External Heating Garments used Post Warm-Up Improve Upper-Body Power and Elite Sprint Swimming Performance

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ABSTRACT

The aim of this study was to determine the effects of using an electrical heating garment during a 30-minute recovery period after a standardized swimming warm-up on subsequent swimming performance and upper-body power output. On two occasions, eight male and four female elite competitive swimmers completed a standardized swimming warm-up, followed by a 30-minute passive recovery period before completing maximal plyometric press-ups and a 50m Freestyle swim. Plyometric press-ups determined starting strength (SS), peak force (PF) and peak concentric power (PCP). During the recovery period, participants wore tracksuit bottoms and (i) a standard tracksuit top (CON) or (ii) jacket with integrated electric heating elements (HEAT). The overall results demonstrated a trend of a relevant (>0.4%) improvement in the 50m Freestyle performance of 0.83% (P = 0.06) in HEAT vs. CON. In male participants, performance in the 50m Freestyle significantly improved by 1.01% (CON 25.18 ± 0.5s vs. HEAT 24.93 ± 0.4s; $P < 0.05$), whereas female participants only showed a trend for an improvement of 0.38% (29.18 ± 0.5s vs. 29.03 ± 1.0s; P = 0.09), in HEAT compared with CON, though statistical power for the latter test was low. Male participants' starting strength, peak force and peak concentric power were 16.5 ± 13%, 18.1 ± 21% and 16.2 ± 21% greater, respectively, in HEAT compared with CON (all P<0.01). In conclusion, external heating of the upper body between completion of the warm-up and performance through the utilization of an electrically heated jacket improves plyometric press-up power output and force production, as well as sprint swimming performance in males. This provides justification for future enhancement opportunities in sporting performance through the utilization of external heating systems. Optimization of the heating system for specific sports is required.

Key Words: MUSCLE TEMPERATURE, SWIMMERS, CLOTHING, PASSIVE HEATING, GENDER

1. INTRODUCTION

The importance of warming-up on the enhancement of exercise performance is well established (1). Its impact on subsequent performance is dependent on the intensity and duration of a competition event and on the recovery duration between the warm-up and the competitive event (2). One of the major contributing factors to a heightened performance is an increase in muscle temperature (T_m), with increases of 3°C - 4°C shown following an active warm-up (3). Not only can T_m maintenance be pivotal between the warm-up and event, but also between multiple races at an event (4). Due to time constraints, a swimmer may not be able to change into a dry racing suit between races; meanwhile, remaining in the wet suit increases body heat loss and speeds T_m cooling.

A warm-up induced rise in T_m results in a number of beneficial physiological effects (5, 6, 7, 8), ranging from increased anaerobic metabolic capacity, increased nerve conduction rates in both the central and peripheral nerves, and increased speed of muscle contractions, to adjustments in muscle sensitivity and calcium production. All these together lead to significantly improved muscle function, force and power production; and subsequently, to improved performance (5, 6), whether T_m is raised as a result of exercise or passive heating (9).

Most of the existing literature advocates the benefits of increased T_m on short duration events (<5 minutes), which have a greater dependence on high levels of power production (5, 10, 11). Bergh and Ekblom (10) revealed a 5% increase in power output, jumping, and sprinting performances for each 1°C increase in T_m, between muscle temperatures of 30 and 39°C, via cooling and warming experiments. Faulkner *et al.* (6) observed a 9% increase in peak power output per-degree-centigrade elevation in T_m. Faulkner *et al.* (6, 12), studying cycling sprint performance, reported on the problems with dropping T_m occurring when the warm-up and race are separated by a period in which the athlete is inactive. For swimmers, such an inactive period between the warm-up and race is common. In national and international competitions, swimmers must report to the call room 20-minutes prior to their race, with most swimmers completing their warm-up up to 45-minutes prior to racing (2). The impact of such a delay was studied by Zochowski *et al.* (2) who observed a ~1.4% better 200m freestyle performance of national standard swimmers after a 10-minute post warm-up recovery/delay, in comparison to a 45-minute recovery/delay period. Similarly, West *et al*. (7) observed 200m swim times to be 1.86 ± 1.37s better when swam within 20-minutes of the warm-up in comparison to 45 minutes, resulting in a difference of a 1.5% improvement in performance. The predicted higher T_m in the shorter recovery periods (6, 12) is assumed to be the underlying cause for these observed performance enhancements.

Such an observed improvement of 1.5% in performance is of great significance to an elite swimmer. According to Pyne *et al.* (13), swimmers can substantially increase their chances of medaling by improving performance by as little as 0.4%, demonstrated at the 2012 Olympics where the bronze medal position and 4th position were separated by just 0.09% (0.02 seconds) and 0.25% (0.07 seconds) respectively in the men's and women's 50m Freestyle.

