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**THE EFFECTS OF HEAT STRESS ON NEUROMUSCULAR ACTIVITY
DURING ENDURANCE EXERCISE.**

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Running Head: The effects of different temperatures on endurance exercise.

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ABSTRACT

Aim: This study analysed the effect of hot (35°C) and cold (15°C) environments on EMG signal characteristics, skin and rectal temperatures and heart rate during progressive endurance exercise. **Methods:** Eight healthy subjects performed three successive 15 min rides at 30%, 50% and 70% of their peak sustained power output and then cycled at increasing (15 W/min) work rates to exhaustion in both 35°C and 15°C environments. Skin and rectal temperatures, heart rate and electromyographic (EMG) data were measured during the trials.

Results: The skin temperatures were higher and the subjects felt more uncomfortable in the hot conditions (Bedford scale) ($P < 0.01$). Rectal temperature was slightly, but not significantly higher in the hot condition. Heart rate was significantly higher in the hot group (between condition $P < 0.05$). Peak power (PPO) (267.4 ± 67.7 W vs 250.1 ± 61.5 W) and time to exhaustion (55.7 ± 16.7 min vs 54.5 ± 17.1 min) (COLD vs HOT) were not different between conditions. There were no differences in integrated electromyography (IEMG) or mean power frequency spectrum (MPFS) between conditions. Rating of perceived exertion increased similarly in both conditions over time.

Conclusions: Although the hot conditions increased heart rate and skin temperature, there were no differences in muscle recruitment or maximal performance, which suggests that the thermal stress of 35°C, in combination with exercise in this study did not impair maximal performance.

Key words: Fatigue, Hot, cold, skin and rectal temperature, heart rate, integrated electromyography (IEMG), mean power frequency spectrum (MPFS), peak power (PWATT), rating of perceived exertion (RPE), thermal comfort.

INTRODUCTION

The thermoregulatory response of humans exercising in different environmental conditions has been the subject of considerable research. For example previous studies have shown that lowering body temperature by either cooling with ice packs or lowering ambient temperature will improve exercise performance (3,10,12). There have however been no studies that have examined neuromuscular activity in these circumstances (20).

The debilitating effect of heat exposure during performance of submaximal, prolonged exercise has also been described (7). Prolonged sub-maximal exercise combined with heat exposure will result in dehydration due to high sweat rates. The body's inability to control its increase in temperature (thermoregulatory failure), cardiovascular changes and changes in metabolic rate may also affect exercise capacity in a hot environment (17,23). It has been suggested that rather than dehydration, energy production or metabolic rate changes, absolute core temperature is the critical factor limiting exercise capacity in the heat (8,25). It is likely that when core temperature reaches critically high levels, an afferent signal is sent to the CNS, which responds by sending an efferent command to alter the neuromuscular recruitment strategy, to prevent cellular damage or rigor from occurring (19).

Petrofsky and Lind (21) showed that the electromyographic (EMG) frequency (MPFS) shifted to the upper part of the mean power frequency spectrum (MPFS) during short duration isometric contractions as temperature increased. Bigland-Richie (2) showed that cooling the muscle and slowing its conduction velocity would produce a general shift to the lower part of MPFS, while heat increased the conduction velocity, therefore producing a general shift towards the upper part of MPFS. This occurrence could account for premature fatigue during exercise in hot conditions. A contributing mechanism towards this premature fatigue could be from the increase in conduction velocity, which could increase the use of larger fatigueable type II fibers. However Bigland-Ritchie (2) independently cooled and heated the peripheral musculature, which does make it uncertain whether the increased conduction velocity is caused by a change in metabolites in the cell or by hot/cold environments acting directly on the nerve or CNS properties. The only study to determine the neural recruitment patterns during submaximal to exhaustive exercise in the heat was Ffactic et al (6) who showed in a group of runners that there was little change in neuromuscular recruitment patterns. However, running involves a greater variability in technique than cycling, which may also result in more variable EMG data. Accordingly, we examined the effects of hot (35°C) and cold (15°C) environment on exercise performance, heart rate, skin and rectal temperature, integrated EMG (IEMG) and MPFS during successive cycling rides at 30%, 50% and 70% of peak work rate and at termination of exercise fatigue.

METHODS

Subjects.

