Title: Exercise heat acclimation and post-exercise hot water immersion improve resting and exercise responses to heat stress in the elderly.

Running title: Heat adaptation in the elderly

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Figures: One

Tables: Two

Abstract word count: 248

Word count: 3088

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Abstract

Objectives: To investigate the efficacy of heat acclimation (HA) in the young (Y_{EX}) and elderly (E_{EX}) following exercise-HA, and the elderly utilising post-exercise hot water immersion HA (E_{HWI}).

Design: Cross-sectional study.

Method: Twenty-six participants (Y_{EX}: n=11 aged 22±2 years, E_{EX}: n=8 aged 68±3 years, E_{HWI}: n=7 aged 73±3 years) completed two pre/post-tests, separated by five intervention days. Y_{EX} and E_{EX} exercised in hot conditions to raise rectal temperature (T_{rec}) ≥38.5°C within 60 min, with this increase maintained for a further 60 min. E_{HWI} completed 30 min of cycling in temperate conditions, then 30 min of HWI (40°C), followed by 30 min seated blanket wrap. Pre and post-testing comprised 30 min rest, followed by 30 min of cycling exercise (3.5 $W.kg^{-1}$ $\dot{H}_{prod}$), and a six-minute walk test (6MWT), all in 35°C, 50% RH.

Results: The HA protocols did not elicit different mean heart rate (HR), T_{rec}, and duration T_{rec} ≥38.5°C ($p>0.05$) between Y_{EX}, E_{EX}, and E_{HWI} groups. Resting T_{rec}, peak skin temperature, systolic and mean arterial pressure, perceived exertion and thermal sensation decreased, and 6MWT distance increased pre to post HA ($p<0.05$), with no difference between groups. Y_{EX} also demonstrated a reduction in resting HR ($p<0.05$). No change was observed in peak T_{rec} or HR, vascular conductance, sweat rate, or thermal comfort in any group ($p>0.05$).

Conclusions: Irrespective of age or intervention, HA induced thermoregulatory, perceptual and exercise performance improvements. Both exercise-HA (E_{EX}), and post-exercise HWI (E_{HWI}) are considered viable interventions to prepare the elderly for heat stress.

Introduction

A combination of an increasingly warmer global climate and sedentary behaviour leading to poor physiological conditioning, make the elderly (>65 years old) vulnerable to heat-related illness during the more frequent and longer-lasting periods of hot weather (i.e. heat waves).[1-3] The elderly are at particular risk during heat wave due to specific age-related deteriorations in their thermoregulatory responses relative to the young. These include decreased cardiac output, a deterioration of autonomic responses and peripheral vascular responsiveness to heat stress, ultimately impairing skin blood flow (SkBF).[3] Furthermore, relative to the young the elderly demonstrate diminished sweat responses, eliciting increased heat storage, rises in core temperature and cardiovascular strain, and a concurrent risk of heat-related illness.[3] The elderly also demonstrate impaired perceptual responses to heat stress which may impair behavioural responses.[4] These factors contribute to multi-organ failure that leads to excess deaths in the elderly during heat waves.[1,2]

Heat acclimation (HA) is considered an effective strategy for mitigating against the previously stated responses to heat strain.[5] HA develops physiological adaptations, including decreased resting and exercise heart rate, and core and skin temperature, increased SkBF, hypervolemia, enhanced sweat sensitivity, output and efficiency.[5] HA also improves perceptual responses to heat, and can improve exercise capacity.[6] Despite HA being a prevalent strategy implemented in athletes and occupational/military personnel to mitigate heat stress,[7-9] and evidence that the elderly can adapt to seasonal temperature change,[10] elderly HA research remains limited.[11-15]

An experiment examining the benefits of three, one hour daily fixed intensity exercise-heat HA sessions in untrained elderly females deemed this approach insufficient (in dose) to induce adaptation.[11] A greater HA dose, specifically nine 90-120 min fixed intensity exercise-heat sessions, demonstrated that trained old participants made comparable adaptations to younger participants during passive heat stress.[12] Furthermore, whilst eight days of 90 min fixed intensity HA induced adaptation in trained young and elderly males, and untrained elderly males, sudomotor adaptations were greater in the young and trained elderly groups.[13] The untrained elderly cohort, whom represent the most at risk population during heat waves, demonstrating an inferior response.[13] This age-fitness interaction has been observed by others[14] who noted that temperature and sweat loss adaptations to six, one hour exercise HA sessions was not uniformly impacted by age, though age did inhibit the adaptive peripheral cardiovascular response, including cutaneous vascular conductance (CVC). It would also appear that peripheral adaptations to the sweat gland are limited in older individuals undertaking exercise HA (targeting a +0.9°C increase in core temperature) for nine days.[15]

That study reported sudomotor responses to iontophoresis during passive heating as unchanged after HA, and whilst maximal ion absorption improved, this decayed within seven days.[15] The success of the longer duration protocols i.e. six to nine sessions[12-15], over shorter protocols i.e. three sessions[11], points to the need to investigate the minimum dose required for adaptation.