With studies finding a significant deterioration in high-power performances of short duration (< 5 minutes) after prolonged periods between the warm-up and competing, development of methods to keep a raised T_m during this recovery period are crucial (3, 6). The main focus in the development of such methods has been on heated trousers. Faulkner *et al.* (6, 12) demonstrated the benefits of external heating (heated trousers) between warm-up completion and racing in sprint cycling, achieving a ~ 1°C higher T_m and a concomitant 9% increase in peak power (6, 12) with a 4% increase in mean power (12), compared to wearing a normal track suit in the 30-minute recovery period.

Since 90% of maximal freestyle velocity is produced by the arms, with only 10% propulsion from the legs (14), upper-body heating for swimmers is more relevant, thus the focus for this sport should be on a heating jacket rather than trousers. Studying national junior swimmers, McGowan *et al.* (15) found that adding the wearing of heated jackets to dryland-based exercise circuits between warm-up completion and racing (30 minutes) further improved the 100m Freestyle swimming performance above the dryland exercises alone, though the heated jackets on their own did not increase performance (15). Given that performances and the impact of performance-altering interventions often relate to the level of athletes investigated and the distance covered, it is unclear whether McGowan *et al.*'s results would also translate into elite senior swimmers and shorter sprint events.

Based on these considerations, it was felt that an additional study investigating the impact of heated garments, and more specifically heated jackets, in the recovery period of elite senior swimmers (rather than McGowan's juniors) was relevant for the evaluation of such techniques. Furthermore, where McGowan *et al.* (15) used the 100m freestyle, it was considered that a 50m freestyle sprint would be most relevant to test the impact of muscle heating, given that the biggest impact of a heating procedure is expected in a short burst of high-power exercise. An improvement would be considered relevant if higher than 0.4%, based on the work of Pyne *et al.* (13). Apart from directly investigating sprint performance, upper-body performance was also investigated as an additional performance measure (16), to see whether the hypothesized higher T_m due to the application of the heating jackets would produce a measurable effect of instantaneous upper-body power in short duration. Bench press exercise has been linked to arm-force production and better swimming times in water (16, 17), but utilizing this exercise was not technically feasible in this setup. Plyometric press-up power output has also been linked to enhanced swimming training and performance (18), be it less directly. Given the general link between plyometric press-up and upper-body power, and the link between the latter and swimming performance, this method was arbitrarily chosen as a secondary measure that could form the basis for any observed improvement in sprint swimming performance.

2. METHOD

Experimental Approach to the Problem

2.1 PARTICIPANTS

Twelve participants, eight elite male swimmers (aged = 21 ± 1.8 yr, height = 1.88 ± 0.06m, body mass = 87.6 ± 7.65 kg, FINA points (2014) = 684 ± 56; mean ± SD) and four elite female swimmers (aged = 20 ± 1.7 yr, height = 1.72 ± 0.09m, body mass = 66.9 ± 10.14 kg, FINA points = 651 ± 10; not controlled for menstrual cycle) volunteered to participate in this study. An elite swimmer is defined as an athlete that is of adult age who is close to or has already reached their top performances, competing regularly at the key national- or international-level competitions (19). Sample size was defined using the model of Hopkins (20) (change in mean in a crossover study), based on the standard deviation of non-tapered performance times and the smallest worthwhile enhancement in performance of 0.4% (13). This analysis indicated the need for 8 participants. Four female participants were added to the group of eight male participants to investigate possible gender impacts on the results. Due to logistical reasons, unfortunately, a complete sample of 8 females, needed for appropriate power to analyze gender data separately, was not achieved. Nevertheless, the data are included here and presented with consideration of the low statistical power. The 50m Freestyle personal best times for male and female participants of this study were 23.83 ± 0.76 seconds and 27.15 ± 0.66 seconds, respectively (mean ± SD). All participants performed at least seven swimming sessions per week (16.7 ± 1.6 h wk^{-1}) along with 2-3 land-based sessions (5.9 ± 0.7 h wk^{-1}), and had 13.3 ± 2.7 years of practice which indicates expert skill (21). Participants were informed of the benefits and risks of the study prior to giving their written informed consent to participate in the study. Participants completed a general health-screen questionnaire and were all non-smokers and free from injury. The study was carried out during the swimmers' competitive season to ensure a high state of physical training. The study was approved by the Loughborough University Ethical Advisory Committee.