Eight healthy males volunteered for this study. All subjects performed recreational sporting activities three or more times per week and were not acclimatized to 35°C. The mean (\pm SD), age, height, body mass and peak power output (PPO) of the subjects were, 25.5 ± 4.4 yr, 179.5 ± 7.9 cm 73.4 ± 11.9 kg and 298.5 ± 47.9 W. All subjects were physically active and each signed an informed consent before the study. The Research and Ethics Committee of the University of Cape Town Medical School approved the study.

Preliminary testing

Peak Power Output (PPO) was measured as described previously by Hawley and Noakes (9). Subjects began riding on a electrically braked cycle ergometer (Lode, Groningen, Netherlands) at a starting work rate of 2.5 W/kg body mass for 150 s, after which the power output was increased by 25 W every 150 s until the subject became exhausted. Exhaustion was defined as a decrease in the subject's pedalling frequency from 90 to <50 revolutions/min. PPO was defined as the last completed work rate in W plus the fraction of time spent in the final non-completed work rate multiplied by 25 W.

Maximal isometric voluntary contraction (MVC).

Within a week of PPO testing, the MVC of the subjects' right knee extensors were measured on an isokinetic dynamometer (Kin-Com Chattanooga Group Inc., USA). Subjects sat on the dynamometer and their hips, thighs and upper bodies were firmly strapped to the seat. In this position their hip angle was at 100° angle of flexion. The right lower leg was then attached to the arm of the dynamometer at a level slightly above the lateral malleolus of the ankle joint and the axis of rotation of the dynamometer arm was aligned with the lateral femoral condyle. The dynamometer arm was then set so that the knee was at a 60° angle from full leg extension. Each subject performed four sub-maximal familiarisation contractions prior to performing two maximal MVC's; the latter of which was used for subsequent analyses. All subjects were encouraged verbally to exert maximal effort during both MVC's.

Progressive exercise

Following the MVC, the subjects reported to the heat chamber and inserted a rectal thermometer (Mon-a-therm, Mallinckrodt, OH, USA) 10cm beyond their anal sphincter. Four surface thermistors (YSI 400, Yellow Springs, OH, USA) were then taped to the sternum region, the "main belly" of the left bicep, left vastus medialis and left gastrocnemius. The subjects then completed one of the two progressive cycle tests in an environmental chamber (Scientific Technology Corporation, Cape Town, South Africa) at an ambient temperature setting of either 15° or 35°C, a relative humidity of 50 ± 0.9 % and a wind velocity of $15 \pm$

0.4 km/h. As with the preliminary PPO testing, the Lode ergometers were used for the endurance testing. After resting in the chamber for 15 minutes the subjects then performed three successive 15 min rides at 30, 50 and 70% of their PPO and then cycled at increasing 15 W/min work rates until they fatigued (Figure 1). Rating of perceived exertion (RPE) and thermal comfort were determined as described by Borg (4) and Bedford (1) (Table 1) respectively. At rest, 10, 25, 40 minutes and at exhaustion, skin and rectal temperatures, heart rate, RPE and thermal comfort were recorded (Figure1). These recording times were chosen because the subjects had completed 10 minutes out of the 15 minute work period and therefore allowed a full 5 minutes to capture all the data. The ride was repeated again with the same methods but during a different temperature.

Electromyographic (EMG) testing.

Prior to maximal isometric strength testing on the Kin-Com isokinetic dynamometer, EMG electrodes were attached to the subject's lower limb midway between the superior surface of the patella and the anterior superior iliac crest over the "belly" of the rectus femoris. The overlying skin on the muscles was carefully prepared. Hair was shaved off, the outer layer of epidermal cells abraded, and oil and dirt were removed from the skin with an alcohol pad. Triode electrodes (Thought Technology USA) were placed on the muscle sites as described above, and linked via a fibre-optic cable to the Flexcomp/DSP EMG apparatus (Thought Technology USA) and host computer. The electrodes were

heavily taped down with cotton swabs to minimise sweat-induced interference. A 50Hz line filter was applied to the EMG data to prevent electrical interference from electrical sources. Each activity was sampled at a 1984 Hz capture rate for 5-second bouts. Data were recorded on the second maximal isometric trial and during the cycling trial at 10, 25, 40 minutes and at exhaustion thus yielding a raw signal. MVC EMG data was recorded prior to both cycle rides to ensure similar normalisation of EMG in both trials.