Further to the additional investigation of the timecourse of adaptations arising from exercise-HA interventions, real-world implementation of HA in the elderly necessitates consideration of accessibility and efficacy issues. The use of passive heating/hot water immersion (HWI) is not a new concept for adapting people to the heat, though it has not been well investigated in the elderly. Exercise is a potent stimuli to improve the physiological profile of older individuals and seems important to retain in an intervention where the participant will be subsequently exercising in the heat.[9] Recently six days of post-exercise HWI was reported to have improved thermoregulatory responses during submaximal exercise in hot conditions in the young.[16] From a practical perspective, post-exercise passive HWI is likely achievable for the majority of the elderly population, and safety considerations aside has the potential to be completed at home. Therefore in addition to further understanding adaptations to exercise-HA, a HWI HA intervention also warrants investigation.

This study sought to investigate the efficacy of HA in the young (Y_{EX}) and elderly (E_{EX}) following exercise-HA, and the elderly utilising post-exercise HWI HA (E_{HWI}). The hypothesis was that the younger exercise HA group, elderly exercise HA group, and post exercise HWI HA in the elderly would induce heat adaptation.

Methods

Twenty-six recreationally active participants volunteered for the study (for group characteristics, see Table 1), which was completed outside of the UK summer months. The experimental protocol was approved by the University ethics committee and conducted in accordance with the principles of the 2013 revision of the Declaration of Helsinki. *A priori* power analysis selecting conventional α (0.05) and β (0.20) levels observed that based on previous work,[17] eight participants in each group were required to detect pre-post HA differences in resting and peak rectal temperature (T_{rec}), and resting and peak heart rate (HR). Participants provided written informed consent, passed a medical questionnaire and subsequently refrained from caffeine (12h), alcohol/strenuous exercise (24h) and arrived euhydrated (urine osmolality <700 mOsm.kg^{-1}) to testing sessions which were conducted in a climate-controlled chamber (TISS, UK).

[Add Table 1 near here please]

Participants completed two preliminary visits separated by 48 hours (pre-test 1, and pre-test 2), five consecutive intervention days, and two visits commencing 48 hours following the intervention (post-test 1, and 24 hr later post-test 2). During pre-test 1, anthropometric (height, nude body mass [NBM], and four site skin fold thickness for body fat [BF] (Harpenden, UK)[4] and baseline measurements (Electro cardio-gram [ECG, elderly], T_{rec}, [Henley Medical, UK], skin temperature [T_{skin}, Eltek Ltd, UK] and HR [Polar Electro, RS800, Finland]) were recorded in line with previously reported techniques.[4] To familiarise participants with the forearm SkBF technique, a 30 min resting exposure to 35°C/50% relative humidity (RH) followed. Systolic and diastolic blood pressure (SBP, DBP, Omron, M4, Japan) were recorded after 20 min to calculate CVC. After rest, a graded exercise test (GXT) was completed.[4] In brief, ~45 sec respiratory gas was collected during rest and the end of each incremental cycling stage (initial stage: young; 50W, elderly; 25W, increments: young; 25W, elderly; 15W) to calculate individualised resting metabolic equivalents (MET) and exercise intensities eliciting 6 METs and 3.5 W.kg^{-1} metabolic heat production ($\dot{H}_{prod}$) for use during pre-test 2. Participants then completed a six-minute walk test (6MWT) on a treadmill (Woodway Pro, Germany), for familiarisation. The 6MWT commenced at 3km.h^{-1}, with participants subsequently adjusting the speed in ±0.2km.h^{-1} increments. These procedures were all repeated during post-test 1. For pre/post-test 2, participants completed a 'simulated activities of daily living protocol'[4] i.e. 30 min rest and 30 min recumbent cycling at 6 METs/3.5 W.kg^{-1} $\dot{H}_{prod}$, followed by the 6MWT as a measure of exercise performance that could be undertaken by all participants, all within a 35°C/50% RH environment. During rest, laser doppler (moorVMS-LDF, Moor Instruments, UK) was used to calculate SkBF. At baseline and throughout testing HR, T_{rec}, and T_{skin} were recorded every 5 min and rating of perceived exertion (RPE), thermal sensation (TS), thermal comfort (TC) were recorded every 10 min as outlined in our previous work.[4] To further characterise the dose of each intervention, area under the curve at T_{rec} = 38.5°C (AUC)[18] and thermal impulse[5] were calculated from T_{rec} data.