2.2 STUDY OVERVIEW

Prior to the experimental trials, participants were familiarized with the testing protocol, as well as measurements and exercise testing. Also preceding the experimental trials, participants completed a two-week pilot study assessing plyometric press-ups as a performance measure, in order to minimize the learning effect during the course of the study. Within-subject coefficient of variation (CV) % calculations indicated starting strength (CV%=8.26) and peak force (CV%=3.44) to have moderate to very high test-retest reliability, in agreement with Hogarth *et al.* (220), whereas peak concentric power (W) (CV%=10.78) demonstrated a CV just above the analytical goal of ≥10% (23).

Participants visited the swimming pool for two testing sessions. Each time, they completed a 30-minute standardized swimming warm-up, followed by a period of 30-minute passive seated recovery, simulating the time between finishing the warm-up and racing. During the 30-minute seated recovery, participants underwent one of two conditions: wearing either the standardized jacket (CON) or the heated jacket (HEAT) (detailed below) followed by, after removal of the clothing, four plyometric press-ups and a maximum long-course 50m Freestyle. A repeated-measures study design was utilized, with each swimmer completing both a control and intervention trial, separated by seven days. Trial conditions were performed in a balanced order and took place at the same time of day (~14:00), aiming to minimize circadian variations effects on performance. Participants completed their performance measures individually to avoid any external influences. Twenty-four hours prior to testing, participants were asked to refrain from caffeine and alcohol consumption, as well as any strenuous exercise. Passive recovery was carried out in a temperature-controlled room (20.0 ± 0.2°C), to simulate competition cool rooms and ensure consistent conditions across tests. Warm-up and swimming tests were carried out in an Olympic standard 50m swimming pool (Pool water temperature 27.6 ± 0.1°C, Air temperature 23.4 ± 0.1 °C, Humidity 55.8 ± 1.4%) at Loughborough University.

Procedures

Participants arrived at the pool after a typical competition-day meal at least two hours prior to testing (repeated over trials). Upon arrival, participants had their height (Esca, Birmingham, United Kingdom) and body mass (M) (Esca 770, Vogel & Halke, Hamberg, Germany) recorded, from which body surface area (A_D) was estimated and surface-to-mass ratios (A_D/M) of the subjects were calculated. Body fat percentage data were based on seven-point skinfold measurements. Participants entered the temperature-controlled room and remained seated for a 15-minute stabilization period. All participants wore a standardized tracksuit: a single layer of uninsulated nylon material consisting of trouser bottoms and a zip-up top. During this time, they were familiarized with the trial procedure. Following the stabilization period, a baseline skin thermal image (FLIR i7, Flir Systems, Wilsonville, USA) of participants in their swimsuit was captured from a distance of 3m, in anatomical position with palms facing forward, along with measurements of tympanic temperature (TT) (Braun ThermoScan PRO 4000, Welch Allyn, Kaz, USA), heart rate (HR) (Polar FT1, Polar Electro Oy, Kempele, Finland), thermal comfort (TC) and thermal sensation (TS) (24).

Participants then completed a standardized heart rate (HR)-monitored swimming warm-up, with the HR noted after completion of the 4 x 50m sprinted bursts. The warm-up is a standardized warm-up as described by West et al. (7), with the 4 x 50m altered to make it more sprint-focused. The warm-up entailed: 400 m Freestyle, 200 m Pull, 200 m Kick, 200 m Drill (Fins), 200 m Individual Medley, 4 × 50m Freestyle: (1) Push 15m u/w fly kick, (2) 15m spin drill, (3) dive 15m race pace, (4) dive 25m race pace (HR measured), 200 m easy.

Promptly after the completion of the warm-up, skin thermal imaging, heart rate, thermal comfort and thermal sensation were recorded as described above. Participants then remained seated for 30 minutes in the temperature-controlled room, simulating a call-room marshalling period. Participants wore a standard pair of tracksuit bottoms, long-sleeve top and one of two types of jackets that made up the intervention: 1) control (CON) where participants wore a standardized tracksuit jacket, or 2) heated jacket (HEAT) where participants wore a jacket with integrated heated elements (Powerlet rapidFIRe

Proform Heated Jacket Liner, Warren, USA). When unheated, both jackets had similar insulation as measured on a thermal manikin (25). The heated jacket was selected based on market research to find the best coverage of the torso and arms with heating elements. The heated elements targeted the major muscle groups: pectoralis major, latissimus dorsi, tricep brachii, and covered the lower deltoids (26) (Fig. 1). The heating elements were powered by 12v 10amp power transformers powering the jacket to full capacity at 105watts, with the elements reaching temperatures of ~50°C (lower on the skin contact). The jacket's stretch panels allow maximum heat transfer, as the material stays in close contact to the body, reducing convection whilst permitting movement. Over the duration of the 30-minute period, measurements of thermal comfort and thermal sensation were recorded every 5 minutes.