The raw signals were full wave rectified and smoothed with a low-pass 2nd order Butterworth filter with a cut off frequency of 5 Hz.

The raw data were divided into 5 x five second epochs. The first epoch included all data collected during the second maximal isometric trial, and the remaining four epochs included data collected on the ride at 10, 25, 40 minutes and at exhaustion. The mean EMG activity at each epoch was calculated. The data for the first epoch were subsequently described as 100% EMG activity, and all subsequent data were normalised by using the first epoch as the denominator for subsequent epoch values.

The frequency spectrum for each epoch was assessed by using a fast Fourier transformation algorithm. The analyses for frequency spectrum were restricted to frequencies of the 5-500 Hz range, due to the EMG signal content consisting mostly of noise when it is outside the range of this bandwidth. From each epoch

of data the frequency spectrum was compared with that from the first epoch, and the quantity of spectral compression was estimated. This technique was performed as described by Lowery et al (14), which is a modification of the work of Lo Conte and Merletti (13) and Merletti and Lo Conte (15). The spectrum of the raw signal of each epoch was obtained and the normalised cumulative power at each frequency was calculated for each epoch. The shift in percentile frequency was then examined (i.e. at 0%...50%...100% of the total cumulative). The estimation of frequency shift was derived by calculating the mean shift in all percentile frequencies (MPFS) during the mid-frequency range, i.e. 5-500 Hz. It has been suggested that this method is a more accurate estimation of spectral compression than analysing median frequency, which only uses a single value of percentile (50th) frequency (14,13,15).

Statistical Analyses

All data are expressed as means \pm SD. A two-way ANOVA for repeated measures was used to evaluate statistical significance of all the variables measured. Post hoc analyses of the main effects over time were done using a Scheffe's test. Single comparisons between temperatures were analysed with a paired Students t-test using two-tailed values of P. Significance was accepted at $P \leq 0.05$.

RESULTS

There were no significant differences for maximum power output at exhaustion (PWATT) and time to exhaustion (TIME) between the 35°C ride (HOT) than the 15 °C ride (COLD) (Table 2).

All skin temperature values taken throughout the cycle ride were significantly higher for HOT than COLD ($P < 0.01$) (Figure 2a-d). Calf skin temperature increased from 40 min to exhaustion in both groups ($P < 0.01$) (Figure 2d). Rectal temperatures increased similarly in both conditions during the trial ($P < 0.05$) (Figure 3). Although there was a tendency for rectal temperature to be higher throughout the HOT trial, this difference was not significant.

Heart rate values were higher in HOT (group main effect $P < 0.05$). Heart rate in both conditions increased similarly over time (time main effect $P < 0.05$) (Figure 4).

IEMG measured throughout the cycle ride and normalised as a percentage of MVC increased ($P < 0.01$) during the ride for both COLD and HOT (Figure 5). Although there was a tendency for IEMG to be higher in HOT vs COLD, this was not significant. There were no differences in MPFS between conditions or over time (Figure 6).

RPE for HOT and COLD increased significantly during the ride ($P < 0.01$) (Figure 7). There were no significant differences for RPE between groups. The RPE for HOT at 10 minutes (12.2 ± 8.6) tended to be higher than COLD (7.2 ± 1.2) although this was not significant. Subjects were significantly more uncomfortable during HOT, which is shown by higher thermal comfort values ($P < 0.01$) (Figure 8). The differences for thermal between HOT and COLD become less as the ride progressed (Figure 8). For example, at the start of the ride the difference was 67%, and this decreased to 30% at the end of the ride.