Daily HA commenced at the same time each day. Following hydration and baseline physiological measurements, on day 1 and day 5 of HA, triplicate capillary blood samples were taken from willing participants (Y_{EX} n=10, E_{EX} n=7, E_{HWI} n=6) to determine plasma volume (PV) changes from haemoglobin [Hb] and haematocrit [Hct]. Exercise HA [young (Y_{EX}), elderly (E_{EX})] occurred within a 35°C/50% RH environment. Participants exercised on a cycle ergometer (Monark 824E, Sweden) using relative exercise intensities (Y_{EX}; men=2.3 $W.kg^{-1}$, women=2.0 $W.kg^{-1}$ [T_{rec}+0.014±0.003°C.min^{-1}], E_{EX}; men=1.5 $W.kg^{-1}$ and women=1.2 $W.kg^{-1}$ [T_{rec}+0.010±0.003°C.min^{-1}]) to increase T_{rec} to 38.5°C (or +1.5°C if baseline T_{rec} = <36.5°C) within 60 min and maintain the increase for an additional 60 min. If the prescribed exercise intensity could not be maintained, then it was reduced to enable exercise continuation. Elderly participant BP was checked throughout and a rest period of 5 min occurred after 30 min of exercise for all participants. Participants were supported as they dismounted the cycle ergometer and were encouraged to move slowly to avoid dizziness. During the HWI intervention (E_{HWI}), identical relative exercise intensities were used during 30 min of cycle ergometry within normothermic conditions (~23°C, 60% RH) though it was not an experimental objective to increase T_{rec} as within the E_{EX} group, end exercise T_{rec} in the E_{HWI} group was ~37.9°C (+0.7-1.0°C; T_{rec}+0.008±0.003°C.min^{-1}). After exercise, E_{HWI} participants completed 30 min of HWI (40°C) within an inflatable bath filled so that water level was approximately to the sternum (mean T_{rec} +0.5°C). For safety, upon completion of HWI, BP was assessed, and participants remained in the bath during emptying. Participants exited the bath slowly with assistance, after drying and changing, they sat covered in blankets for 30 min.

All data are presented as mean ± SD and were assessed for normality and sphericity prior to further statistical analyses. When the assumption of sphericity was violated the Greenhouse-Geisser adjustment was used. For parametric data, one-way between groups ANOVA, and Bonferroni pairwise comparisons were used to determine differences in baseline characteristics between groups, intervention data, and the pre-post change in dependent variables between groups. The Kruskal-Wallis test and Wilcoxon signed ranks were used in place of one-way ANOVA for non-parametric data. Mixed two-way ANOVA [time (2; pre and post)*group (3; Y_{EX}, E_{EX}, E_{HWI})] were used to analyse changes before and after the intervention. Bonferroni-corrected post-hoc comparisons were completed if interaction and main effects were observed. Following a main effect for time, two-one-sided t-tests' equivalence testing (TOST)[19] utilising individual Hedges *g* effect sizes (per dependent variable) from a published meta-analysis[6] were used alongside 95% confidence intervals to identify similarity. For all analyses, significance was set at $p<0.05$.

Results

Participants. By design, participants in the E_{EX} and E_{HWI} groups were older ($p<0.05$) than Y_{EX} with effective matching for NBM, BMI and BSA across groups. In addition to age, there was a significant difference between Y_{EX} and E_{HWI} for height and body fat, and between E_{EX} and E_{HWI} for age and height (Table 1).

Heat acclimation intervention. Mean HR (%HR_{max}), mean T_{rec}, mean duration T_{rec} ≥38.5°C, T_{rec} AUC38.5°C and mean whole body sweat rate (WBSR) (%NBM.hr^{-1}) were not different between groups/interventions ($p>0.05$). Group differences ($p<0.05$) were observed between Y_{EX}, and E_{EX} and E_{HWI} for mean exercise duration and mean HR (b.min^{-1}), mean RPE, mean TC, and mean TS, and Y_{EX} and E_{HWI} for mean thermal impulse. E_{EX} and E_{HWI} differed ($p<0.05$) in mean exercise duration, mean thermal impulse and mean HR (b.min^{-1}) (Table 1).

[Add Table 2 near here please]

Pre and Post testing. An effect of time ($p<0.05$) was observed between pre-post HA highlighting a reduction in resting T_{rec}, peak T_{skin}, resting HR, SBP and mean arterial pressure (MAP), RPE, and TS, and an increased 6MWT distance. Interaction effects were observed whereby resting HR was lower at post HA in Y_{EX} only (Table 2). Between group differences ($p<0.05$) were observed for the magnitude of change in resting T_{skin}, DBP, MAP, and 6MWT distance. Post hoc analysis observed group differences whereby resting and peak T_{skin}, peak HR, and DBP and MAP were different between Y_{EX} and E_{HWI}. Resting T_{skin} was different between E_{EX} and E_{HWI}. When comparing pre-post changes between groups (Figure 1), a group effect was observed for resting HR where Y_{EX} was different to E_{EX} ($p<0.001$). No difference in pre-post HA change was observed in the for rest T_{rec} or T_{skin}, peak T_{rec}, T_{skin}, HR, PV, WBSR, SBP, DBP, MAP, CVC, RPE, TS, TC or 6MWT distance between groups ($p>0.05$) (Figure 1). TOST analysis identified no significant differences ($p>0.05$), thus whilst the change was *not different* following ANOVA between groups, it is not possible to state that the response was *equivalent*.

[Add Figure 1 near here please]

Discussion

This study implemented an exercise-HA protocol with the elderly for five consecutive days and examined adaptations to a young group completing a comparable exercise-HA protocol. Also, examined were the benefits of post exercise HWI in the elderly. All groups demonstrated acclimation via a reduction in resting T_{rec} during the post-test simulated activities of daily living protocol, and improved performance during the subsequent 6MWT. Peak T_{rec} and HR was not reduced at the end of simulated activities of daily living protocol, therefore the protocol did not completely reduce the thermal strain of participants. Further consideration of intensity, duration and application of thermal stress to induce adaptations is therefore required in the elderly.