Subsequently, tracksuit garments were removed and a further skin thermal image was captured in their swimsuit alone. Thermal images were analyzed using ThermaCAM Researcher Software (Flir, Wilsonville, USA) to measure mean skin temperature (T_{sk}) of the upper body (torso and upper arms) using the freeform tool. Muscle temperatures (T_m) were estimated from mean skin temperature as: $T_m = 1.02T_{sk} + 0.89$ (r^2=0.98), based on work by De Ruiter *et al*. (27). Tympanic temperature, heart rate, thermal comfort and thermal sensation were also recorded.

Each participant then performed four separate maximal-effort plyometric press-ups (without the heating garment), with ~10s rest in between, on a force platform (400S Force Plate, Fittech, Skye, Australia, sampled at 600Hz) whereby kinetic data were collected and analyzed using Ballistic Measurement System Software. After the force platform was reset, participants were instructed to place their hands at a self-selected width, with elbows straight. Male participants performed a regular press-up with feet together, whereas female participants performed bent-knee press-ups, a lower-intensity press-up variation (28). Succeeding a three-second count down, participants performed the countermovement action of the plyometric press-up as quickly as possible, aiming for maximal height of trunk elevation. Force data were analyzed to determine Starting Strength (SS, also called 'maximal rate of force development', calculated as the steepest slope of the force time curve), Peak Force (PF, highest measured value) and Peak Concentric Power (PCP). After completion, participants placed the respective jacket back on and prepared themselves to perform a 50m Freestyle time trial at maximum effort (~2 minutes after completing press-ups).

For the swim trial, a starter system (HS-200 Horn Start, Daktronics, Inc., Brookings, SD, USA) was used to replicate the signal used in competitions. Participants began their swim (without a race suit) from the blocks (Omega® OSB11, Swiss Timing, Switzerland) to simulate race conditions, and the 25m split, stroke rates (at ~20m & 40m, i.e. Stroke Rate 1 and Stroke Rate 2) and total stroke count over the whole distance were recorded. An official electronic timing system with an accuracy of 1/1000s (Omega Ares 21, Swiss Timing, Switzerland) was used to determine the overall swim time, with 25m splits taken by the coach using a stopwatch (Fastime 9, Pyramid Technologies, Meriden, CT). Immediately after completion, the HR was measured, followed by thermal comfort, thermal sensation and rating of perceived exertion (RPE) using Borg's 15-point-scale (29).

Statistical Analyses

All statistical tests were processed using IBM SPSS Statistics Software Version 22. The Shapiro-Wilk test of normality revealed the data were normally distributed. Participant characteristics were analyzed using an independent-samples T-test. Performance data were analyzed using a one-tailed, paired T-test based on the directional hypothesis. T_{sk}, TT and HR were analyzed (two tailed) using a one-way repeated measures ANOVA (Condition * Time). RPE, TC and TS data among participants were analyzed using the Freidman Test. Significant effects were followed up with the Wilcoxon Signed-Rank Test, and the Kruskal-Wallis test was followed up by the Mann-Whitney *U* Test for between genders. The accepted level of significance was $P < 0.05$, with a trend level of $0.05 < P < 0.1$ also being acknowledged. Data are presented as mean ± SD. The 50m Freestyle performance was further analyzed using Hopkins' (20) published spreadsheet that used log transformation to estimate the effect of passive heating as the difference in the mean percent change between the experimental and control groups. The spreadsheet provided the precision of the estimate and the chances that the true effect was practically beneficial or harmful at a 90% confidence limit. For calculations of the chances of benefit and harm, the value of 0.4% for the smallest worthwhile effect was used (13). Quantitative chances of benefit or harm were assessed qualitatively as follows: <1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99, very likely; and >99%, almost certain.

3. RESULTS

3.1 PARTICIPANT CHARACTERISTICS

The male participants were significantly taller than the female participants (1.88 ± 0.06 vs 1.72 ± 9 m, $P < 0.05$) and had a greater body mass (87.6 ± 7.6 vs 66.9 ± 10.1 kg, $P < 0.05$); thus, they had a significantly larger body-surface-area (2.1 ± 0.1 vs 1.8 ± 0.2 m^2, $P < 0.05$) but lower body-surface-area to mass-ratio than the female participants (245 ± 7 $.10^{-4}$ vs 269 ± 14 $.10^{-4}$ m^2 kg^{-1}, $P < 0.05$). The male participants had a significantly lower body fat percentage than the female participants (6.1 ± 2.2 vs 21.0 ± 4.6% $P < 0.05$).