DISCUSSION

Previous studies of exercise in hot environments have shown an earlier onset of fatigue (7). It is considered that this premature fatigue is caused by a reduced cardiac output from thermoregulatory mechanisms, which will limit the quantity of oxygen delivered to the working muscle (21). Our study showed a significant increase in skin temperature and a higher heart rate and similar rectal temperature values in the HOT condition with no differences in performance. This indicates the successful involvement of thermoregulatory response mechanisms in the HOT condition. These results suggest that increased skin temperature results from increased skin blood flow (18). It has been previously shown (8,18) that increased skin blood flow causes a reduction in cardiac return in an attempt to move more blood to the periphery to transfer heat out of the body by convection. As a consequence of reduced cardiac return the stroke volume decreases (24), therefore to compensate, the heart rate becomes elevated (8), which is shown in this study. Therefore, it would appear that because heat is effectively being transferred out of the body, core temperature in our study was controlled without compromising performance. Also, the 15 minute period of rest before the cycle ride during the COLD condition would have caused lower skin blood flow and increased venous tone. This would have resulted in increased venous return and stroke volume and lower heart rate (23). Also, the pre-shivering muscle tone could have initially decreased muscle efficiency, therefore to compensate may have required a higher recruitment of motor units (11).

Consequently, because core temperature remained unchanged, possibly because of an effective thermoregulation mechanism, the afferent command to the CNS from the periphery resulted in similar efferent neural recruitment strategies from CNS to the working muscle in both conditions. Similar EMG recordings were shown in both conditions. First, there was similar IEMG recordings in both conditions, although there was a slight increase in IEMG for the HOT group, which does suggest a tendency for efferent command changes to recruit additional motor units (16) to compensate for a possible decline in cardiac output.

Second, there were similar MPFS values, which also indicates that central drive was similar in both HOT and COLD conditions. Bigland-Ritchie (2) concluded that conduction velocity slows down when the muscle is cooled resulting in lower MPFS, conversely by heating the muscle the conduction velocity increased causing an increase in MPFS. However, this was found in an in vitro study and has not been confirmed in an exercising human model, which will involve other variables such as changes in intramuscular pressure, haemodynamics and resulting metabolite accumulation. Accordingly, because there were similar MPFS values in both conditions, suggests that the muscle temperature did not increase sufficiently in the HOT condition to change conduction velocity. These findings indicate that skin temperature changes and increased thermal comfort values do not result in significant efferent neural command changes.

Furthermore, subjects were significantly more uncomfortable during the HOT conditions, which would counteract motivation and gradually reduce the drive to exercise (5). However, this being the case a reduced MPFS and exercise performance would be expected in this study. Therefore, in this study even though the subjects' report differences in thermal comfort, it is likely that effective thermoregulation resulted in similar RPE values that are shown in this study.

Similar performance in both conditions could be because first, the ramp protocol used meant the subjects were only working at 70% of PPO in the latter 15 minutes, after which the load increased to 15W/min thereafter to exhaustion (Figure 1). Therefore, it could be argued that the time spent at a high intensity during the protocol was too short for any significant changes in core temperature and consequently performance to occur. Second, the environmental conditions may not have been optimal. Previous studies have shown reduced performance in cyclists at temperatures of 40°C (8,20) and Galloway and Maughan (7), showed significant differences at only 30°C, however the humidity and windspeed was 70% and 2.52 km/h respectively compared to 50% and 15km/h in this study. Therefore the low heat storage shown in this study could have been from: i) the absolute temperature in the HOT condition being too low; ii) humidity too low and windspeed too high and iii) different subject characteristics allowing for more efficient thermoregulation.

Finally, there was a sudden increase in skin temperature in the calf of the COLD group at exhaustion. This suggests that because of the final large power output at exhaustion, there will inevitably be an increase in blood flow to the working muscle with increased blood volume to the vascular beds (22). These changes may cause a rapid increase in temperature to the calf region in the COLD group. The HOT group did not show the same increase at exhaustion as COLD, probably because the skin had reached equilibrium with an ambient temperature of 35°C conditions.

In conclusion, EMG was not altered in the presence of elevated skin temperature and thermal comfort. RPE was the same for both HOT and COLD, suggesting that peripheral mechanisms resulted in unchanged central drive. This study and other studies indicate a number of factors that will affect exercise capacity under hot and cold conditions. However, in this study the HOT protocol caused changes in skin temperature and heart rate, but not in rectal temperature. Therefore, it appears that during HOT, effective peripheral thermoregulation mechanisms control core temperature, resulting in an unchanged neuromuscular recruitment strategy. Further work is needed to assess the affect of changes in core temperature as opposed to peripheral temperature changes on neural recruitment changes during fatiguing activity.

ACKNOWLEDGEMENTS

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TABLES

Table 1. Thermal Comfort Rating as described by Bedford (1).