Central to understanding the efficacy of a heat adaptation intervention is evoking the potentiating stimuli for adaption i.e. elevated T_{rec} and T_{skin}, and elevated sweat rates.[5] Though T_{skin} was not measured during intervention visits, and thermal impulse differed between EX and HWI trials, mean HR, T_{rec}, duration T_{rec} ≥38.5°C, AUC38.5°C and WBSR responses did not differ between groups during the intervention. To support efficacy considerations between E_{EX} and E_{HWI} these two groups also did not differ with regards to mean duration T_{rec} +1.5°C and RPE, TC, TS. The mean thermal,[16,20-22] and sudomotor[16,20-22] stimuli (Table 1) was similar to previous work which have demonstrated heat adaptation within a five-day isothermic/HWI HA interventions. The similarity in thermal stimuli between our groups and the cited previous experimental work gives confidence that an effective dose of HA was administered.

The ability for young healthy individuals to adapt to heat has been well evidenced.[6] This experiment adds to the comparatively small body of work examining the capacity for acclimation in elderly adults. The maximal observed changes in resting T_{rec} within both E_{EX} (-0.33°C) and E_{HWI} (-0.39°C) interventions are similar to Y_{EX} (-0.30°C) and that which might be expected from equivalent duration interventions in the young.[7] It should be noted that the greatest change occurred on day 5 of HA, rather than during the post test. The timing and impact of the other intense post-tests on T_{rec} e.g. GXTs, may therefore be relevant considerations for future experimental work in the elderly. Reductions in resting HR in Y_{EX} (-11±8 b.min^{-1}) were not observed in E_{EX} and E_{HWI} though this is unsurprising as *i)* the variability in PV expansion led to insignificant group changes[5] and *ii)* age-related impairments in cardiovascular adaptations to HA have been established.[14] Likewise CVC did not change, suggesting that no intervention modified the baseline SkBF response in the same manner as evidenced following longer interventions in younger vs older trained individuals.[14] Together these data indicate the likely need to increase the intervention duration to improve cardiovascular responses to heat stress in the elderly effectively. The reduction of physiological strain likely facilitated the improved TS and RPE during the 6MWT, and exercise capacity for the same cardiovascular strain occurred to improve 6MWT performance by ~10% in E_{EX} and E_{HWI} compared to Y_{EX} (+4%). The null WBSR response may be an artefact of the short-term intervention, with longer interventions demonstrating larger magnitudes of sudomotor adaptation.[9] The null WBSR response, and the relatively short duration (30 min exercise) of the fixed intensity post test protocol[22], are probable reasons for the null response in peak T_{rec}. An interesting additional finding was the improvement in SBP and MAP, which adds to the increasing body of support for heat as a supplemental stimuli to exercise for improving cardiovascular health.[23]

Given logistical challenges in administering exercise-HA in the elderly, this study sought to understand whether post exercise HWI would be an appropriate alternative (at a physiological level). With the exceptions of resting T_{skin}, few statistical differences occurred between adaptations observed in E_{EX} and E_{HWI} groups supporting this proposal. The ability for post exercise HWI to induce adaptations which do not differ in magnitude to EX protocols for a lesser impulse is a noteworthy experimental consideration for future HA work. Irrespective of intervention type, this experiment enhances our understanding of the number of sessions required to induce heat adaptations. With three days of HA proving insufficient in females,[11] the use of a five day exercise HA/post exercise HWI protocol now appears to have some efficacy, though it remains likely that more complete adaptations will be achieved with longer protocols e.g. as observed using a nine day intervention.[12] In addition to clarifying the delayed induction peripheral cardiovascular adaptations, our data supports the notion that longer protocols should also be implemented to induce substantial changes in the sudomotor response, particularly in untrained elderly individuals.[13] To enable the elderly to engage with prolonged HA interventions, scheduling adjustments, for example intermittent day protocols may also be considered.[7] Further to known intraindividual variability in HA,[24] which may further increase with age, this study utilised a mixed-sex cohort which may have impacted the observed magnitude of adaptive response to a five day intervention given females may display a delayed temporal pattern to adaptation.[21] Visual inspection of the responses in females participants (Figure 1), does not necessarily support this within our cohort. Although some classical HA adaptations were evident after E_{EX} and E_{HWI}, further heat/exercise stimulus maybe required to develop greater magnitudes of adaptation and develop significant adaptation in other pertinent heat illness markers such as renal function[25] and gut-permeability.[26] Future work should investigate these variables, alongside cellular/molecular responses including heat shock proteins (HSPs) given the importance of HSPs in heat adaptation,[27] and age-related declines in HSP inducibility.[28]