3.2 SWIMMING PERFORMANCE

When observing both male and female participants, a trend was shown in the 50m Freestyle time where HEAT performance was faster compared to that in CON by 0.83% ($P = 0.06$), with a significant 1.06% improvement in the 25m split time ($P < 0.05$) (Table 1). Eight of the twelve participants (six of the eight males and two of the four females) showed a clear improvement in swimming performance, improving by more than 0.4%- the smallest worthwhile enhancement in swimming (Fig. 2) (13). Stroke rate 1, stroke rate 2 and total stroke count were significantly greater in HEAT compared to CON ($P < 0.05$, $P < 0.01$, $P < 0.01$ respectively) (Table 1). Male participants showed a 1.01% improvement in the 50m performance in HEAT over CON ($P < 0.05$); and stroke rate 1, stroke rate 2 and stroke count were higher in HEAT compared to CON ($P < 0.01$, $P < 0.05$, $P < 0.01$, respectively) (Table 1). For female participants, the 50m Freestyle times showed a trend to be 0.38% ($P = 0.09$) faster in HEAT over CON, just under 0.4%- the value of the smallest worthwhile enhancement (13)- and stroke rate 2 and stroke count were higher ($P < 0.05$, $P < 0.1$ respectively) in HEAT compared to CON (Table 1). When the

50m Freestyle time was analyzed according to Hopkins (20), the practical inference of HEAT was ‘likely beneficial’ (93.1%) for both genders combined and ‘very likely beneficial’ (97.5%) when looking at male participants alone. Female participants alone demonstrated a ‘possible benefit’ from HEAT, with any harmful negative effect from the condition being ‘very unlikely’ (0.9%).

3.3 Plyometric press-up

Absolute data for plyometric press-ups are shown in Fig. 3. Starting Strength and Peak Force were greater in HEAT compared to that in CON (Fig. 3) by 10.1% ($P < 0.05$) and 10.7% ($P = 0.097$). However, there was no difference in Peak Concentric Power when looking at all participants together (Table 1, Fig. 3). Male participants alone showed a 16.5%, 18.1% and 16.2% improvement in SS, PF and PCP, respectively, in HEAT over CON (all $P < 0.01$). There was no difference found in female participant SS ($P = 0.157$) or PF ($P = 0.112$), though there was a trend in PCP ($P = 0.07$) (Table 1).

3.4 Tympanic temperature, skin temperature & muscle temperature

There was no difference between conditions in mean torso T_{sk} before the warm-up or following the warm-up. After completion of the warm-up, T_{sk} had declined by ~4°C in both conditions, with a slightly higher torso T_{sk} observed in CON compared to HEAT (29.5 ± 1.1 vs. 29.1 ± 1.0 °C) ($P < 0.05$). Following the recovery period, however, T_{sk} was 2.3°C higher in HEAT than CON ($P < 0.001$). There was no difference in tympanic temperature between conditions (Table 2). T_m was estimated to be 36.7°C in the HEAT condition in comparison to that of 34.3°C in the CON condition following the recovery period.

3.5 HR, RPE, Thermal comfort and sensation

There was no effect between conditions on either HR (Table 2) during the trials or RPE (17.5) for swimming performance. Thermal sensation was higher (towards ‘‘hot’’) for HEAT compared to that for

CON between 5 minutes into the exercise and the end of the recovery period ($P < 0.01$). Despite this difference, thermal discomfort for the conditions did not differ at any time points when observing all participants combined. There were no differences in thermal sensation between female and male participants (5.5 ± 0.9 vs 5.4 ± 0.6, respectively). There were no differences found in thermal discomfort scores between genders at the baseline, warm-up or post-50m Freestyle. However, a trend was observed in the magnitude of thermal discomfort scores between genders, with female participants showing a trend of scoring higher at 10- and 25-minutes during the HEAT recovery period ($P = 0.056$, $P = 0.082$, respectively).

4. DISCUSSION

This study compared 50m freestyle performances and plyometric press-up measurements of a mixed-gender elite swimming group wearing heated jackets versus standard jackets for 30 minutes between the warm-up and racing, i.e. the period during competition events in which the swimmers tend to be in a holding area with limited ability to perform exercise. A trend for a relevant (>0.4%) magnitude (0.83%) of a 'likely beneficial' (300) improvement in the 50m Freestyle performance and a significantly improved force production was observed in the heated condition. Considering gender, the heated garment significantly improved the swimming performance of male participants by 1.01%, the effect being 'very likely beneficial', and also improving plyometric press-up measurements of both force and power production. However, the results for the female participants were less clear due to mixed results and the low number of participants in this group, showing a 'possible benefit' and 'unlikely to have harmful negative effects for the 50m times.