Thermal comfort	Rating
Much too warm	7
Too warm	6
Comfortably warm	5
Comfortable	4
Comfortably cool	3
Cool	2
Much too cool	1

Table 2. Peak watts (PWATT) coinciding with volitional exhaustion: and time taken to reach exhaustion (TIME) during 15°C (COLD) and 35°C (HOT) trials.

	COLD	HOT
PWATT (W)	267.4 \pm 67.7	250.1 \pm 61.5
TIME (min)	55.7 \pm 16.7	54.5 \pm 17.1

All values are mean \pm SD

FIGURES

Figure 1. Progressive cycle exercise test protocol. Rating of perceived exertion (RPE), rectal temperature (T_{rec}), skin temperature (T_{sk}), electromyography (EMG), heart rate (HR) and thermal comfort were all recorded at 10, 25, 40 minutes and at exhaustion during the ride.

Figure 2. Skin temperature values were taken from the (a) sternum, (b) bicep, (c) mid-thigh and (d) calf regions at rest, 10, 25, 40 mins and exhaustion during the cycle ride during 15°C (COLD) and 35°C (HOT). (** - $P < 0.01$)

Figure 3. Rectal temperature values captured at rest, 10, 25, 40 mins and exhaustion during the cycle ride during 15°C (COLD) and 35°C (HOT) (* $P < 0.05$ increase over time for both conditions).

Figure 4. Heart rate values captured at rest, 10, 25, 40 mins and exhaustion during the cycle ride during 15°C (COLD) and 35°C (HOT) (* $P < 0.05$ differences between conditions and over time).

Figure 5. Mean amplitude values (IEMG) captured at 10, 25, 40 mins and exhaustion during the cycle ride have been normalised as a percentage of Maximal voluntary contraction (MVC) for both 15°C (COLD) and 35°C (HOT) (* $P < 0.01$ increase over time for both conditions).

Figure 6. Normalised EMG mean power frequency spectrum (MPFS) data values for both 15°C (COLD) and 35°C (HOT).

Figure 7. Rate of perceived exertion values captured at 10, 25, 40 mins and exhaustion during the cycle ride during 15°C (COLD) and 35°C (HOT) (* $P < 0.01$ increase over time).

Figure 8. Thermal comfort values captured at rest, 10, 25, 40 mins and exhaustion during the cycle ride during 15°C (COLD) and 35°C (HOT) (** $P < 0.01$).