Given increased exercise prescription is required for exercise HA, elderly HA using the HWI model could be the focus for future work to provide a more logistically viable intervention. This intervention should be assessed against younger individuals, with the absence of this direct comparison a limitation of the current study. Further consideration of the intervention data (Table 1) also acknowledges that despite a lack of statistical difference, the Y_{EX} and E_{HWI} group experienced numerically different stimuli, yet comparable adaptive responses were induced. This may be an artefact of the elderly possessing a lower threshold for adaptation, thus adapting effectively to 'reduced' stimuli relative to the young. This may be advantageous for this cohort, and examination of the required absolute thresholds for adaptation in this population would provide mechanistic and applied insight. In addition, future elderly HA research should investigate the possibility of age-related differences in the time-course of heat adaptation/retention/decay/re-acclimation. In a young population, re-acclimation develops the same or greater magnitude of adaptations to the heat when compared to the original HA.[29] Therefore, re-acclimation/acclimation memory is a pertinent future direction for elderly HA. Furthermore, chronic interventions such as HA should be examined against, and in conjunction with, acute heat alleviation interventions[30] in the elderly to further guide health policy.

Conclusion

This study showed exercise HA develops improvements in physiological (reduced resting T_{rec}, peak T_{skin}, resting HR, SBP and MAP), perceptual (reduced RPE and TS) and exercise performance (increased 6MWT distance) responses to heat stress in the young and elderly. Furthermore, a novel post-exercise HWI protocol elicits improved responses to heat stress suggests its also a viable intervention to prepare the elderly for heat waves.

Practical implications

- Five sessions of exercise heat acclimation induced improvements in physiological, perceptual and exercise performance responses during heat stress in young and elderly participants.
- The implementation of post exercise hot water immersion also induced thermoregulatory, perceptual and functional improvements in the elderly.
- Future work should investigate practical heat acclimation strategies across a broad spectrum of variables aligned to heat illness to further our understanding of the capacity for heat adaptation in older age, and guide mitigating strategies for heat illness risk in the vulnerable.

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Legends

Table 1. Mean ± SD Participant characteristics and summary data from each intervention by group (Y_{EX}; young exercise-HA, E_{EX}; elderly exercise-HA, E_{HWI}; elderly HWI). *=difference from Y_{EX}. †=different from E_{EX}.

Table 2. Mean ± SD (95% CI). Physiological and perceptual variables pre and post intervention for young exercise-HA (Y_{EX}), elderly exercise-HA (E_{EX}), and elderly HWI (E_{HWI}) groups.* represents a significant ($p<0.05$) with group difference from Pre. ^ represents a significant ($p<0.05$) overall difference from Pre. # represents a significant ($p<0.05$) difference compared to Y_{EX} within timepoint. $ represents a significant ($p<0.05$) overall difference from Y_{EX}. † represents a significant ($p<0.05$) difference compared to E_{EX} within timepoint. ‡ represents a significant ($p<0.05$) overall difference from $E_{EX.}$

Figure 1. Mean ± 95% CI. Change in physiological and perceptual variables pre and post intervention for young exercise-HA (Y_{EX}; circles), elderly exercise-HA (E_{EX}; diamonds), and elderly HWI (E_{HWI}; triangles) groups. Female participants are identified by open symbols. * Denotes individual group difference ($p<0.05$), ^ represents a significant ($p<0.05$) overall difference from Pre.

Acknowledgements

The authors wish to thank the study participants, researchers and staff for their contribution to the research. We would also like to that the Eastbourne Leisure Trust for their financial contribution to the research.

Figure 1

Click here to access/download;Figure;Figure 1 PrePost Change data (MF symbols).pdf