4.1 Relevance to swimmers' routines

This study addresses the current issue raised by West *et al*. (7) of swimmers being unable to compete within the recommended timeframe of between 5- and 20-minutes after a warm-up, with time spent putting on the competition swimsuit, plus time in the holding areas often exceeding 30 minutes. Current literature examining the effects of different passive post warm-up procedures on swimming performance is scarce and contradictory. Carlyle (31) demonstrated that swimmers who had an eight-minute hot shower or a ten-minute massage achieved 1% greater swim velocity than swimmers without any warm-up procedure; while conversely, De Vries (32) established that a ten-minute massage did not alter performance. McGowan *et al*.'s (15) recent study demonstrated that the passive heating (jacket) alone did not improve the overall 100m performance times (0.37%, $P > 0.05$), though performance in the first half improved by 0.18%. However, the combination of passive heating as well as dryland-based activation exercises significantly improved time-trial performance (~1.1%, $P < 0.01$) (15). While Faulkner *et al.* (6, 12) and Raccuglia *et al.* (33) demonstrated for cyclists that heated tracksuit pants alone were sufficient in maintaining part of the warm-up T_m increase during a 30-minute transition period, or could even abolish the drop in T_m completely, the present study looked at testing the use of passive heating in swimmers with a more senior and elite group of participants, and for a shorter performance distance than in McGowan *et al.*'s (15) study. The positive effects observed in the present study are all around or above the 0.4% level of the smallest worthwhile enhancement in swimming (13), and the size of the improvements are similar to the combination strategy McGowan *et al.* tested. The observed results, especially for the male participants, give us great confidence in terms of practical relevance, as the analysis was a direct measure and simulation of a swimming race; and passive heating would therefore be recommended as a method to enhance a competition performance. Of the various differences between the present study and McGowan *et al.'s* study, the shorter distance of the event tested here (50m vs 100m) may be the most important, pointing to the impact of muscle heating mainly in short sprint type exercises, where central factors may be of little or no importance (34).

The female participants demonstrated an average 0.38% ($P = 0.09$) improvement in the 50m performance, just outside the set value of 0.4%. Though with only four data points the statistical power is low, the fact that half of the female participants improved in performance while half declined in performance indicates that even with a larger group, achieving a significant positive effect may be difficult, suggesting a potential gender effect.

As mean velocity is the product of the stroke rate and distance moved through the water with each completed stroke (Velocity [$m.s^{-1}$] = stroke rate [s^{-1}] * distance per stroke [m]), the increases observed in swimming velocity after wearing the heated garment are thought to be achieved mainly by the higher stroke rate (35). Greater stroke rates of 5% ($P < 0.05$) and 3.8% ($P < 0.01$) in stroke rate measures 1 and 2 respectively were observed (Table 1). Studies have displayed that higher stroke rates have a clear relationship with an improved sprint freestyle performance (19, 36). An increase in stroke rate consequently decreased the distance per stroke, displayed in the 50m Freestyle by the higher stroke count in HEAT ($P < 0.01$). The higher stroke rates are likely enabled by the greater preservation of muscle temperature between warm-up and performance under the HEAT condition.

4.2 Muscle temperature

Although muscle temperature was not directly measured in the present study, it seems valid to suggest the HEAT strategy would have lessened the decline in muscle temperature following the completion of the warm-up (6, 12, 33). This is supported by the data which indicated that wearing the heated jacket following the warm-up for a 30-minute period raised T_{sk} by over 2°C more than T_{sk} without the heated jacket (Fig. 4). From this it is estimated that T_m was 36.7°C after HEAT in comparison to that of 34.3°C in the CON condition (27), though the validity of De Ruiter *et al*.'s equation for the present application may be questioned. Nevertheless, based on the above, it is believed the post warm-up decline in T_m was smaller after the HEAT condition than that after the CON condition; and given that a difference in T_m as little as 0.3°C may critically affect performance (12), HEAT is assumed responsible for the positive effect on subsequent performances.