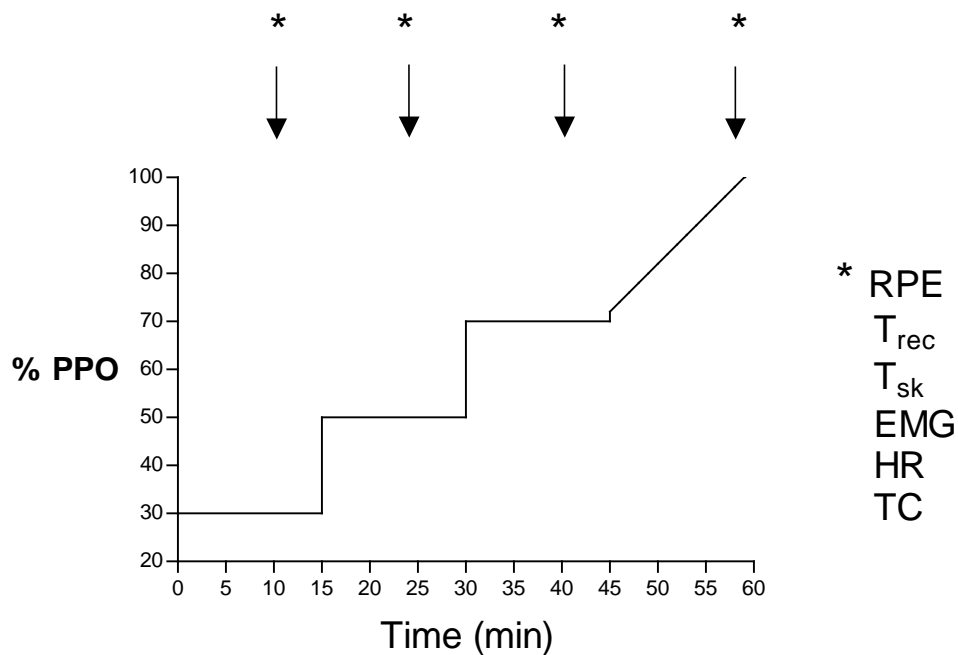


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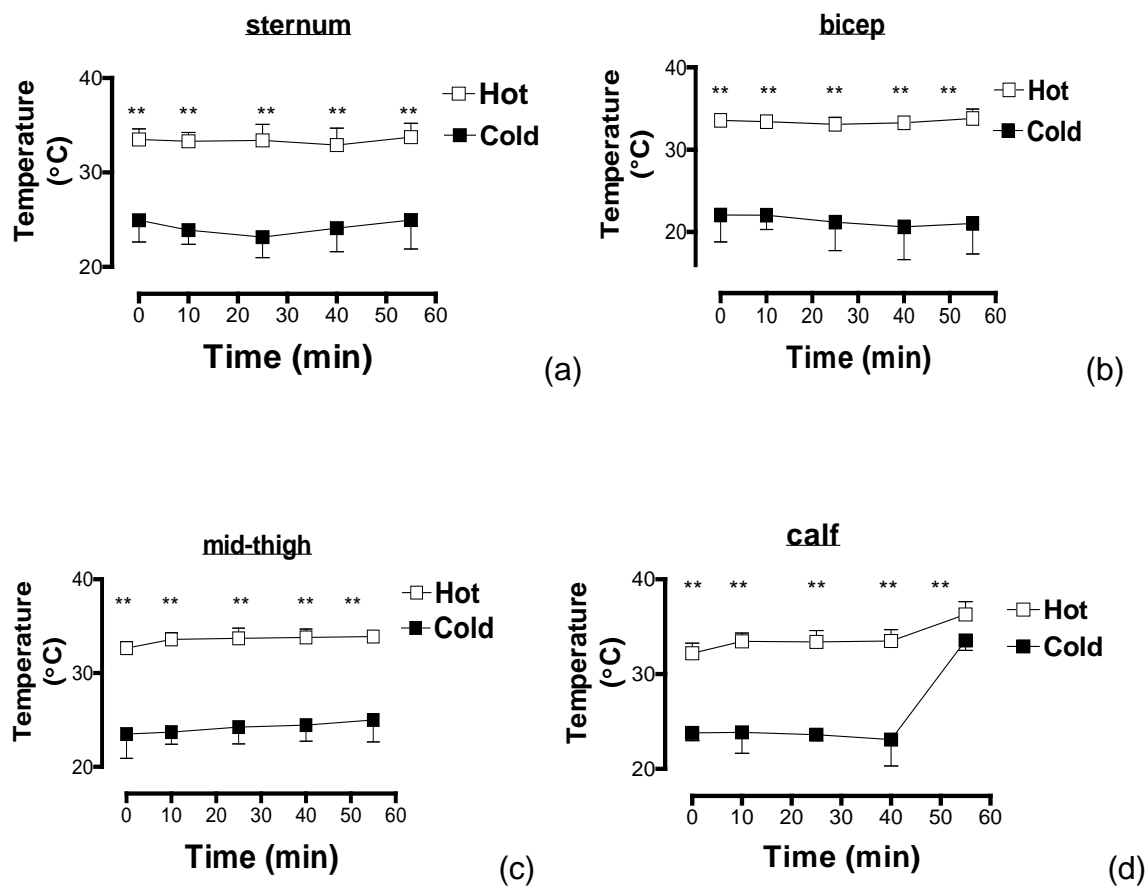