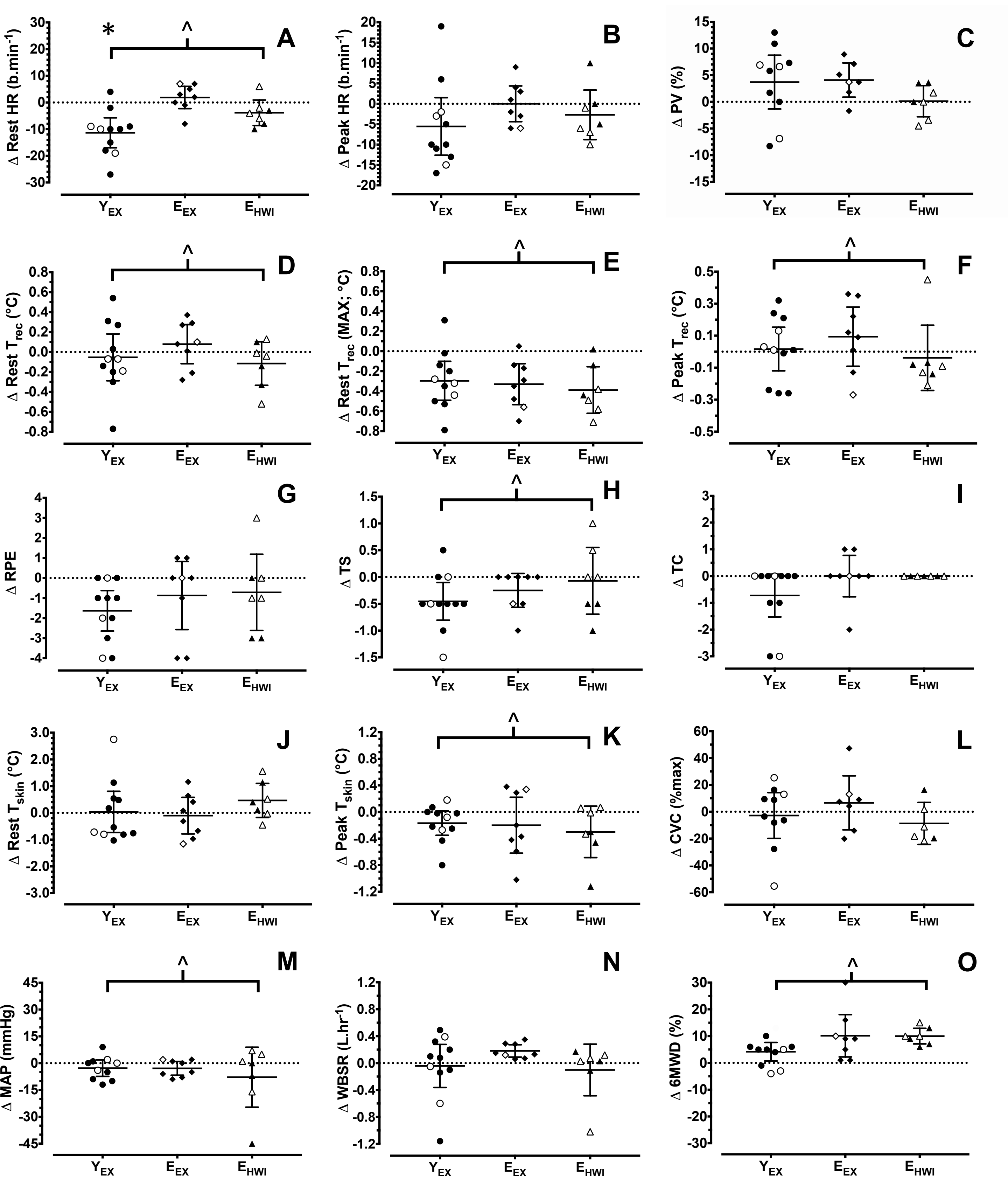

Table 1.

Participant characteristics	Young (Y_{EX})	Elderly (E_{EX})	Elderly HWI (E_{HWI})	Statistical summary
Sex (M/F)	8M, 3F	7M, 1F	3M, 4F	
Age (yrs)	22 ± 2	68 ± 3 *	73 ± 3 *†	F= 912.3, p < 0.001
Height (cm)	175 ± 6	175 ± 9	162 ± 7 *†	F= 8.8, p = 0.001
NBM (kg)	74.0 ± 13.5	74.1 ± 11.1	71.7 ± 20.4	F= 0.1, p = 0.942
BMI ($kg.m^2$)	23.9 ± 3.5	24.2 ± 2.8	27.1 ± 5.8	F= 0.5, p = 0.621
BSA (m^2)	1.89 ± 0.18	1.89 ± 0.17	1.75 ± 0.26	F= 1.2, p = 0.333
Body fat (%)	18 ± 7	18 ± 7	29 ± 10 *	F= 4.4, p = 0.025
Intervention summary				
Mean exercise duration (min)	109 ± 12	120 ± 0 *	30 ± 0 *†	F= 271.0, p < 0.001
Mean HR ($b.min^{-1}$)	144 ± 11	113 ± 9 *	100 ± 12 *†	F= 42.1, p < 0.001
Mean HR ($\%HR_{max}$)	73 ± 6	74 ± 5	68 ± 8	F= 2.3, p = 0.119
Mean T_{rec} (°C)	38.11 ± 0.15	37.91 ± 0.36	38.01 ± 0.13	F= 1.8, p = 0.191
Mean T_{rec} AUC 38.5°C ($°C.min^{-1}$)	4.5 ± 3.4	2.4 ± 3.4	3.1 ± 2.7	F= 1.0, p = 0.381
Mean thermal impulse ($°C.min^{-1}$)	2546 ± 459	2564 ± 549	1874 ± 464 *†	F= 4.9, p = 0.016
Mean duration T_{rec} ≥38.5°C (min)	31 ± 20	23 ± 24	15 ± 11	F= 1.5, p = 0.245
Mean duration T_{rec} ≥ +1.5°C (min)	53 ± 15	14 ± 12 *	5 ± 6 *	F= 37.7, p < 0.001
Mean WBSR ($\%NBM.hr^{-1}$)	1.2 ± 0.3	1.0 ± 0.3	1.1 ± 0.7	F= 0.7, p = 0.936
Mean RPE	12 ± 2	10 ± 3 *	9 ± 4 *	χ^2 = 10.8, p = 0.005
Mean TC	5 ± 1	2 ± 2 *	3 ± 2 *	χ^2 = 8.8, p = 0.012
Mean TS	6.3 ± 0.5	5.3 ± 0.5 *	5.0 ± 0.5 *	χ^2 = 11.1, p = 0.004

Table 1.
Abbreviations: M; male, F; female, NBM; nude body mass, BMI; body mass index, BSA; body surface area, BF; body fat, HR; heart rate, T_{rec}; rectal temperature, RPE; rating of perceived exertion, TC; thermal comfort, TS; thermal sensation. * represents a significant ($p < 0.05$) difference from Y_{EX}. † represents a significant ($p < 0.05$) difference from E_{EX}. Note RPE, TC and TS reported as median ± interquartile range.

