Similar opposite individual responses were also observed in a previous study on older adults where nine subjects demonstrated longer, while four demonstrated shorter, cycle time during the second half of a 3-h prolonged free walk [13]. These data demonstrate the high individual variation in adaptation strategies during walking in a fatigue condition.

In the present study, treadmill exercise forced the artificial condition of constant speed. However, to study exercise in TPC and SCBA in a hot environment while collecting high resolution physiologic data required a laboratory setting. Different adaptations in gait pattern may be observed in a free walking environment where both step length and step frequency can vary simultaneously. Decreased walking speed can be a compensatory strategy to improve local dynamic stability in order to prevent falling [36]. It is reasonable to assume that subjects will slow down during overground walking as they become fatigued. A study by Hong and Cheung [30], however, showed that school boys carrying loads up to 20% of body weight did not change their walking speed after 2 km of overground walk. It could be argued that subjects in the present study carried heavier load (approximately 25% of body weight) and exercised at a higher ambient temperature and for a longer duration than the study by Hong and Cheung [30]. Thus, decrease in speed and changes in other gait variables may be seen during overground walking. Future studies are needed to confirm this.

4.2. Gait variability

Gait variability has been successfully used to retrospectively distinguish fallers and non-fallers [6–11] as well as prospectively predicting falls [5]. We hypothesized that fatigue would lead to an increase in gait variability. We found increased variability in the double-support time supporting our hypothesis that fatigue can lead to gait instability and that firefighters may be more prone to a fall after operating in heat for an extensive period of time. The fact that increased variability was only observed in one out of the five variables measured, however, questions the confidence in the response of spatio-temporal gait variability to fatigue. It is interesting to note that no main effect of sex was found in double-support time variability as measured by SD despite the difference seen in CV. This may be the result of an artificial inflation effect resulting from dividing by a smaller number ($CV = SD/mean \times 100\%$) since females had a shorter double-support time.

There are very limited studies in the literature examining the effect of fatigue on gait variability. In a study investigating gait characteristics in older adults, an increase in step length variability but not step width variability was seen after repeated sit-to-stand until volitional fatigue [14]. Another study comparing gait cycle time variability during 3 h of free walking among older adults also demonstrated a split response. Some subjects displayed increases while others displayed decreases in gait cycle time variability [13]. These data, together with those in the present study, suggest a potential relationship between spatio-temporal gait variability and physiological fatigue. Future studies are needed to clarify the differences among gait variables and to investigate the possible influence of individual variation.

4.3. Gait symmetry

We did not observe changes in left–right symmetry between the beginning and the end of the protocol. One study showed that elderly fallers displayed greater gait asymmetry than healthy elderly controls [12]. However those findings are difficult to interpret since the healthy control group was nearly 10 years younger than the fallers. Our data show a high degree of symmetry (indicated by low SI and SA values) compared with those of kinetic and kinematic variables observed in other studies [27,28]. This suggests that spatio-temporal gait variables during walking are highly symmetrical and are relatively insensitive to fatigue as measured in this population and under these conditions. It is worth noting that the two methods (SI and SA) we used to quantify left–right gait symmetry yield the same findings for all measured variables. While the SI has been criticized to be sensitive to the reference values used in normalization, this may not influence our results since spatio-temporal gait variables are highly symmetrical [28].

4.4. Conclusions

This study compared the spatio-temporal gait characteristics of individuals at the beginning and end of walking on the treadmill in heat while wearing firefighting thermal protective clothing (TPC) and SCBA. General spatio-temporal gait characteristics and left–right symmetry are insensitive to hypohydration, hyperthermia, and physiological fatigue. However, prolonged walking in heat while wearing TPC and SCBA may alter gait variability of double-support time increasing the likelihood of a fall. Future studies are needed to confirm the potential relationship between hypohydration, hyperthermia, fatigue, equipment configuration, and gait variability and to investigate the possible influence of individual variation and the potential relationship to falls and fall-related injuries among firefighters.

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Conflict of interest statement

No personal relationship or financial support from any organizations would inappropriately influence this study.

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