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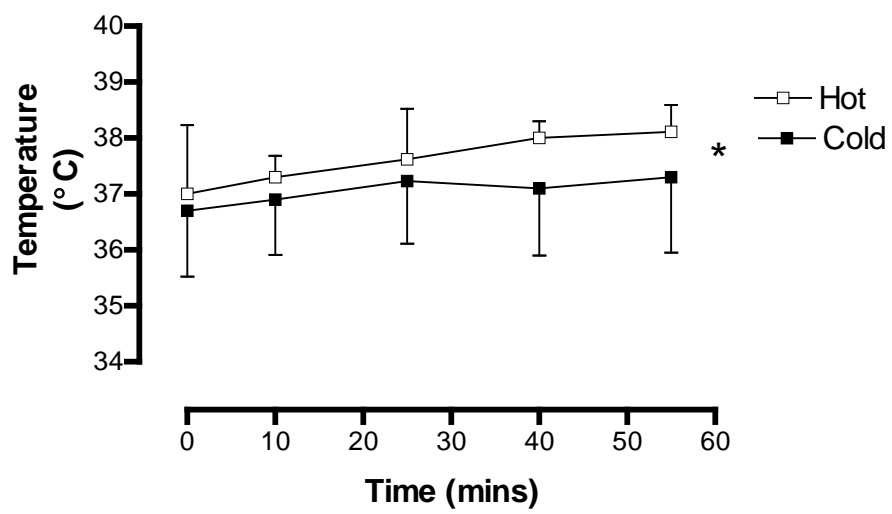


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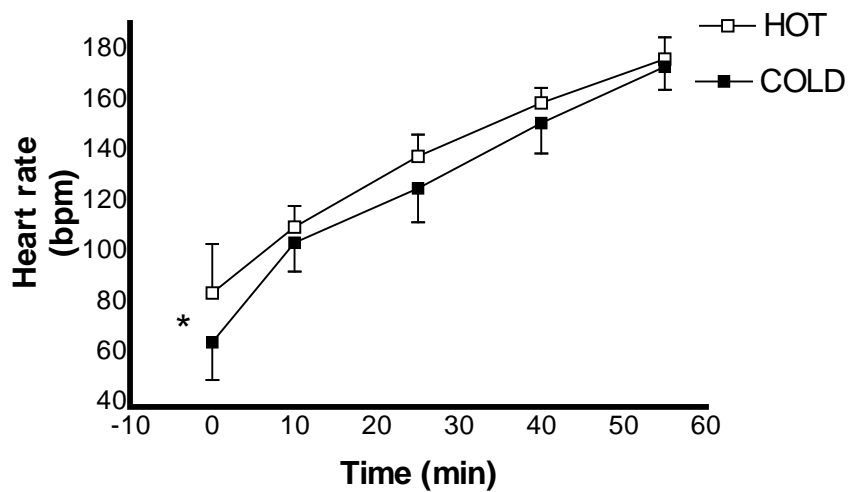


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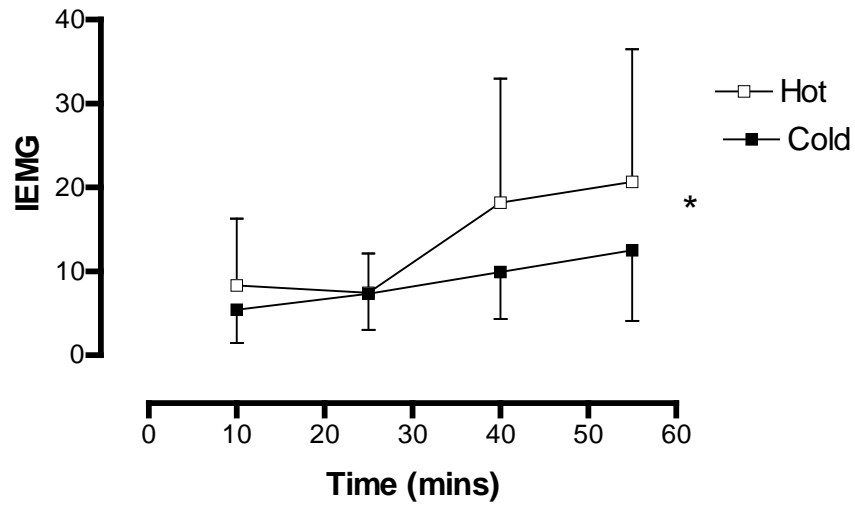