Table 2.

	Pre Heat Acclimation			**Post Heat Acclimation**			**Pre-Post Heat Acclimation Change**			**Statistical outcomes**		
	Y_{EX}	E_{EX}	E_{HWI}	Y_{EX}	E_{EX}	E_{HWI}	Y_{EX}	E_{EX}	E_{HWI}	Time	Group	Group*Time
Rest T_{rec} (°C)	37.07 ± 0.42	37.08 ± 0.54	37.27 ± 0.29	37.02 ± 0.37	37.16 ± 0.45	37.16 ± 0.16	-0.05 ± 0.34 (-0.26 – 0.15)	+0.08 ± 0.23 (-0.08 – 0.24)	-0.12 ± 0.24 (-0.29 – 0.06)	F = 0.3, p = 0.607	F = 0.4, p = 0.647	F = 0.9, p = 0.419
Rest T_{rec} HA (°C)	36.96 ± 0.38	37.20 ± 0.43	37.40 ± 0.30	36.91 ± 0.30 ^	36.92 ± 0.50 ^	37.08 ± 0.20 ^	-0.04 ± 0.32 (-0.23 – 0.15)	-0.28 ± 0.26 (-0.46 – -0.10)	-0.33 ± 0.35 (-0.58 – -0.07)	F = 12.0, p = 0.002	F = 1.8, p = 0.182	F = 2.2, p = 0.133
Rest T_{rec} MAX (°C)	37.15 ± 0.35	37.25 ± 0.48	37.40 ± 0.30	36.85 ± 0.33 ^	36.92 ± 0.50 ^	37.02 ± 0.17 ^	-0.30 ± 0.29 (-0.47 – -0.12)	-0.33 ± 0.25 (-0.50 – -0.16)	-0.39 ± 0.25 (-0.58 – -0.20)	F = 40.2 , p < 0.001	F = 0.8, p = 0.471	F = 0.3, p = 0.777
Peak T_{rec} (°C)	37.38 ± 0.25	37.52 ± 0.45	37.81 ± 0.33	37.41 ± 0.28	37.62 ± 0.38	37.77 ± 0.24	+0.03 ± 0.20 (-0.10 – 0.14)	+0.09 ± 0.22 (-0.06 – 0.25)	-0.04 ± 0.22 (-0.20 – 0.12)	F = 0.3, p = 0.581	F = 3.4, p = 0.052	F = 0.7, p = 0.490
Rest T_{skin} (°C)	30.35 ± 0.82	30.74 ± 0.73	31.24 ± 0.62 $‡	30.38 ± 0.58	30.63 ± 0.97	31.71 ± 0.58 $‡	0.04 ± 1.14 (-0.64 – 0.71)	-0.10 ± 0.82 (-0.67 – 0.46)	0.47 ± 0.69 (-0.05 – 0.98)	F = 0.5, p = 0.484	F = 8.5, p = 0.002	F = 0.7, p = 0.488
Peak T_{skin} (°C)	36.19 ± 0.31	36.25 ± 0.13	35.97 ± 0.44 $	36.03 ± 0.28 ^	35.98 ± 0.50 ^	35.69 ± 0.71 ^$	-0.17 ± 0.27 (-0.33 – -0.01)	-0.27 ± 0.58 (-0.55 – 0.15)	-0.28 ± 0.40 (-0.60 – 0.01)	F = 7.9, p = 0.010	F = 5.1, p = 0.14	F = 0.2, p = 0.786
Rest HR ($b.min^{-1}$)	72 ± 11	62 ± 13	71 ± 11	61 ± 8 *	64 ± 13	67 ± 12	-11 ± 8 (-16 – -6)	+2 ± 5 (-2 – 5)	-4 ± 5 (-8 – 0)	F = 11.0 , p = 0.003	F = 0.6, p = 0.572	F = 9.2, p = 0.001
Peak HR ($b.min^{-1}$)	129 ± 15	110 ± 19	122 ± 20	123 ± 14	110 ± 22	118 ± 21	-6 ± 10 (-12 – 1)	+0 ± 5 (-4 – 4)	-4 ± 5 (-8 – 2)	F = 2.8, p = 0.107	F = 2.0, p = 0.156	F = 1.1, p = 0.361
Peak HR ($\%HR_{max}$)	64.9 ± 7.5	72.2 ± 12.7	83.0 ± 14.3 $	62.1 ± 7.3	72.0 ± 14.6	80.2 ± 14.5 $	-2.8 ± 5.3 (-8 – -3)	-0.2 ± 3.4 (-1 – 3)	-2.8 ± 3.6 (-5 – 1)	F = 2.4, p = 0.132	F = 5.1, p = 0.015	F = 0.8, p = 0.446
PV (%)	-	-	-	-	-	-	+ 3.7 ± 7.1 (-0.5 – 7.9)	+ 4.1 ± 3.5 (1.7 – 6.5)	+ 0.1 ± 3.2 (-2.2 – 2.5)		F = 1.3, p = 0.304	
WBSR ($L.h^{-1}$)	1.07 ± 0.35	0.73 ± 0.14	1.07 ± 0.58	1.03 ± 0.38	0.92 ± 0.20	0.96 ± 0.41	-0.04 ± 0.48 (-0.32 – 0.24)	+0.18 ± 0.11 (0.11 – 0.26)	-0.10 ± 0.41 (-0.41 – 0.21)	F = 0.0 , p = 0.873	F = 1.3, p = 0.281	F = 1.2, p = 0.320