The majority of the beneficial effects of a warm-up have been attributed to temperature-related mechanisms (9). The relationship between muscle temperature and muscle function has been well established (10, 37, 11). Racinais & Oksa (5) concluded that muscle temperature may be the crucial factor in determining the outcome of short duration performance (R=0.91). Therefore, maintaining a raised muscle temperature through a warm-up is fundamental in achieving optimum sprint performance. Heightened muscle temperature enhances performance due to decreased stiffness of muscles and joints, increased transmission rate of nerve impulses, an altered force-velocity relationship and increased glycogenolysis, glycolysis and high-energy phosphate degradation (9). Thus, for a given force, the muscle-fiber conduction velocity should have increased following a heated recovery compared to that of the control (10). Greater muscle temperatures have also been linked to increases in myosin adenosine triphosphatase (ATPase) activity, increasing the rate of ATP turnover and calcium sequestration by the sarcoplasmic reticulum (5, 38). These physiological changes explain why a greater power output is achieved at higher muscles temperatures. As muscular power is a major factor in swimming success, determining the ability to generate propelling forces, it is vital that muscle temperature is maintained (39).

Currently, there is no generally adopted method of maintaining muscle temperature during swimming competitions. Consequently, swimmers compete with less-than-optimal muscle temperatures, as warm-ups are generally completed from anywhere between 45 minutes to even 3 hours before racing. This is far from the optimum time frame of 5–20 minutes between cessation of warm-up and racing (2, 3); but due to lack of warm-up facilities and competition time constraints, optimizing the warm-up timing is not feasible. Durations longer than the suggested window to compete result in lower-than-optimal muscle temperatures, as postulated in the control condition. This will subsequently effect muscle contractile properties, producing slower, less powerful contractions (27, 37). As a result, swimmers may not present themselves at the optimum physical condition, thus decreasing their chances of achieving their greatest performance times. Any improvement that can be achieved would provide the individual swimmer with a competitive advantage.

4.3 Plyometric press-up data

In order to analyze the arm forces and power production separately from other factors affecting swimming performance, plyometric press-ups were assessed. The focus of the study was based on upper-body measurements, as arm strength is the main criterion used to explain sprint swimming performance (16). The muscle activation required during a press-up involves three of the four main swimming muscles used to propel a swimmer through the water: pectoralis major, deltoids and triceps brachii (26). Hence, press-up measurements are assumed to be a valid indicator of swimming performance, requiring the same muscle groups as a bench press (except in the prone position), which has been associated with swimming velocity (16). This, along with the pilot study, displayed plyometric press-up reliability and validity as a functional measurement of upper-body power output within swimmers.

While the male participants showed clear and substantial improvements due to the use of the heated garment (>15%), the female participants did not display any improvements in peak concentric power or force production after HEAT relative to CON. This may be due to the physiological differences between the female and male participants, and the differences in weekly exercise routines (Time in gym: Male: 5.5 ± 0.4 vs Female: 2.6 ± 1.1 hours). But again, due to the small sample size of female participants, the chance of type II error is dramatically increased.

It can be assumed that the levels of greater force and power observed in the plyometric push-ups would have transferred into the 50m Freestyle performance. Whereby, improvements in arm strength may result in higher levels of maximum force per stroke and greater power would increase the stroke rate, producing faster swimming velocities displayed in the study (16). These findings are consistent with previous literature, presenting a positive relationship between the body temperature's effect on movement velocity and performance (5). This study supports previous literature in that, with every 1°C rise in muscle temperature, there is an estimated 4%–10% improvement in peak power output; as in the present study, T_m is thought to be ~2°C greater in HEAT than that of CON (10, 11, 12), with a 16% to

18% increase in SS, PF and PCP. The studies to date assessing passive heating have focused on assessing lower-body measurements of power output. To the authors' knowledge, this is the first study to assess passive heat maintenance on upper-body measurements of force production and power output; therefore, the enhancements observed are an important addition to the literature.

Thermal sensation and comfort

It can be seen as positive that the only difference in subjective measurements was thermal sensation (P < 0.01) between the two conditions, likely due to the increased T_{sk} (P < 0.0001) (Table 2) after HEAT. However, importantly, thermal comfort (Table 2) did not differ, signifying that the participants regarded both the heating and the lack-of-heating conditions as thermally acceptable. The conformity of the perceived comfort is fundamental, as pre-exercise thermal discomfort has been associated with impaired performance (40). However, when comparing gender scores, female participants rated significantly higher for thermal discomfort over the 30-minute recovery period under the HEAT condition, suggesting they were slightly uncomfortable in comparison to the male participants showing ratings of discomfort (2.9 ± 0.4 vs 1.6 ± 0.3, HEAT vs CON, respectively $P < 0.05$). This may have affected the female particpants' performances, as only two out of the four female participants demonstrated improvements in the 50m Freestyle performance under the HEAT condition.