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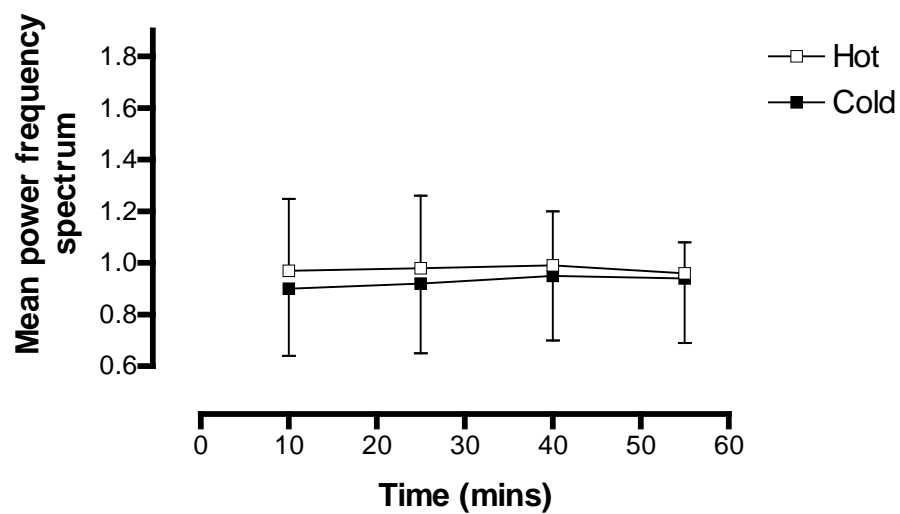


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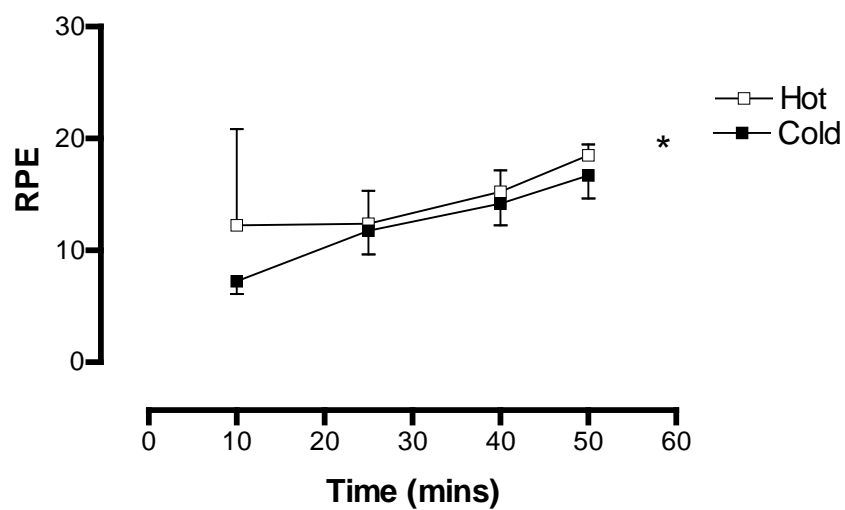


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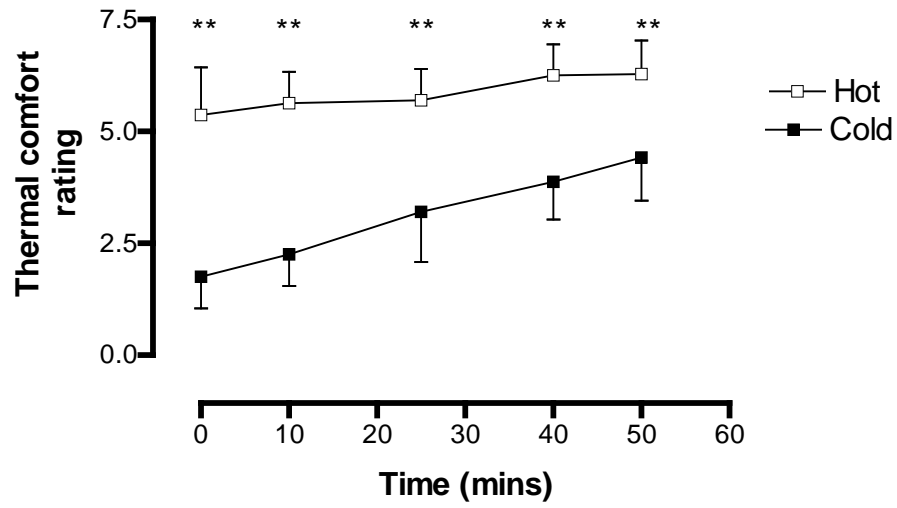


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