SBP (mmHg)	122 ± 19	121 ± 10	139 ± 28	119 ± 14 ^	114 ± 13 ^	130 ± 30 ^	-3 ± 12 (-10 – 4)	-7 ± 10 (-14 – 0)	-7 ± 15 (-18 – 4)	F = 5.3, p = 0.031	F = 0.7, p = 0.491	F = 0.3, p = 0.783
DBP (mmHg)	66 ± 9	71 ± 9	85 ± 16 $	64 ± 6	70 ± 10	77 ± 13 $	-2 ± 8 (-7 – 3)	-1 ± 3 (-3 – 2)	-8 ± 21 (-24 – 7)	F = 2.3, p = 0.145	F = 7.0, p = 0.005	F = 0.7, p = 0.486
MAP (mmHg)	85 ± 9	88 ± 7	103 ± 15 $	72 ± 8 ^	85 ± 10 ^	95 ± 18 ^$	-3 ± 7 (-7 – 1)	-3 ± 4 (-6 – 0)	-8 ± 18 (-21 – 6)	F = 4.3, p = 0.050	F = 4.3, p = 0.027	F = 0.6, p = 0.572
CVC (%peak)	51.7 ± 20.2	57.8 ± 19.3	52.1 ± 21.7	48.9 ± 17.4	74.9 ± 37.5	56.2 ± 62.9	-2.8 ± 23.8 (-17 – 11)	+6.7 ± 21.8 (-8 – 22)	+7.3 ± 44.7 (-26 – 40)	F = 0.3, p = 0.578	F = 0.6, p = 0.542	F = 0.3, p = 0.743
Peak RPE	12 ± 2	12 ± 2	14 ± 3	10 ± 2 ^	11 ± 2 ^	14 ± 4 ^	-2 ± 2 (-3 – 1)	-1 ± 2 (-2 – 1)	-1 ± 2 (-2 – 1)	F = 8.7 , p = 0.007	F = 2.5, p = 0.102	F = 0.7, p = 0.517
Peak TS	5.7 ± 0.5	5.9 ± 0.5	6.1 ± 0.9	5.3 ± 0.3 ^	5.6 ± 0.4 ^	6.1 ± 1.1 ^	-0.4 ± 0.5 (-0.8 – 0.1)	-0.3 ± 0.4 (-0.5 – 0.0)	0.0 ± 0.4 (-0.6 – 0.4)	F = 6.0, p = 0.022	F = 2.2, p = 0.133	F = 1.2, p = 0.334
Peak TC	3 ± 1	3 ± 1	4 ± 1	2 ± 1	3 ± 1	4 ± 2	-1 ± 1 (-1 – 0)	0 ± 1 (-1 – 1)	-1 ± 1 (0 – 0)	F = 1.7, p = 0.208	F = 3.0, p = 0.69	F = 1.9, p = 0.170
6MWT distance (m)	746 ± 42	589 ± 140 #	497 ± 134 #	778 ± 67 *	639 ± 115 *#	544 ± 137 *#	+32 ± 39 (16 – 55)	+50 ± 30 (12 – 68)	+47 ± 16 (7 – 57)	F = 46.5, p < 0.001	F = 12.2, p < 0.001	F = 0.4, p = 0.413

Abbreviations: T_{re}; rectal temperature, T_{skin}; skin temperature, HR; heart rate, PV; plasma volume WBSR; whole body sweat rate, SBP; systolic blood pressure, DBP; diastolic blood pressure, MAP; mean arterial pressure, CVC; cutaneous vascular conductance, RPE; rating of perceived exertion, TS; thermal sensation, TC; thermal comfort, 6MWT; six minute walk test. Notes: All variables analysed during pre/post test 2 with the exception of Rest T_{rec} HA which compares day 1 and day 5 of HA, and Rest T_{rec} MAX which calculates the greatest change in Trec irrespective of timepoint.

Table 2.

* represents a significant (p < 0.05) with group difference from Pre. ^ represents a significant (p < 0.05) overall difference from Pre

represents a significant (p < 0.05) difference compared to Y_{EX} within timepoint. $ represents a significant (p < 0.05) overall difference from Y_{EX}

† represents a significant (p < 0.05) difference compared to E_{EX} within timepoint. ‡ represents a significant (p < 0.05) overall difference from E_{EX}