This variance may be due to morphology differences in body size and body composition between the genders affecting thermoregulation. As the female participants had a significantly higher body-surface-area to mass-ratio and body-fat percentage than the male participants, they may have experienced a greater heat strain (41). However, as tympanic temperature did not significantly differ between genders and both were far from 39°C, the higher ratings for thermal discomfort may not be due to heat strain (5). Instead, the female participants may have felt slightly more uncomfortable, possibly due to a higher thermoreceptor density based on having a significantly lower body-surface area (42). Females are more sensitive to innocuous heat (40 °C) stimulation than males (42). Consequently, the differences observed in performances between male and female participants may not be due to differences in the thermal state of the body, but to thermal perception. As performance intensity is strongly influenced by the thermal status of the body, detected by thermal comfort, this may have had a negative impact on the female performances (40). This highlights the importance of studies testing both male and female participants rather than generalizing findings of both genders. Consequently, females may favor a reduced heating power and reduced temperature for the heated jackets, a point for further study.

4.4 Limitations

Measures of T_m were not recorded during the trials due to its invasive nature and the problems with keeping sterility when entering the pool. This does not detract from the meaningfulness of this data, as although attenuation of the T_m drop is vital for performance enhancement, estimates of T_m were calculated based on its linear relationship with T_{sk} (27, 43). Also, given that previous studies from our lab, most recently Faulkner *et al.* (6, 12) and Raccuglia *et al.* (33), have demonstrated T_m maintenance with the use of passive external heating, it is highly likely that T_m in the present study would have followed similar time course changes. In addition, another limitation to this study was a relatively small number of female subjects tested (*n*=4) due to logistical problems, increasing the risk of type II errors and limiting the possibility of gender comparisons. To confirm the observed response differences between genders, future research should test a greater number of female swimmers, with the possibility of a self-adjustable temperature control in order to avoid any possible negative effects of thermal discomfort and subsequent negative impacts on performance.

4.5 Conclusions

This study has demonstrated that a 30-minute period of upper-body external heating using electrically heated jackets post warm-up leads to a significant and relevant improvement in sprint-swimming performance, upper-body force and power output when compared to a non-heated control in elite male swimmers. No significant effect was observed for the female group on its own, suggesting a gender difference with possible links to gender differences in experienced discomfort; but given the small female group size, further research should be carried out. This study provides an important practical application of heated garments for swimmers due to the unavoidable timeframe between completion of warm-up and racing. These findings may be relevant to all sports that experience delays after warm-up or have an intermittent nature, and are reliant on high peak-power output, as in sprint exercises. Given that the jackets used in this testing were mainly designed for thermal comfort in motorcyclists, it is hypothesized that the heating provided can be further improved by designing the jackets' heater distribution to align with the major muscle groups used in swimming. Additional leg heating (though limited impact is expected in freestyle) could also be considered, e.g. for breaststroke. In addition, personal control of the heating power may contribute positively to the acceptance of the heating jackets, especially for female participants.

5 PRACTICAL IMPLICATIONS

This study supports the use of heated garments for the upper body to be used by competitive swimmers to maintain muscle temperature between the warm-up and the event, or between events, in order to improve performance. More work is needed to understand why this benefit was evident in male participants but not clear in the tested female participants. It is possible that females' higher sensitivity to heat could influence the benefit of the used warming procedure, and would require an adjustable heating system.

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CONFLICT OF INTEREST

No conflicts of interest are reported.

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Table Captions:

Table 1. Male and Female (n=12), Male only (n=8), Female only (n=4), 25m split, 50m Time, Stroke Rate 1 (SR1), Stroke Rate 2 (SR2), Stroke Count (SC).

Table 2. Tympanic temperature (TT), skin temperature (T_{sk}), HR, thermal sensation (TS) and thermal comfort (TC) at baseline (BASE), after warm-up (30 WUP), after passive recovery (30REC) and straight after the maximal 50m Freestyle (POST50) for control (CON) and heating (HEAT) conditions (n=12).

Figure Captions

Figure 1. Thermogram of Powerlet rapidFIRe Proform Heated Jacket Liner

Figure 2. Mean and Individual 50m Freestyle swimming performance times for control (CON) and heating (HEAT) for Males and Females. * $P < 0.05$, HEAT < CON. § $P < 0.1$, HEAT < CON.

Figure 3. Mean (±SD) values of starting strength (SS) and peak force (PF) and Peak Concentric Power (PCP) for control (CON) and heating (HEAT). § $P < 0.1$ HEAT > CON. *$P < 0.05$, HEAT > CON. ** $P < 0.01$, HEAT > CON.

Figure 4. Mean (SD) upper-body mean skin temperature measures prior to warm-up (0WUP), straight after warm-up (30WUP), and after 30 minutes seated recovery (30REC) in control (CON) and heating (HEAT) (n=12). * $P < 0.05$, CON > HEAT. † $P < 0.0001$, HEAT > CON.